Vulnerability Assessment of Coastal Bend Bays

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Abstract

There is concern about rising salinities in the Coastal Bend region of Texas. Salinities could rise due to several long-term changes, such as, increasing temperature that increases evaporation, reduced freshwater inflow that provides less seawater dilution potential, or industrial brine discharges. The purpose of this project is to identify and map areas of particular ecological importance and/or vulnerability in the Corpus Christi Bay region based on seasonal salinity modeling, living marine resources distribution and abundance, and species-specific salinity tolerances. The result of the project contributes to achieving Coastal Bend Bays Plan objectives FW-1, BTR-3, MC-1, HLR-1, and WSQ-1 (CBBEP 2020).

The Corpus Christi Bay region has high annual average wind speeds, temperatures, and salinities, and circulation in the region is sluggish. In combination, this means that the region is sensitive to changes in water borne materials because they are easily concentrated by the high evaporation rates and hard to disperse because of low flushing rates.

Overall community diversity is related to salinity, and as salinity increases past the optimal range, species diversity declines. The optimal salinity to maintain high diversity in bag seine samples that were collected along the shorelines of Corpus Christi Bay is between 22 and 24. However, the average salinity in the whole Corpus Christi Bay system is 28.5. In fact, the average salinity in the whole system is only about 25.5 in wet years, so on average, the system is already suffering from high salinity stress. For Corpus Christi Bay alone, the salinity is much higher, averaging 31.4 from 1987 to 2016.

Salinity changes affect various species differently. The most sensitive species to salinity increases were blue crab, Atlantic croaker, and white shrimp. Because the average salinities are already at levels that could impact species abundance and diversity, small increases in salinity could add additional pressure to a system that is already experiencing salinity stress.

Introduction

There is concern about rising salinities in the Coastal Bend region of Texas. Salinities could rise due to several long-term changes, such as, a hotter and dryer climate in the Southwest (Seager et al. 2007), which leads to less streamflow (Miller et al. 2021); reduced freshwater inflow from diversions (Asquith et al. 1997); increased evaporation; and/or industrial brine discharges from oil and gas production, desalination, or other industrial practices. All of these potential changes can either reduce freshwater inflow and decrease the dilution of seawater, or increase salinity by concentrating existing salt in the bay. Rising sea water temperatures and salinities have been documented in the Coastal Bend (Montagna et al. 2011a). This is especially true for the period since 1982 and impoundment of the Choke Canyon Reservoir (Asquith et al. 1997, NBBEST 2011). The rising salinities in Nueces and Corpus Christi Bays is giving rise to concern about the effects of increased salinity on living resources of the region.

It is well known that salinity distributions define estuaries both in the context of its spatial structure, which are the observed horizontal and vertical gradients, and temporal variability on time scales that range from hours to years (Orlando et al. 1993). Estuarine species typically have preferred salinity ranges (Nelson 1993, Pattillo et al 1993, Freshwater Inflow Tools 2021). Thus, salinity zones have long been recognized as defining estuary habitat (Table 1). Many nekton species occurring in coastal waters share a common estuarine-dependent life history strategy characterized by near-shore spawning in the Gulf of Mexico with larvae migrating through tidal inlets into shallow estuarine nursery habitats. Access to high quality habitat and spawning grounds via tidal inlets is essential for reproduction, growth, survival, and maintenance of these populations.

Table 1. Salinity modifiers used in a salinity zone classification system (Venice System 1959 modified and adapted from Cowardin et al. 1979).

Coastal Modifiers	Salinity	Specific Conductance (µMhos at 25°C)
Hyperhaline	> 40.0	> 60,000
Euhaline	30.0 - 40.0	45,000 - 60,000
Polyhaline	18.0 - 30.0	30,000 - 45,000
Mesohaline	5.0 - 18.0	8,000 - 30,000
Oligohaline	0.5 - 5.0	800 - 8,000
Fresh	< 0.5	< 800

The purpose of the current project is to identify and map areas of particular ecological importance and/or vulnerability in the Corpus Christi Bay region (Corpus Christi Bay, Nueces Bay, and Redfish/South Aransas Bay) based on seasonal salinity modeling, and juvenile fish and invertebrate species distribution. This project contributes to achieving Coastal Bend Bays Plan objectives FW-1, BTR-3, MC-1, HLR-1, and WSQ-1 (CBBEP 2020).

This report is an analysis based on existing data. No new data was collected. The approach was to compare salinity and fishery data in wet year and dry year combinations to determine how the living resources changed in response to changes in salinity over time. Then to compare the relative magnitude of the change, which allows prediction of how the estuary might respond to future increases in salinity.

Methods

Secondary data was acquired and added to Geographic Information System (GIS) layers. The GIS layers included: 1) salinity model output for wet and dry years obtained from the Texas Water Development Board (TWDB) via Joe Trungale, and 2) juvenile fish and invertebrate abundance and distributions obtained from long-term, fisheries-independent bag seine surveys conducted by the Texas Parks and Wildlife Department (TPWD). Bag seine samples are collected along shorelines, which are more likely to be affected by changes in adjacent land-use patterns.

Visualizations for the project area including localized and broader environmental impacts are key tools managers can use to make informed decisions regarding various aspects of project design and implementation. Heat maps, which are graphical representations of data using a matrix of colors, are useful for visualizing attributes of ecosystems. This approach has been used successfully to create a heat map of ecosystem services provided by habitats within the CBBEP area so that valued ecosystem components could be identified for ecosystem-based management approaches (Montagna et al. 2011b, Hutchison et al. 2013). A new tool and updated charts identifying salinity model outputs during average, wet, and dry years, and consequent changes in species diversity and distribution of juvenile fish and invertebrates species. These heat maps can serve as a valuable tool to better understand the bay system and inform future protection and restoration.

Salinity Data

The primary source of salinity data is the input file for the TWDB Nueces Bay System TxBlend salinity circulation model. The TxBlend computer model is designed to simulate water circulation and salinity condition in estuaries. The model output includes time-varying depth and vertically averaged horizontal velocity components of flow and salinity throughout the model domain. TxBlend thus provides water velocity and direction, surface elevation, and salinity at each node in the grid. The model provides information about horizontal variation, such as salinity zonation patterns throughout the estuary. Much of the TWDB data can be found at Water Data for Texas website: https://www.waterdatafortexas.org/coastal/hydrology.

The TxBlend computational grid for the Nueces Estuary contains 11,009 nodes and 19,035 triangular elements (Figure 1). In addition to the bays of the Nueces Estuary system, the model grid also represents Copano and Aransas bays to the northeast and upper Laguna Madre and Baffin Bay to the southwest. These bays were excluded to yield better simulation. Salinity was obtained monthly from a 30-year (1987 to 2016) period.

Figure 1. TXBlend nodes for monthly salinity (black dots) and daily
average salinity (green dots).

TxBlend salinity data were classified into wet, average, and dry years based on quartile analysis.
The quartile measures the spread of values above and below the median by dividing the
distribution into four groups. A quartile analysis divides data into three sections or quarters of
more or less equal size, which are a lower quartile, median quartiles, and upper quartile, forming
four groups of the dataset. Salinity was averaged over all nodes by month, then all months, then
all years for the sampling period. Sample salinities below the first quartile (Q1) were classified
as 'Wet' years, samples above the third quartile in the fourth quartile (Q4) were considered 'Dry'
years, and thus sample salinities within the interquartile range (Q2-Q3) were classified as
Average years.

Mapping of saline areas was accomplished using Kriging Geostatiscal Techniques. Kriging is an
interpolation method to estimate values at unknown points based on the values at known points
by a weighted averaging of nearby samples. Kriging was used to interpolate sample salinity
values in order to create salinity maps for wet and dry years. Interpolated maps were constructed
in ArcGIS Pro based on average salinity for each year.

Contrasts between wet and dry years was calculated using ArcGIS Pro Raster Calculator (Spatial
Analyst) to build and execute Map Algebra using Python syntax. The difference in salinity
between the dry and wet years were calculated. The new raster was obtained by estimating the
difference between the two rasters using the following syntax used: {dry_Year_raster} –
{wet_year_raster}

There is controversy about salinity units. Originally, salinity was measured gravimetrically, and the units were clearly g/kg and often expressed as parts per thousand (ppt or ‰). Today, salinity is measured by electronic probes that are actually measuring conductance and converting it to a salinity-like unit. From this came the designation of practical salinity units (psu). Many oceanographers argue that salinity is unitless and the numbers should be reported without units or designation, so the psu and unitless conventions are followed here.

Fishery Data

Fish and Invertebrate Sampling

Fish and invertebrate data were collected as part of the Texas Parks and Wildlife Department (TPWD) fishery-independent monitoring program (Martinez-Andrade 2015). Twenty bag seine samples are collected monthly within each major bay system of the Texas coast based on a stratified, random sampling design; though, the monthly sample size for each bay system ranged between 10-16 samples prior to 1992. Bag seine samples (n = 8021) collected from 1987 to 2016 from Aransas Bay, Corpus Christi Bay, and upper Laguna Madre and located within the study area were analyzed. Bag seines (18.3 × 1.8 m, with 19-mm stretched mesh in the wings and 13-mm stretched mesh in the bag) were deployed in shallow habitats (q 2 m depth) and pulled parallel to shore for 15.2 m (further details of sampling protocols are described in Martinez-Andrade 2015). Captured fish and invertebrates greater than 5 mm total length were identified to the lowest taxonomic level and counted. The bag seines used in this study were designed to sample juvenile estuarine fish and invertebrates, and only a small number of juveniles are captured in other deeper-water sampling gears (e.g., otter trawls; Olsen 2019). Hydrological data including salinity, water temperature (°C), dissolved oxygen (mg/L), and turbidity (nephelometric turbidity units, NTU) were recorded from surface waters (0 - 15 cm) at each sampling site. The minimum and maximum depth (m) of each bag seine haul were also recorded, and for this study, depth is defined as the mean depth of each seine haul.

The TPWD uses a random sampling design, which means different stations are sampled on different occasions. However, salinity gradients exist in relatively fixed location, so it is necessary to aggregate stations to force the data into a quasi-synoptic sampling design to allow comparison of change in location over time. For analysis, bag seine sample locations were assigned to four minor bay subregions (or areas): Redfish and South Aransas Bays, North Corpus Christi Bay, South Corpus Christi Bay, and Nueces Bay (Figure 2), which have different long-term average salinities (Table 2). The following abbreviations are used for each location: RB = Redfish and South Aransas Bays, NC = North Corpus Christi Bay, SC = South Corpus Christi Bay, and NB = Nueces Bay.
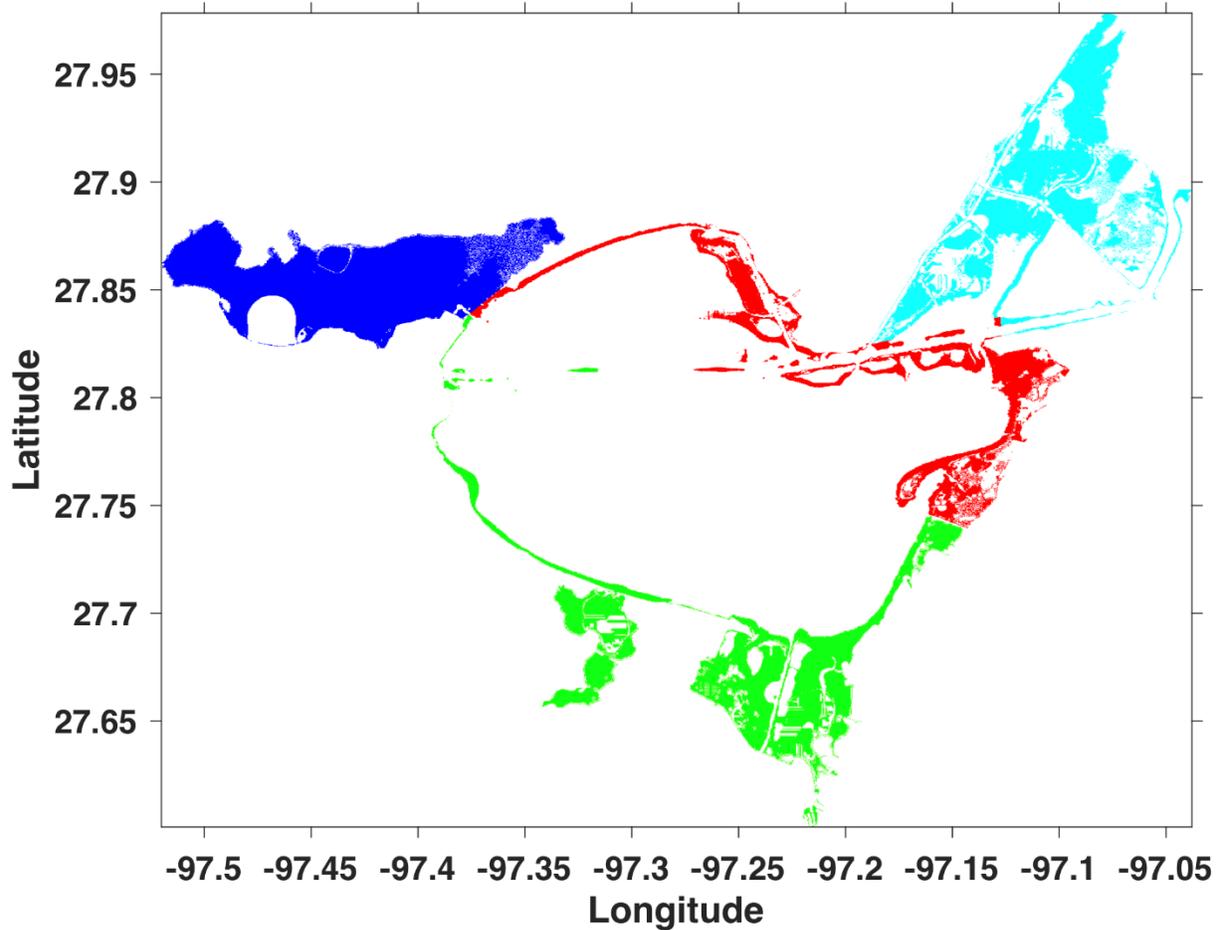
Figure 2. Corpus Christ Bay region. Shaded portions denote waters q 2 m depth and are separated into four subregions for analysis of the spatial distribution of suitable habitats: Redfish and South Aransas Bays (cyan), North Corpus Christi Bay (red), South Corpus Christi Bay (green), and Nueces Bay (blue).

Table 2. Average salinities (with standard deviation) measured by TPWD in subareas of the Corpus Christi Bay system between 1987 and 2016.

Minor Bay Name	Area	Samples	Salinity	
Nueces Bay	NB	1590	26.69	(10.27)
South Corpus Christi Bay	SC	1716	32.29	(6.87)
North Corpus Christi Bay	NC	2605	30.82	(5.03)
Redfish/South Aransas Bays	RB	2110	27.99	(6.31)

Diversity

Diversity is calculated using Hill's diversity number one (N1) (Hill, 1973). It is a measure of the effective number of species in a sample and indicates the number of abundant species. It is calculated as the exponentiated form of the Shannon diversity index:

$$N1 = eH' \qquad (1)$$

As diversity decreases N1 will tend toward 1. The Shannon index is the average uncertainty per species in an infinite community made up of species with known proportional abundances (Shannon and Weaver, 1949). The Shannon index is calculated by:

$$H' = -\sum[(n_i/n)\ln(n_i/n)] \qquad (2)$$

Where n_i is the number of individuals belonging to the ith of S species in the sample and n is the total number of individuals in the sample.

Salinity Preference Modeling

It is necessary to identify salinity preference ranges for the living resources to calculate how organisms respond to salinity as a driver. The functional relationship between biological metrics to salinity has been explained using a nonlinear model in Texas (Montagna et al. 2002) and Florida estuaries (Montagna et al. 2008). The assumption behind the model is that there is an ideal range for ecological drivers and macrofauna responses decline prior to and after reaching a maximum threshold driver value. The relationship resembles a right-skewed bell-shaped curve such as a log-normal distribution. The nonlinear log-normal equation is fit to the dataset using the Max Bin approach (Turner and Montagna 2017). The model can be used to characterize the nonlinear relationship between biological characteristics where dependent variables could be abundance, biomass, or diversity and the independent variables could be salinity, temperature, or depth. The three parameters characterize different attributes of the curve, where a is the peak of the dependent value (Y-axis), b is the skewness or rate of change of the response as a function of X, and c the optimal value of the independent variable on the X-axis (Eq. 3).

$$Y = a \times \exp\left(-0.5 \times \left(\ln\frac{\left(\frac{X}{c}\right)}{b}\right)^2\right) \qquad (3)$$

Habitat Suitability Modeling

Three fish (pinfish, *Lagodon rhomboides*; Atlantic croaker, *Micropogonias undulatus*; sheepshead minnow, *Cyprinodon variegatus*) and three invertebrate (white shrimp, *Litopenaeus setiferus*; brown shrimp, *Farfantepenaeus aztecus*; blue crab, *Callinectes sapidus*) species were selected for habitat suitability analyses based on ecological and economic importance, varying salinity tolerances (Tolan 2013), and suitable sample sizes. These species represent a range of taxonomic groupings (i.e., invertebrates and vertebrates), life history strategies (i.e., oceanic spawners and estuarine spawners), and trophic levels (abundant forage species and juvenile predatory species). Preliminary analyses indicated that catch data were skewed, including many zero or low values and few large observations, which is typical of many fishery datasets. Black drum (*Pogonias cromis*), spotted seatrout (*Cynoscion nebulosus*), red drum (*Sciaenops ocellatus*), southern flounder (*Paralichthys lethostigma*), and Gulf menhaden (*Brevoortia patronus*) were also explored; however, salinity was not retained as a predictor in best-fit models and thus these species were excluded from further analysis.

A generalized additive model (GAM) framework was used to investigate the influence of spatiotemporal variables on the probability of capture or occurrence (presence/absence) for each

species using a binomially distributed response with a logit link function. Candidate predictor variables included minor bay region, year, month, depth, and hydrological data recorded at each bag seine sampling site. Collinearity between candidate predictor variables was assessed with Pearson correlation coefficients and variance inflation factors (VIF) using the 'corvif' function (Zuur et al. 2009) in R (R Core Team 2020). Thin plate regression splines were estimated for each environmental variable, whereas month was modeled using a cyclic cubic regression spline, which constrains the start and end points of the smooth term to be the same (Wood 2017). To prevent overfitting (i.e., unrealistic ecological responses), the gamma parameter was set to 1.4 in all models (Wood 2017), and each regression spline was automatically penalized from a specified maximum degrees of freedom (df =5, excepting month df = 12) and the degree of smoothing selected by minimizing the restricted maximum likelihood (REML) score (Wood 2011). Model flexibility using alternative maximum degrees of freedom was explored; however, df = 5 was optimal based on the maximization of cross-validation area under the receiver operating characteristic curve (AUC; see below and Furey and Rooker 2013 for additional methodological details). GAMs were constructed in R using the 'mgcv' package (Wood 2017), and model selection was based upon an information-theoretic approach through minimization of the second-order Akaike Information Criterion (AIC$_c$; Burnham and Anderson 2002) using the 'MuMIn' package (Bartoń 2020). Models with substantial support were selected based on a ΔAIC$_c$ < 2 from the model with the lowest AIC$_c$ and included in model averaging based on Akaike weights (w; Burnham and Anderson 2002). Significant predictor variables ($p < 0.05$) with high relative importance were retained in the final model used for evaluation of model predictive performance, graphical representation of terms, and habitat suitability mapping. The partial deviance explained by each predictor variable i was calculated as the difference between the deviance explained by the final model and submodel lacking i divided by the deviance explained by the null model (intercept only). To compare with the full model, smoothing parameters for the remaining terms in the submodels were set equal to their estimates from the full model.

The predictive performance of GAMs was assessed using cross-validation in two configurations. First, models were refit on a randomly selected 75% training subset of observations, and the resulting model was used to predict the probability of occurrence on the withheld 25% test subset. This process was then repeated ten times. Second, each year was omitted from the training dataset when refitting the model to examine interannual predictive performance. The cross-validation process generated two mean (± standard error) estimates of AUC for each final model using the ROCR package (Sing et al. 2005) in R. AUC is a threshold-independent statistic that represents the relationship between the false-positive ratio (1 - specificity) and the true-positive ratio (sensitivity) and ranges from 0 (no predictive capability) to 1 (perfect predictive capability). A value of 0.5 indicates that model predictive performance is no better than random, and generally, values from 0.7 to 0.8 are considered acceptable, 0.8 to 0.9 are good, and >0.9 represents excellent model performance (Hosmer and Lemeshow 2000).

Habitat Suitability Mapping

Following Furey and Rooker (2013), spatial grids of 493 m^2 resolution were generated for all areas of the Corpus Christi Bay region ≤2 m depth (total area = 221.94 km^2) using bathymetry data from NOAA's National Geophysical Data Center (NGDC 2007). Hydrological data

recorded at bag seine sampling sites were interpolated across each grid cell throughout the Corpus Christi Bay region using ordinary kriging from the 'automap' package (Hiemstra et al. 2009) in R. Spatial grids were generated for each month during 2007 (wet year), 2008 (average year), and 2009 (dry year) to compare strong interannual contrasts in salinity (annual means of 22.6, 30.7, and 34.7, respectively). The final GAMs for each species were used to predict the probability of occurrence during months with a high abundance of juvenile recruitment (based on catch per unit effort [CPUE]; individuals per bag seine haul, ~300 m^2 or 0.03 ha) during each year under average environmental conditions and across an increasing salinity gradient (1-10 increase in salinity from baseline). Predictions from the fitted GAM models were averaged across high recruitment months for each year to examine interannual changes in habitat suitability. The percent change in habitat suitability relative to 2008 (average year) was calculated to identify spatially explicit changes in predicted occurrence throughout the study area. The highest 10% of predicted values for each species in 2008 were used to designate areas of highly suitable habitat each year. Areas of highly suitable habitat within each minor bay region were then divided by the total amount of available habitat (i.e., ≤2 m depth) within the same region (Redfish and South Aransas Bays: 60.94 km^2; North Corpus Christi Bay: 36.05 km^2; South Corpus Christi Bay: 56.98 km^2; Nueces Bay: 67.97 km^2) to provide the proportion of habitat designated as highly suitable habitat in each year and examine predicted changes in habitat along an increasing salinity gradient from baseline conditions.

Results

Salinity

The bay-wide annual average salinity dataset was used to classify climatic periods based on a quartile analysis (Table 1). Sample salinities below the first quartile (Q1) were classified as 'wet' years with average salinities < 25.5. Samples above the third quartile (i.e, Q4) were considered 'dry' years with average salinities > 32.1. Thus, sample salinities within the interquartile range (Q2-Q3), averages 25.5 to 32.1, were classified as average years. The overall average salinity was 28.5 (± 4.3 standard deviation). A total of eight of the 30 years were categorized as "dry" years including 1988, 1989, 1990, 1996, 2009, 2012, 2013, and 2014; and eight years were classified as "wet" years including 1992, 2002, 2003, 2004, 2010, 2015, and 2016. In general, "dry" years have salinity levels above 32.1 which is 6.6 units higher than "wet" years with salinity of about 25.5.

Table 3. Average salinity for each calendar year and classification period.

Year	Salinity	Classification
1987	26.7	Average
1988	32.9	Dry
1989	34.4	Dry
1990	33.4	Dry
1991	31.5	Average
1992	22.6	Wet
1993	30.0	Average
1994	30.3	Average
1995	28.6	Average
1996	34.9	Dry
1997	27.0	Average
1998	28.1	Average
1999	27.0	Average
2000	31.3	Average
2001	28.9	Average
2002	21.8	Wet
2003	23.2	Wet
2004	21.6	Wet
2005	26.7	Average
2006	31.6	Average
2007	22.6	Wet
2008	30.7	Average
2009	34.7	Dry
2010	21.7	Wet
2011	27.6	Average
2012	32.2	Dry
2013	32.8	Dry
2014	32.2	Dry
2015	22.8	Wet
2016	25.1	Wet

Regardless of the annual mean, salinity varies from month-to-month as well as year-to-year (Figure 2). The percentage of the Corpus Christi Bay area within 5 salinity bins (0 - 5, 6 - 10, 11 - 15, 16 - 20, 21 - 25, 25 - 30, 30 - 35 and > 35) was calculated. The bins are color-coded from blue (0 – 5) to red (> 35), thus a long vertical bar of one color represents a large area of the bay within that salinity range. Blue to green colors represent extended periods of low salinities while orange to red colors represent high salinities during dry periods. While salinities generally increase each summer, there are extended periods of wet weather, such as 2002 to 2005, and dry weather such as 2011 to 2015.
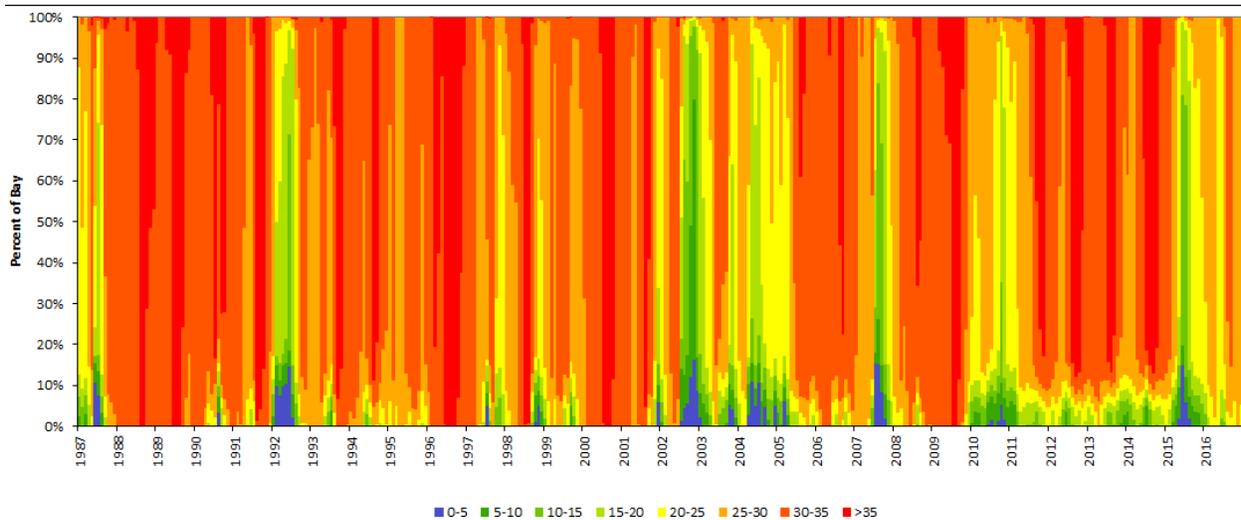
Figure 3. Percent of Corpus Christi and Nueces Bays area within 5 salinity bins each month.

A time series of the spatial variation of average salinity within the bays was mapped on a monthly basis (Appendix 1). Nueces Bay typically has a salinity gradient. In contrast, it is very common for large portions of Corpus Christi Bay to be uniform in salinity, but particularly pronounced during the droughts.

The approach to determine effects of salinity changes was to compare years with a strong contrast in salinity. Four years were chosen for the salinity comparison study of TxBLEND data, which represent two adjacent, paired, dry to wet periods: 2009 versus 2010, and 2014 versus 2015. One of the largest adjacent year-pairs was between 2009 and 2010. 2009 was very dry with an average salinity of 34.7, and 2010 was very wet with an average salinity of 21.7, which was a drop of 13 units, or 37%. The salinity in 2014 was 32.2 and dropped 9.4 units to 22.8 in 2015, which was a 29% decrease.

During the dry year of 2009, the average salinity varied very little across the bay system with salinity ranging from 30 to 36 (Figure 3). However, it was a reverse estuary with the lowest salinities near Aransas Channel, which is connected to Aransas Pass, and the highest salinities near the Nueces River mouth. Overall, the salinity was uniformly high everywhere in the bay system.
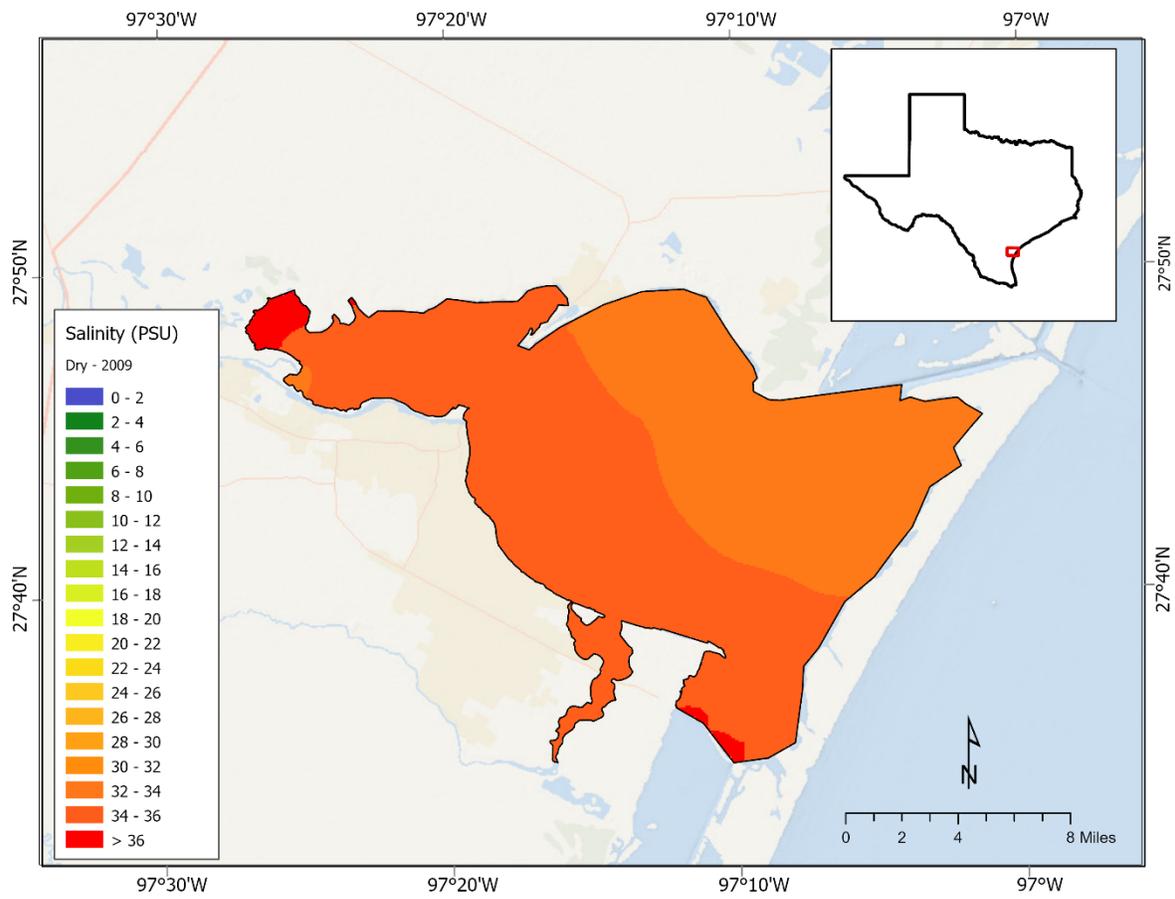
Figure 4. Average salinity in Nueces and Corpus Christi Bays 2009, a dry year.

In contrast, 2010 was a wet year (Figure 4). There was a nice gradient in salinity during the wet year with salinities close to 2 near the Nueces River and increasing to about 22 near the Aransas Channel, which is connected to the Gulf of Mexico. The salinity gradient is most steep in Nueces Bay covering a difference of 14 salinity units.
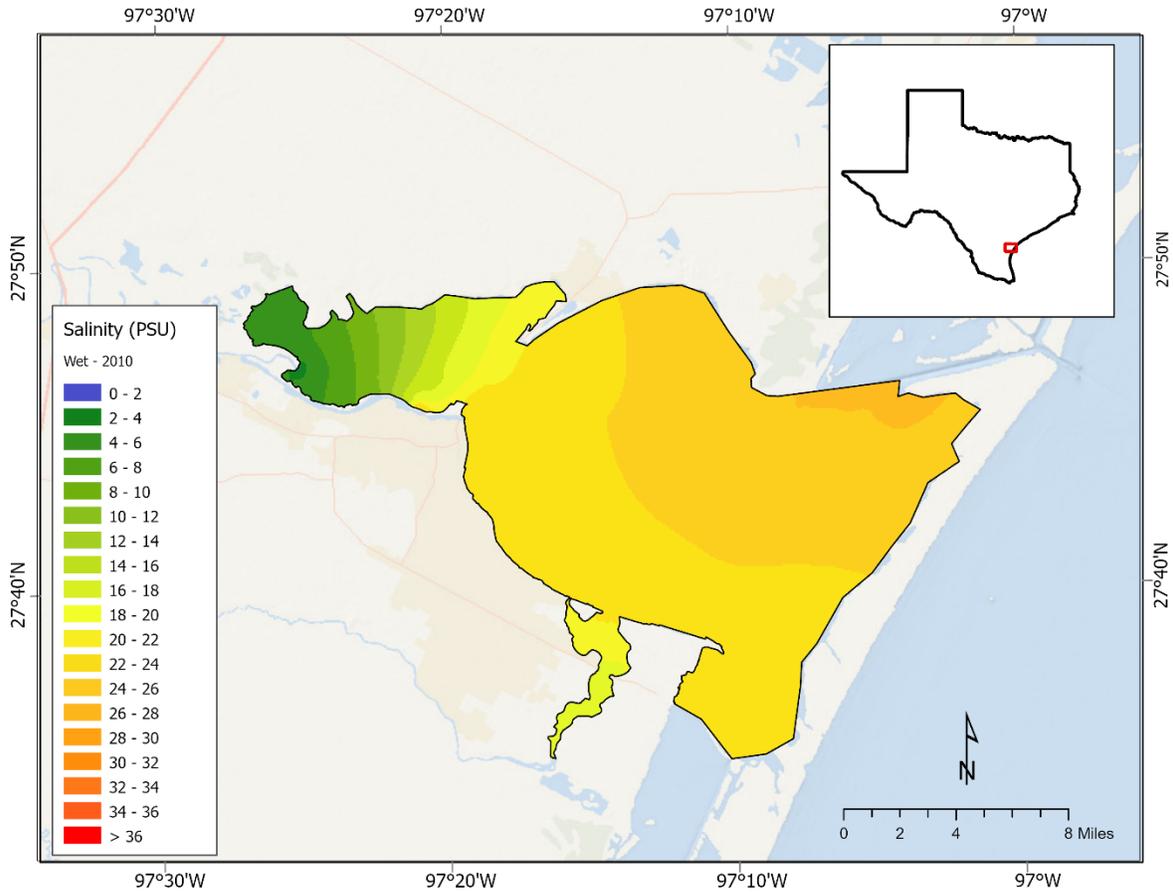
Figure 5. Average salinity Nueces and Corpus Christi Bays in 2010, a wet year.

The Difference in salinity between the dry (2009) wet (2010) years, is most pronounced in Nueces Bay where it is as high at 28.8 psu compared to Corpus Christi Bay where it is always less than 5 psu.
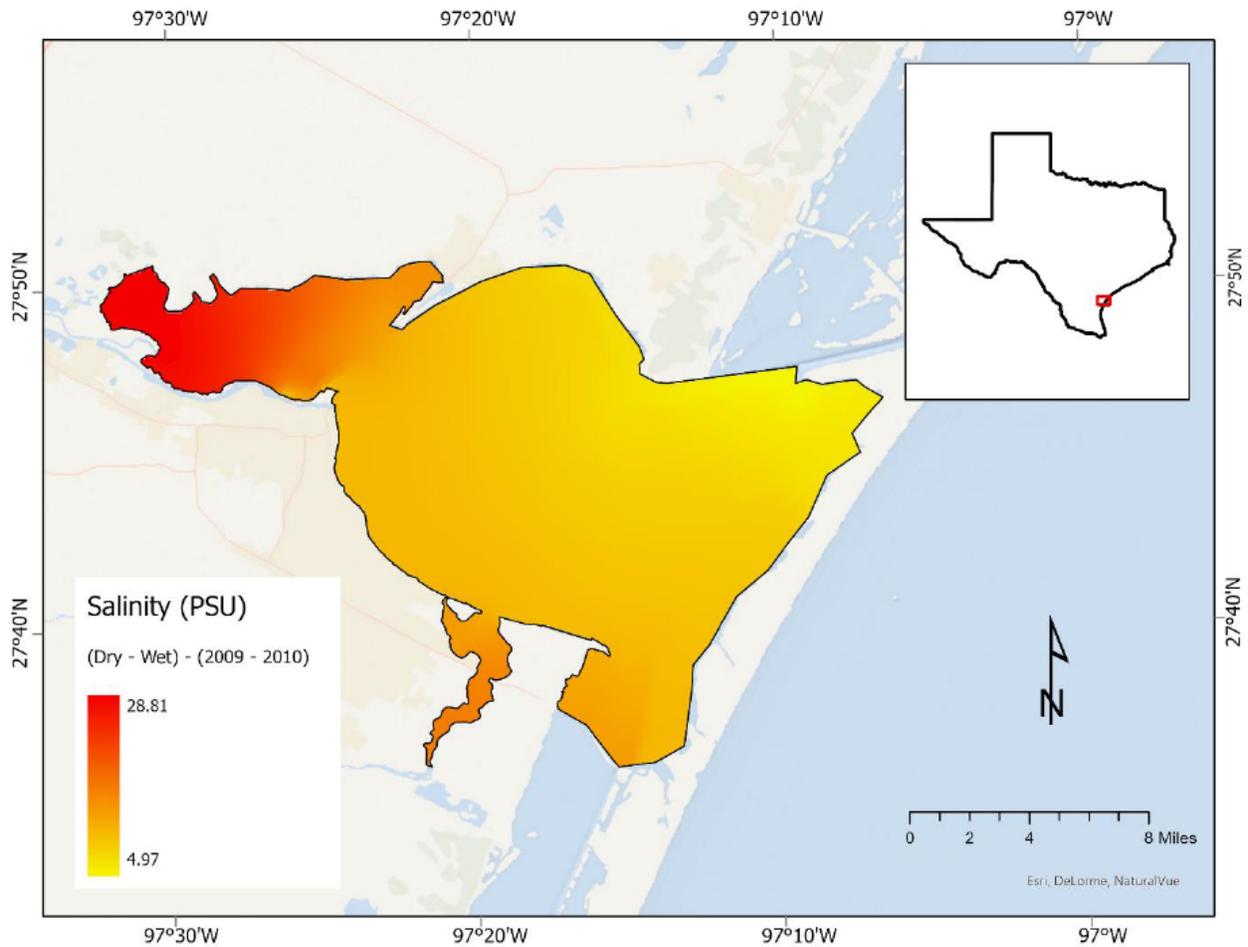
Figure 6. Spatial salinity difference between dry (2009) and wet (2010) years for Corpus Christi and Nueces Bays.

The next pair was 2014 – 2015. The dry year 2014 was different from 2009 in that there was more of a normal salinity gradient in the estuary (Figure 5). In Nueces Bay the salinities ranged from about 10 near the Nueces River to about 30 where Nueces Bay meets Corpus Christi Bay. Corpus Christi Bay had a relatively uniform distribution of salinity of around 30 throughout the bay.
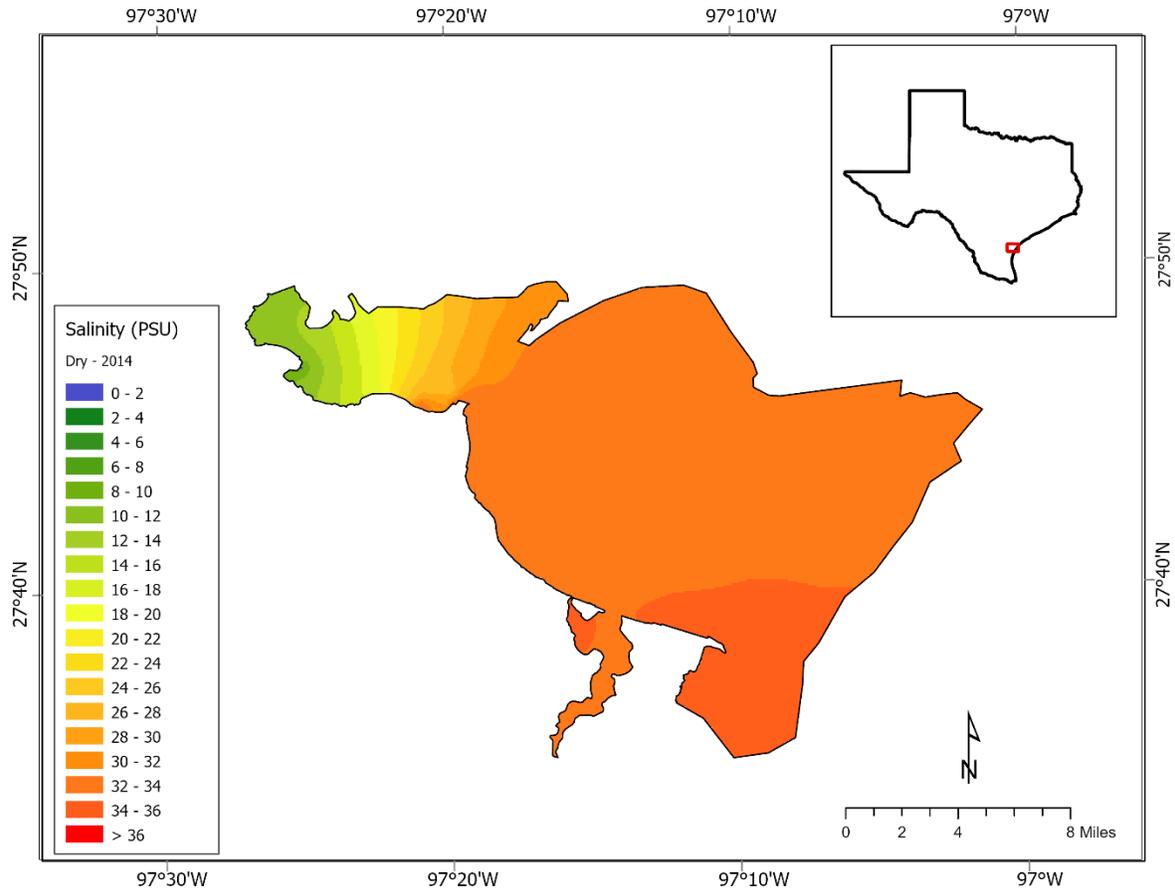
Figure 7. Average salinity in Nueces and Corpus Christi Bays in 2014, a dry year.

The wet year 2015 resembled 2010 with a strong salinity gradient throughout the estuary (Figure 6). Another interesting structure is that there is a split-gradient from northeast to southwest in Corpus Christi Bay, rather than the east-west gradient typical of Nueces Bay. The split in Corpus Christi Bay is seen in 2009 and 2010.
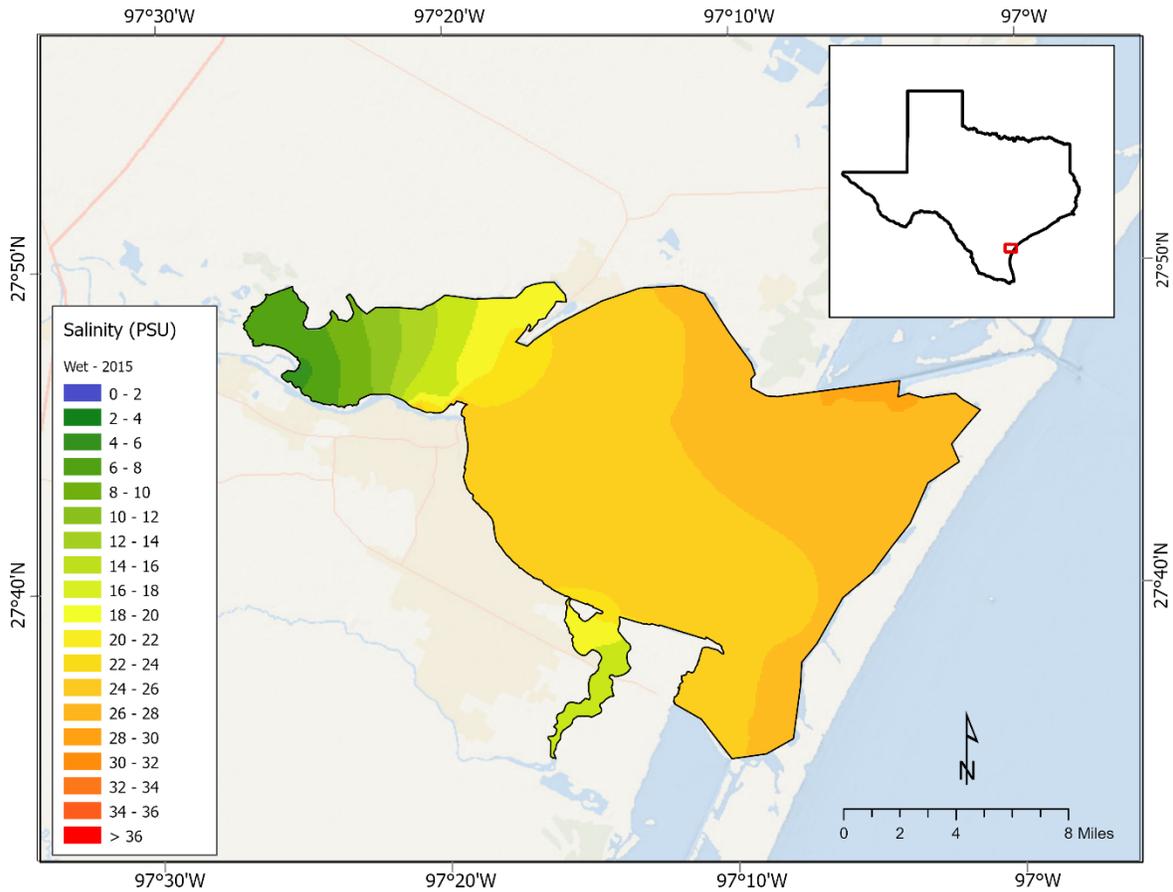
Figure 8. Average salinity in Nueces and Corpus Christi Bays in 2015, a wet year.

The Difference in salinity between the dry (2014) wet (2015) years, is again most pronounced in Nueces Bay, but because the differences were less, only 17 psu in Nueces Bay, the spatial extent of change is less pronounced. Again, Corpus Christi Bay had differences always less than 5 psu.
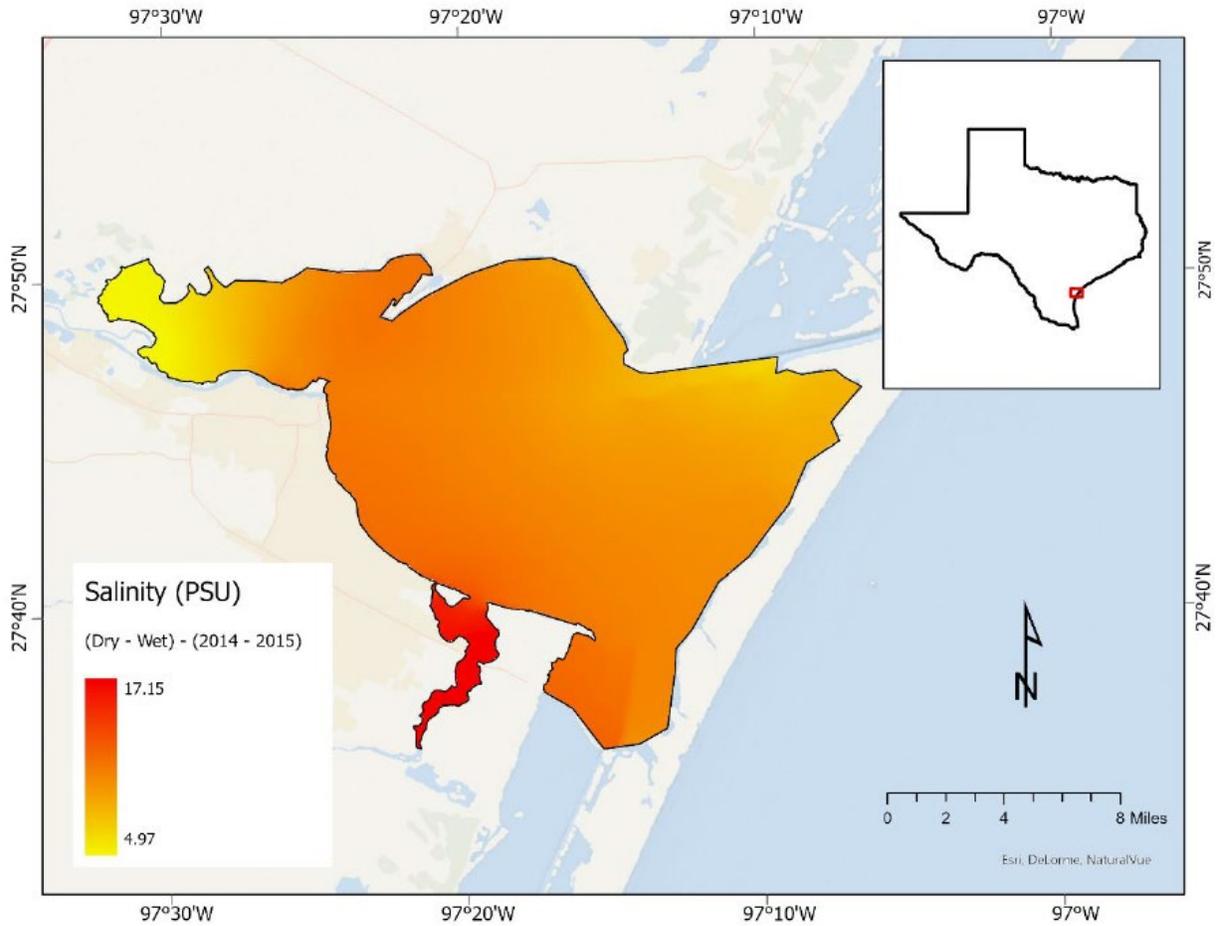
Figure 9. Spatial salinity difference between dry (2014) and wet (2015) years for Corpus Christi and Nueces Bays.

Measured versus Predicted Salinity

While the predicted salinity values by the TxBLEND model are important to understand the spatial and temporal change in salinity, they are modeled predicted values. In contrast, the TPWD values are actual measurements. The problem is that the TPWD measurements are biased because they are not taken synoptically, meaning two values in two places can be taken on different days, or weeks; and the sampling is random, meaning that the same locations are not always sampled. So, as might be expected the average annual salinities for the two systems are different (Figure 10). The TxBLEND mean values (28.5) are lower than the TPWD values (29.7) by 1.2 psu (paired t-Test, $P = 0.0010$, df=29). Therefore, the TPWD salinity values were used to compare the response to salinity in the biological analyses.
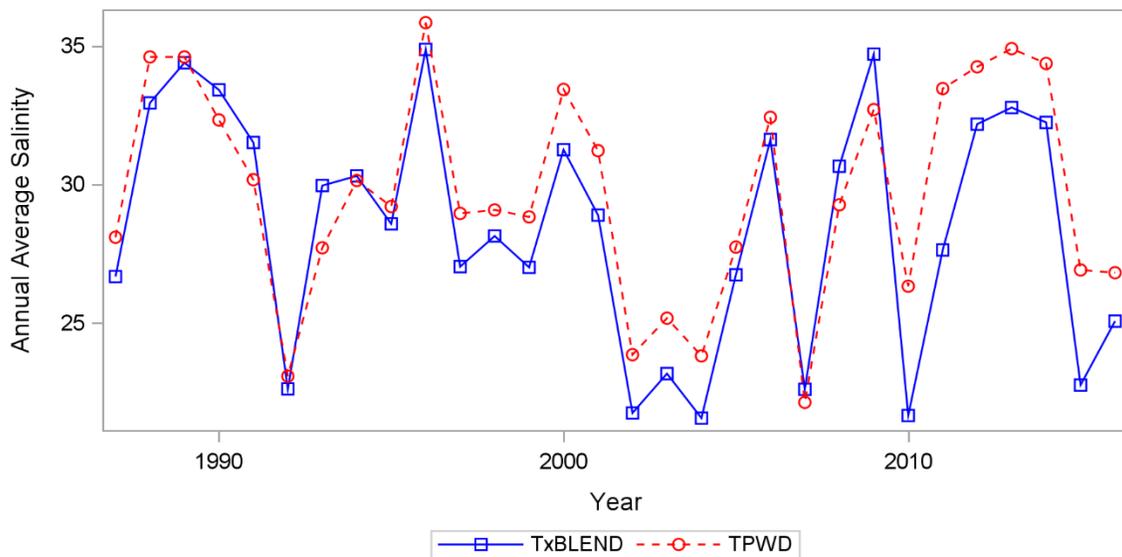
Figure 10. Comparison of average annual salinity form TxBLEND model predictions and TPWD field measurements.

Fisheries

The Corpus Christi Bay system was subdivided into four subregions for analysis based on the salinity analyses, which showed that there were differences within Nueces Bay, south Corpus Christi Bay, north Corpus Christi Bay, and Redfish/south Aransas Bays. Therefore, diversity analyses were performed independently for each subregion. Similarly, subregion (or minor bay) was included as a candidate predictor variable in GAM analyses.

Salinity-Diversity Relationships

The relationship between salinity and species diversity (of juvenile fish and invertebrates) collected from TPWD bag seines was analyzed by subregion using the MaxBin technique where salinity was divided into 10 bins or categories. (Figure 11). In all subregions, diversity increased with increasing salinity to a maximal salinity point, then decreased. The maximum

diversity was reached at increasing salinities with distance from the freshwater inflow source, i.e., the Nueces River (Table 4). The salinity where diversity is maximum is estimated as parameter c and it is 13 for Nueces Bay, 24 for south Corpus Christi Bay, 22 for north Corpus Christi Bay, and 36 for Redfish and south Aransas Bays.
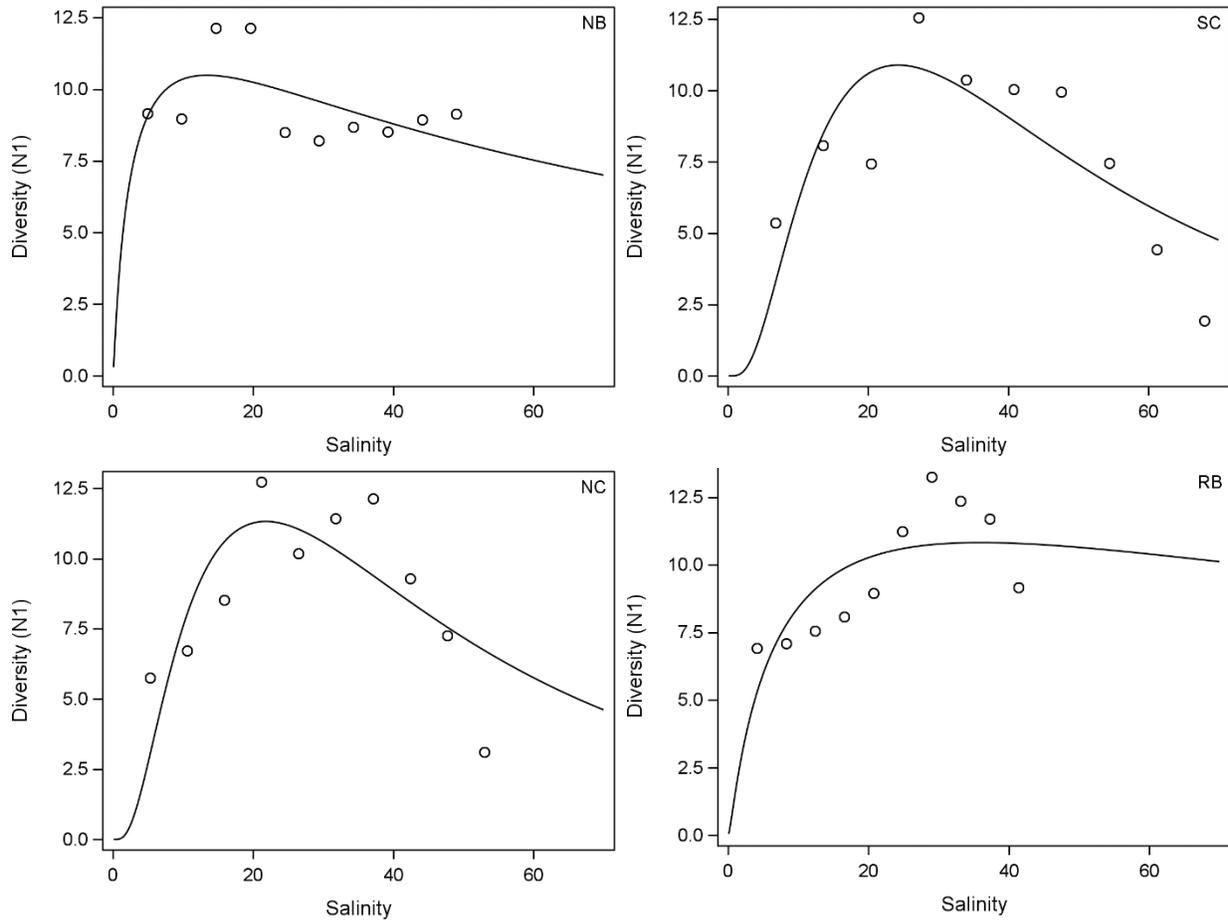
Figure 11. Salinity-diversity relationship. Fit using MaxBin method. NB) Nueces Bay, SC) south Corpus Christi Bay, NC) north Corpus Christi Bay, and RB) Redfish/south Aransas Bays.

Table 4 . Parameters from nonlinear regressions to predict diversity from salinity. The parameters are parameters for (a) maximum diversity value, (b) rate of change, and (c) salinity in which maximum diversity occurs, and standard deviation for parameters in parentheses.

Location	Estimate (Standard Error)		
	a	b	c
Nueces Bay	10.49 (0.76)	1.84 (0.62)	13.42 (3.62)
Redfish/South Aransas Bays	10.82 (0.97)	1.81 (1.15)	36.00 0.00
North Corpus Christi Bay	11.32 (1.28)	0.87 (0.18)	21.81 (2.87)
South Corpus Christi Bay	10.89 (1.29)	0.82 (0.15)	24.30 (3.08)

Diversity and Salinity Change Relationships

Average salinity changes from year to year so comparing diversity change with salinity change can indicate what might happen if salinity continues to rise over time or in specific spaces. The average salinity for each year was calculated for each subregion, along with the diversity for each year. Then the change from year to year was calculated and plotted (Figure 12). There was a decline in diversity with increases in salinity in only one area, the north Corpus Christi Bay subregion (Table 5).
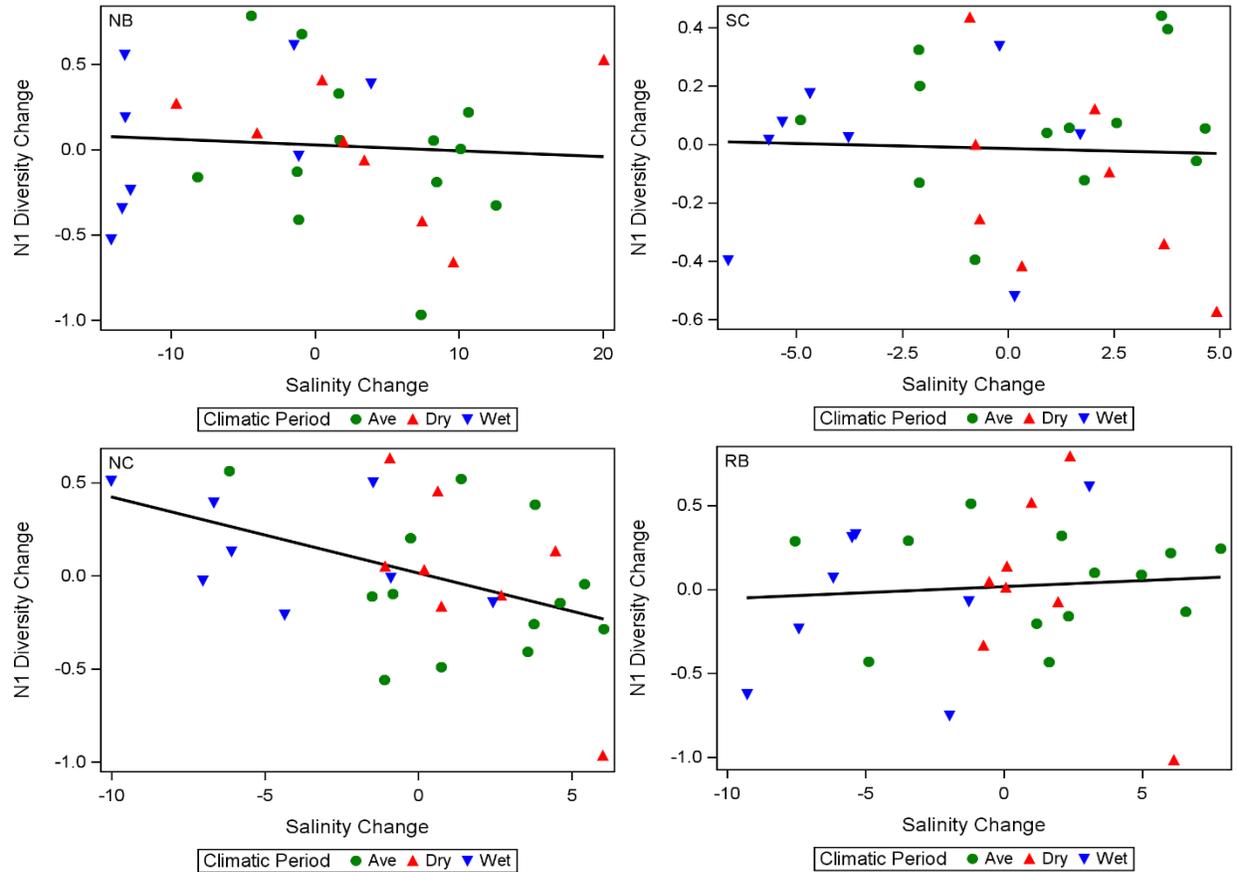
Figure 12. Salinity and Hill's N1 diversity change from year to year from 1987 to 2016. Each classified according to Table 2. NB) Nueces Bay, SC) south Corpus Christi Bay, NC) north Corpus Christi Bay, and RB) Redfish/south Aransas Bays.

Table 5. Regression parameterss for the salinity change - diversity change relationship.

Location	Intercept		Slope		t-value	P
Nueces Bay	0.027	(0.080)	-0.003	(0.009)	-0.38	0.7062
Redfish/South Aransas Bays	-0.014	(0.053)	-0.003	(0.016)	-0.21	0.8322
North Corpus Christi Bay	0.013	(0.064)	-0.041	(0.015)	-2.66	0.0131
South Corpus Christi Bay	0.015	(0.078)	0.007	(0.017)	0.41	0.6824

Habitat Suitability

Hydrological and depth data were absent for a minor portion of bag seine samples (n = 56); thus, a total of 7965 bag seine samples from the Corpus Christi Bay region were analyzed using GAMs. Absolute Pearson correlation coefficients were < 0.21 and variance inflation factors (VIFs) were < 1.70 indicating low collinearity between candidate predictor variables. Spatial, interannual, and intra-annual (seasonal) variability in the occurrence of each species was detected as the minor bay region, year, and month candidate predictor variables were retained in all final models for pinfish, Atlantic croaker, and sheepshead minnow (Figure 13); and white shrimp, brown shrimp, and blue crab (Figure 14).

The depth and all hydrological candidate predictor variables were retained within the final models for each species, except for dissolved oxygen in the models for Atlantic croaker (Figure 15) and white shrimp (Figure 16).
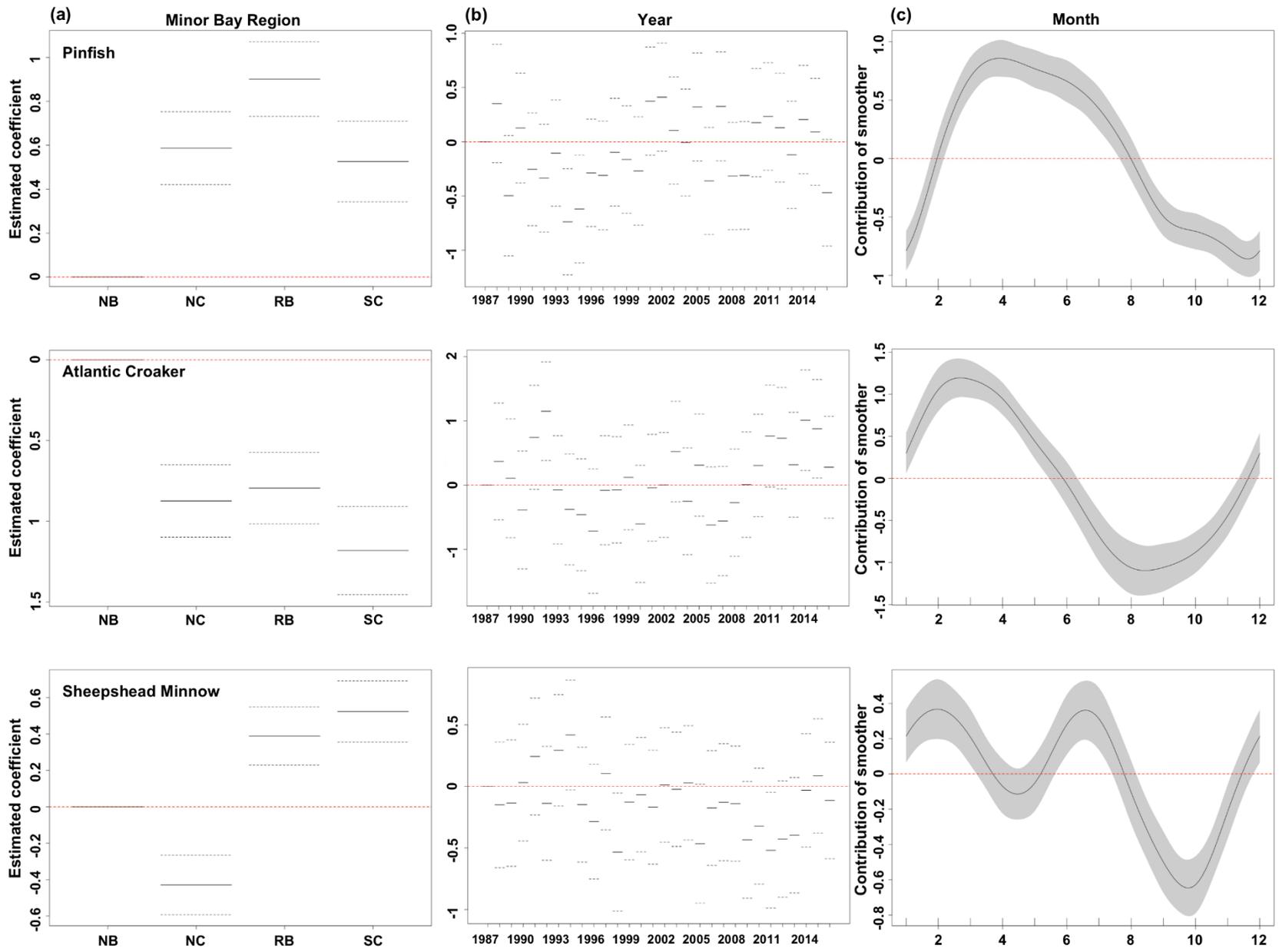
Figure 13. Estimated partial coefficients for the parametric terms the final generalized additive models for pinfish, Atlantic croaker, and sheepshead minnow on occurrence (presence/absence).
A) Four minor bay regions. and dashed lines represent 95% confidence limits. B) Years. C) Estimated response curves (solid black line) of component smooth functions for month on species' occurrence from the final models. Shaded areas represent 95% confidence limits of uncertainty in the centered smooth. Vertical axes are partial responses (estimated, centered smooth functions) on the scale of the linear predictor. Ticks on the x-axis denote values for which there are data. Positive values on the y-axis (above the dashed red line) indicate an increased probability of occurrence for each species.
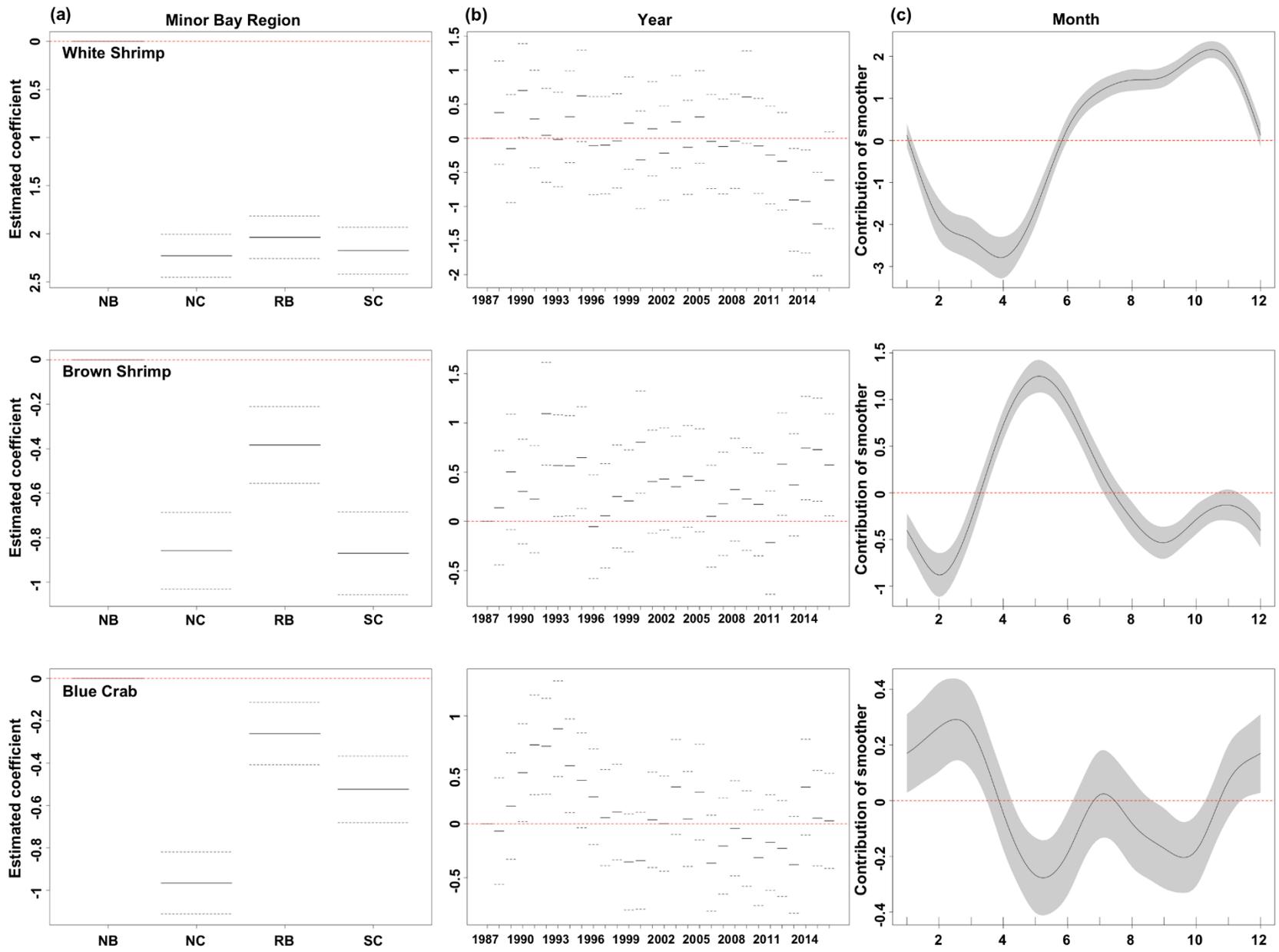
Figure 14. Estimated partial coefficients for the parametric terms on occurrence (presence/absence) from the final generalized additive models for pinfish, Atlantic croaker, and sheepshead minnow.
A) Four minor bay regions. and dashed lines represent 95% confidence limits. B) Years. C) Estimated response curves (solid black line) of component smooth functions for month on species' occurrence from the final models. Shaded areas represent 95% confidence limits of uncertainty in the centered smooth. Vertical axes are partial responses (estimated, centered smooth functions) on the scale of the linear predictor. Ticks on the x-axis denote values for which there are data. Positive values on the y-axis (above the dashed red line) indicate an increased probability of occurrence for each species.
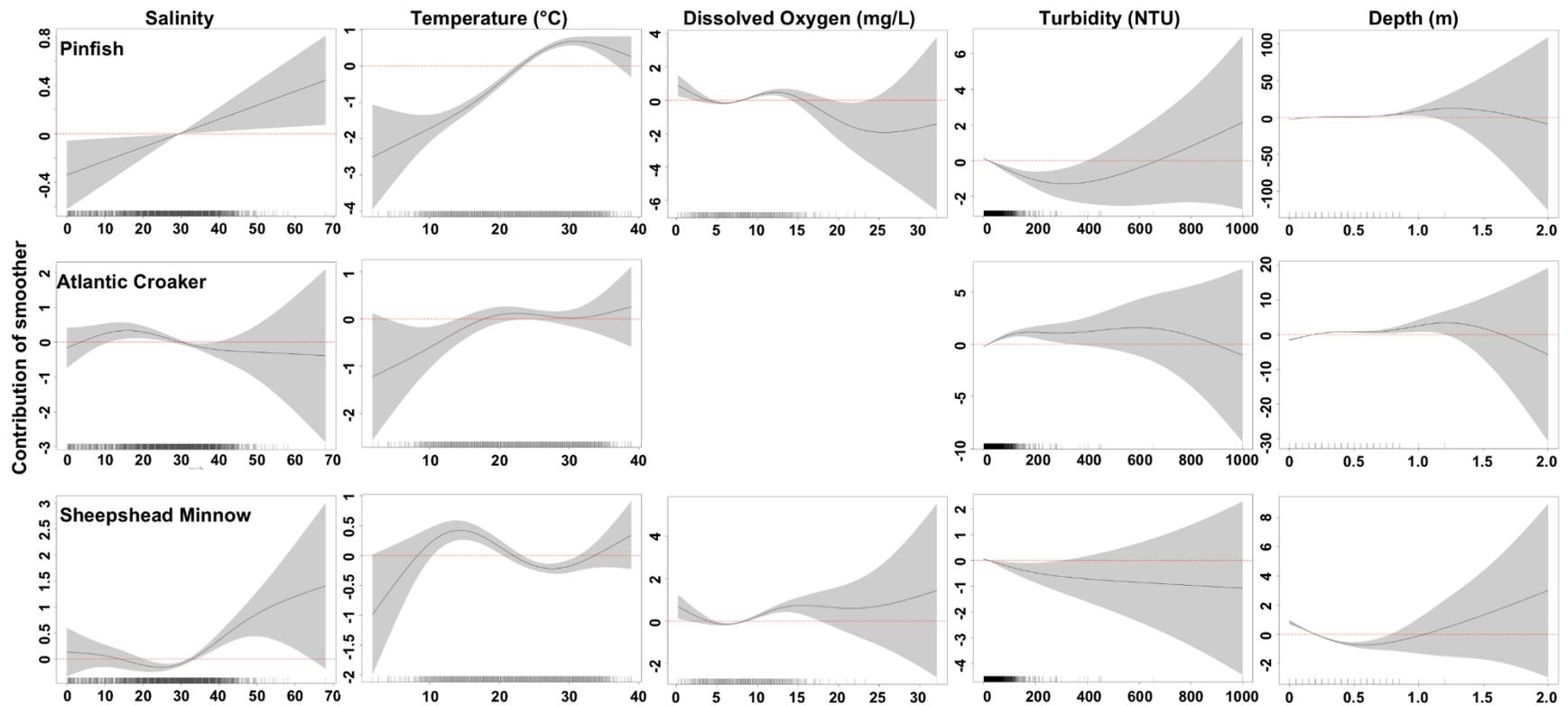
Figure 15. Estimated response curves (solid black line) of component smooth functions on occurrence (presence/absence) from the final generalized additive models for pinfish, Atlantic croaker, and sheepshead minnow.

Shaded areas represent 95% confidence limits of uncertainty in the centered smooth. Vertical axes are partial responses (estimated, centered smooth functions) on the scale of the linear predictor. Ticks on the x-axis denote values for which there are data. Positive values on the y-axis (above the dashed red line) indicate an increased probability of occurrence for each species.
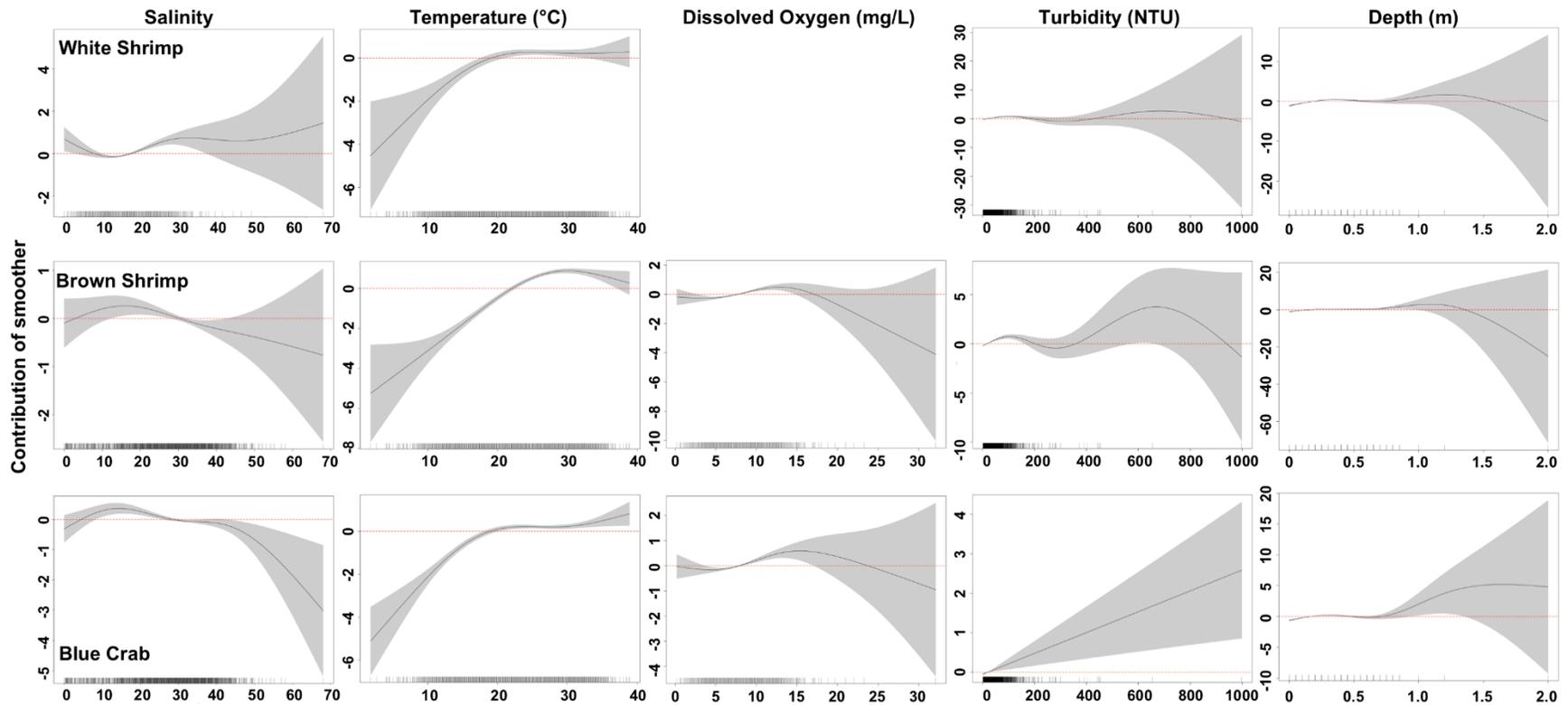
Figure 16. Estimated response curves (solid black line) of component smooth functions on occurrence (presence/absence) from the final generalized additive models for white shrimp, brown shrimp, and blue crab.

Shaded areas represent 95% confidence limits of uncertainty in the centered smooth. Vertical axes are partial responses (estimated, centered smooth functions) on the scale of the linear predictor. Ticks on the x-axis denote values for which there are data. Positive values on the y-axis (above the dashed red line) indicate an increased probability of occurrence for each species.

White shrimp, blue crab, and Atlantic croaker exhibited similar response curves for their occurrence across the range of recorded salinity values (Figure 15 and Figure 16). The preferred salinity ranges for white shrimp and blue crab were approximately 15 - 25 and 10 - 25, respectively, and the population abundance decreased at higher salinities exceeding 30 - 40. Similarly, the preferred salinity ranges for Atlantic croaker were 15 - 25; though, their response to salinities exceeding 40 is highly variable. Brown shrimp appear to tolerate a wide range of salinities; however, their probability of occurrence declined at salinities less than 12. Pinfish and sheepshead minnow exhibited the greatest tolerance to high salinities beyond 30 - 35.

The generalized additive models (GAMs) explained between 8.34% and 34.25% of residual deviance, indicating additional factors beyond our models explain a significant portion of each species' occurrence (Table 6). Spatial (i.e., minor bay region and depth) and temporal (i.e., year and month) predictor variables explained the highest partial percent deviance across each species apart from temperature in the models for brown shrimp (3.47%) and blue crab (1.94%) (Table 7). Salinity consistently ranked as the predictor variable that explained the lowest partial percent deviance (≤ 0.34 %), except for the model for sheepshead minnow, where turbidity was ranked lowest (0.08 %). Model fit to 75 % training/25 % test validation data, measured by AUC, was highest for pinfish (0.815 ± 0.002), brown shrimp (0.817 ± 0.003); and white shrimp (0.866 ± 0.003), acceptable for sheepshead minnow (0.701 ± 0.007) and Atlantic croaker (0.784 ± 0.004), and marginal for blue crab (0.659 ± 0.008) (Table 6). Cross-validation by year resulted in mean AUC values (0.659 to 0.867) (Table 6) closely resembling those generated during the first validation configuration indicating acceptable to good interannual predictive performance.

Table 6. Final generalized additive model output and performance statistics for species occurrence (presence/absence). %Presence is the percentage of bag seine samples (n = 7965) where each species is present. Recruitment months used in habitat suitability mapping. %DE is the percent deviance explained. CV is cross-validation. SE is standard error.

Species	% Presence	Recruitment Months	Adjusted R^2	%DE	AIC	CV AUC (SE)	Interannual CV AUC (SE)
Atlantic Croaker	6.6	Jan-May	0.146	17.622	4436	0.775 (0.004)	0.784 (0.004)
Pinfish	38.9	Feb-Oct	0.304	25.223	8349	0.815 (0.002)	0.811 (0.007)
Sheepshead Minnow	23.1	Jan-Dec	0.117	10.502	8939	0.710 (0.002)	0.701 (0.007)
White Shrimp	12.9	Jul-Nov	0.353	34.248	4841	0.866 (0.003)	0.867 (0.006)
Brown Shrimp	33.5	Apr-Jun	0.300	25.885	8085	0.817 (0.003)	0.815 (0.007)
Blue Crab	31.5	Jan-Dec	0.103	8.335	10198	0.678 (0.002)	0.659 (0.008)

Table 7. The partial percent deviance explained by each predictor variable retained in the final GAMs for species occurrence (presence/absence). Variable ranking in parentheses.

Species	Minor Bay Region	Year	Month	Salinity	Temperature	DO	Turbidity	Depth
Atlantic Croaker	1.85 (4)	3.10 (3)	4.84 (1)	0.25 (7)	0.26 (6)		1.00 (5)	3.35 (2)
Pinfish	1.05 (5)	1.17 (4)	4.69 (2)	0.06 (8)	1.92 (3)	0.42 (6)	0.33 (7)	7.94 (1)
Sheepshead Minnow	2.20 (1)	0.83 (4)	1.26 (3)	0.34 (7)	0.36 (6)	0.50 (5)	0.08 (8)	1.90 (2)
White Shrimp	7.84 (2)	1.82 (3)	16.77 (1)	0.17 (7)	0.65 (5)		0.62 (6)	1.13 (4)
Brown Shrimp	1.22 (4)	0.94 (5)	4.36 (1)	0.22 (8)	3.47 (2)	0.41 (7)	0.59 (6)	1.26 (3)
Blue Crab	1.93 (2)	1.83 (3)	0.55 (6)	0.27 (8)	1.94 (1)	0.73 (4)	0.53 (7)	0.63 (5)

Habitat suitability maps for the wet year had higher probabilities of occurrences for pinfish and sheepshead minnow than average or dry years (Figure 17). In contrast, the dry year had higher probabilities of occurrences for Atlantic croaker (Figure 17) and white shrimp (Figure 18). Predicted maps of habitat suitability revealed increasing (2009; dry year) or decreasing (2007; wet year) salinity regimes from the average year (2008) resulted in reduced probability of occurrences for brown shrimp and blue crab (Figure 18).
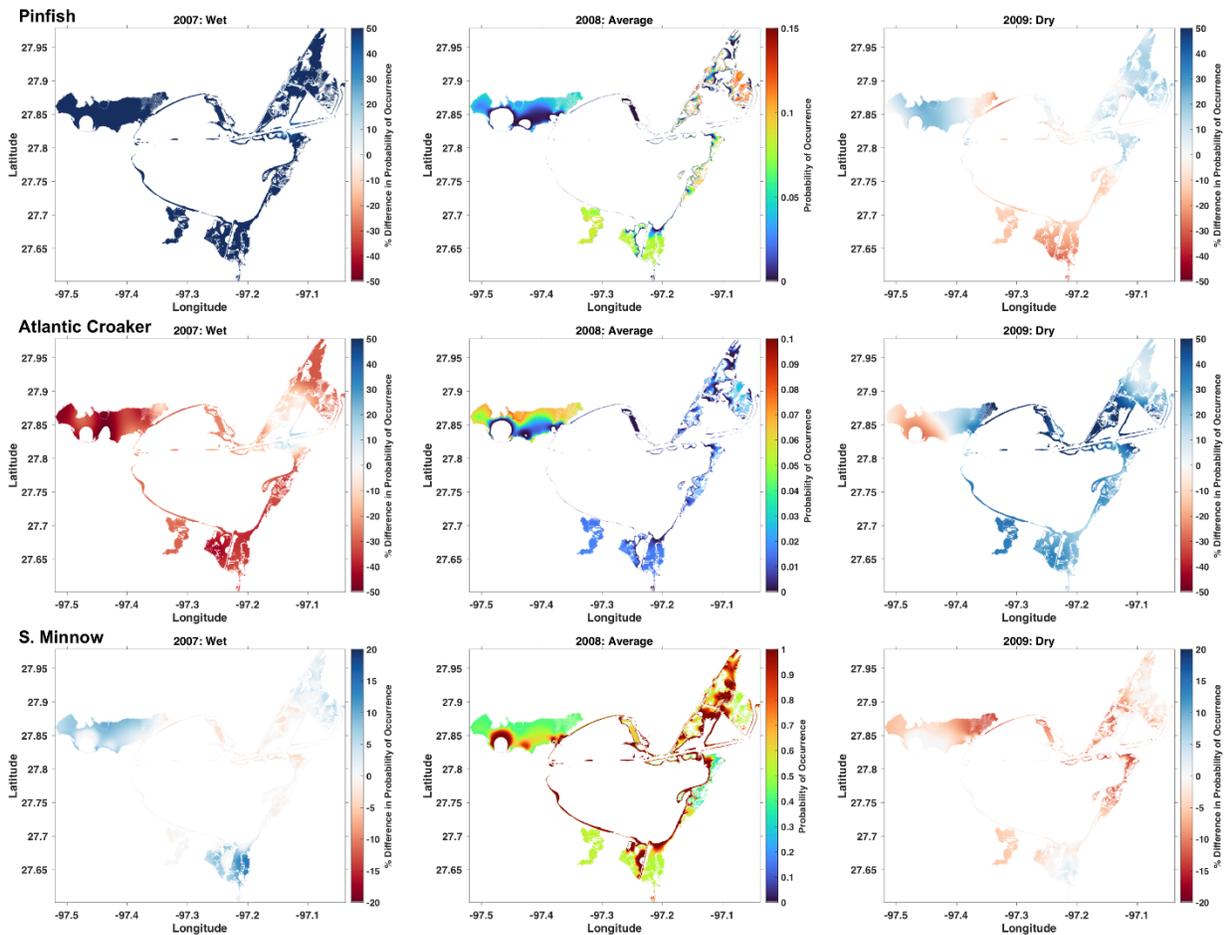
Figure 17. Spatial distribution of habitat suitability, defined as the probability of occurrence predicted from the final GAM models, for pinfish, Atlantic croaker, and sheepshead minnow across the Corpus Christi Bay region during wet (2007), average (2008), and dry (2009) years. Color scales for wet and dry years represent the percent change in habitat suitability values from the average year. Percent change values beyond ±50% were observed for pinfish and Atlantic croaker and truncated for clearer illustration.

Full-page, high resolution, maps of all the habitat suitability models (Figures 17 and 18) are provided in Appendix 2.
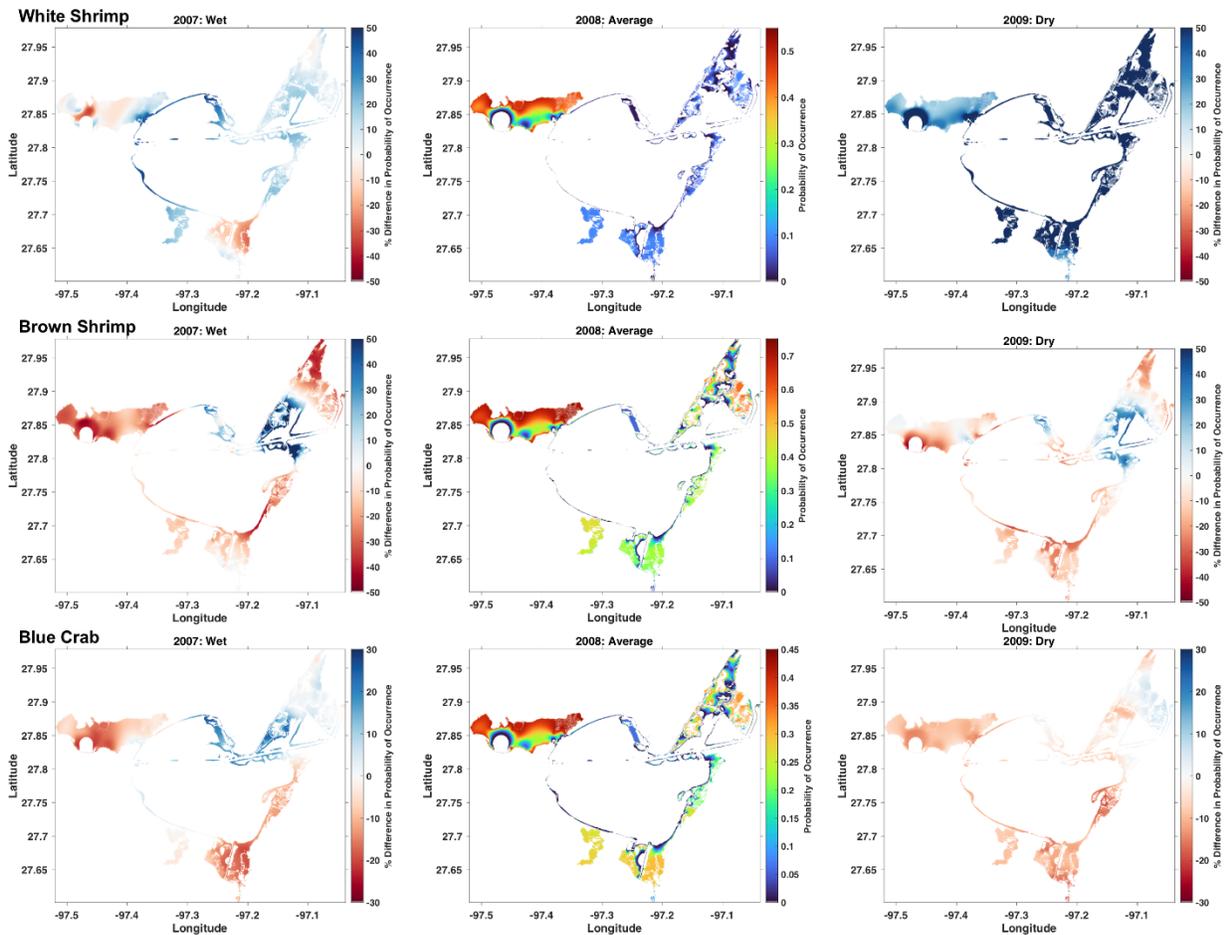
Figure 18. Spatial distribution of habitat suitability, defined as the probability of occurrence predicted from the final GAM models, for white shrimp, brown shrimp, and blue crab across the Corpus Christi Bay region during wet (2007), average (2008), and dry (2009) years. Color scales for wet and dry years represent the percent change in habitat suitability values from the average year. Percent change values greater than ±50% were observed for white shrimp and truncated for clearer illustration.

The spatial distribution of predicted highly suitable habitat was exclusively in Nueces Bay for all three invertebrate species and Atlantic croaker (Figure 13, Figure 14, Figure 17, Figure 18, Figure 19, and Figure 20). In contrast, the largest proportion of highly suitable habitat for pinfish was in South Corpus Christi Bay in 2007 (wet year) and 2008 (average year) and shifted to Redfish and South Aransas Bays in 2009 (dry year) (Figure 17 and Figure 19). Highly suitable habitat was distributed across all four minor bay regions from 2007-2009 for sheepshead minnow, with the largest proportion consistently within North Corpus Christi Bay.
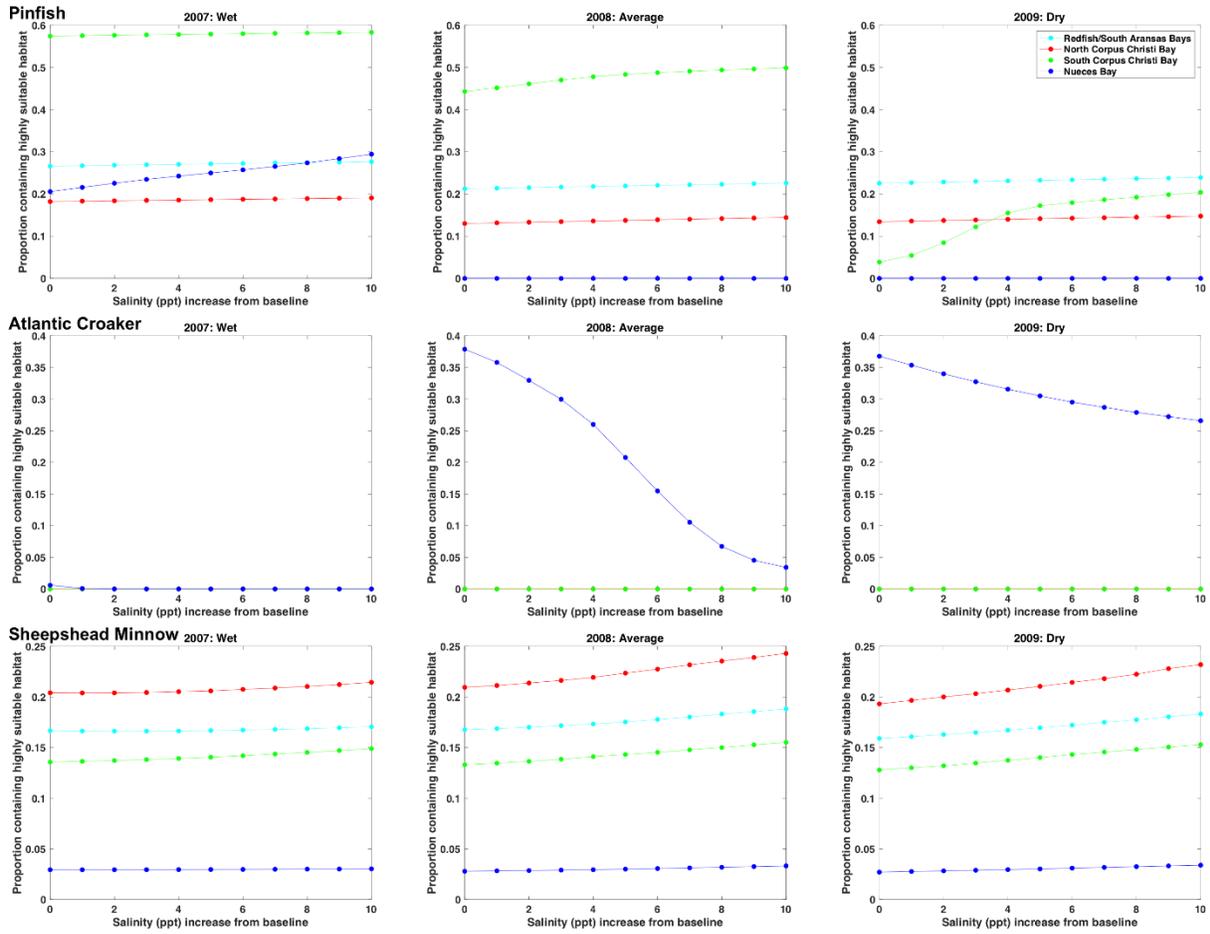
Figure 19. The proportion of each minor bay within the Corpus Christi Bay region that contains highly suitable habitat (highest 10% of predicted values for pinfish, Atlantic croaker, and sheepshead minnow in 2008) along an increasing salinity gradient from baseline conditions during wet (2007), average (2008), and dry (2009) years.
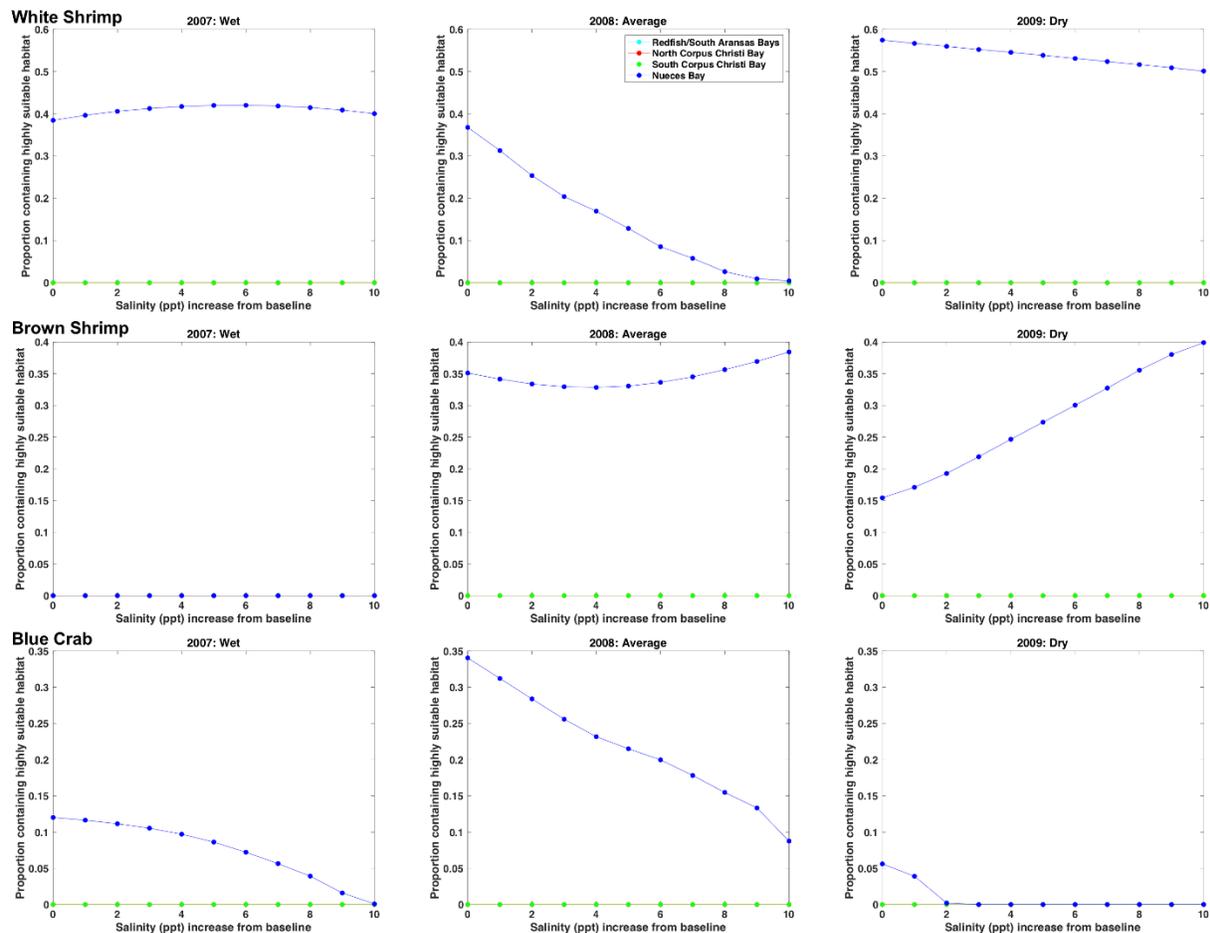
Figure 20. The proportion of each minor bay within the Corpus Christi Bay region that contains highly suitable habitat (highest 10% of predicted values for white shrimp, brown shrimp, and blue crab in 2008) along an increasing salinity gradient from baseline conditions during wet (2007), average (2008), and dry (2009) years.

The six species examined exhibited varying predicted impacts among increasing salinity gradients from baseline conditions each year (Figure 19 and Figure 20). The proportion of highly suitable habitat decreased with increasing salinity for blue crab, Atlantic croaker, and white shrimp across each year; however, there was a marginal difference in highly suitable habitat for white shrimp during 2007 (wet year) across the increasing salinity gradient. In contrast, the proportion of highly suitable habitat increased with increasing salinity for brown shrimp during 2008 (average year) and 2009 (dry year). There was a marginal increase in highly suitable habitat for pinfish across the increasing salinity gradient, except for Nueces Bay in 2007 (wet year) and South Corpus Christ Bay in 2009 (dry year). Similarly, there was a marginal increase in highly suitable habitat for sheepshead minnow across the increasing salinity gradient.

Discussion

Rising salinity levels have been a concern in the Coastal Bend since the 1990's (CBBEP 2018, Montagna et al. 2009). Originally, the concern was over reductions of freshwater inflow from the Nueces River to Nueces Bay after construction of the Choke Canyon Reservoir, and then to brine discharge into Nueces Bay from produced waters. After public complaints, the Texas Water Commission (now the Texas Commission on Environmental Quality) issued a series of orders beginning in May 1990 requiring the City of Corpus Christi to meet the special conditions contained in their water right permit that required provision of freshwater inflows to the estuary. The original permit required releases of more than 151,000 ac-ft ($185\ 10^6\ m^3$) of fresh water per year to the Nueces Estuary to maintain ecological health and productivity of living marine resources. By April 1995, the Agreed Order reduced the inflow requirement to 138,000 ac-ft ($170\ 10^6\ m^3$) per year delivered in a monthly-inflows to mimic natural hydrographic conditions in the Nueces Basin. There were three other important revisions: 1) the <u>minimum</u> mandatory inflows were changed to <u>targeted</u> monthly inflows, 2) the <u>releases</u> were changed to <u>pass-throughs</u>, and 3) <u>drought relief was granted</u> in the form of different pass-through requirements <u>based on the reservoir level</u>. In March 2014, inflow requirements were changed again due to rules adopted under the 2007 Senate Bill 3 Environmental Flow law. Currently, required pass-through inflow requirements can be as low as 30,000 ac-ft/year during dry years (Texas Administrative Code §298.430(a)(3), Table 8). There are three inflow standards for wet years (Level 1), average years (Level 2), or dry years (Level 3) for Nueces Bay and Nueces Delta. The target inflow volumes also vary by season because July through October is typically the wettest time of the year, November through February is typically the driest time of the year, and March through June has more intermediate conditions during a typical year.

Table 8. Bay and estuary freshwater inflow standards for Nueces Bay and Delta (af = acre-feet).

Inflow Regime	Target Volume November - February (Target Frequency)	Target Volume March - June (Target Frequency)	Target Volume July - October (Target Frequency)	Target Volume Annual Inflow Target (Target Frequency)
Level 1	125,000 af (11%)	250,000 af (11%)	375,000 af (12%)	750,000 af (16%)
Level 2	22,000 af (23%)	88,000 af (30%)	56,000 af (40%)	166,000 af (47%)
Level 3	5,000 af (69%)	10,000 af (88%)	15,000 af (74%)	30,000 af (95%)

The 2014 inflow standards (Table 8) are based on hydrological statistics only. This is problematic because at any given time, any flow level is essentially within the standard, and thus may not be protective. For example, the standards will allow flows as low as 30,000 af/year 95% of the time, but the Nueces BBEST (NBBEST 2011) estimated that these were attained only 85% of the time between 1983 and 2009 since the Choke Canyon Reservoir was constructed. The Nueces BBEST committee recommended that 160,000 to 166,000 af/year is needed to maintain a

sound ecological condition in Nueces Bay and Nueces Delta, yet this is only required 47% of the time. The net result is that the current standards do allow the system to be salinity stressed at least 53% of the time. From 2000 to 2020 the attainment of annual flows greater than 166,000 ac/year has been only 29% according to estuary inflow data from the Nueces River Authority (NRA 2021). Subsistence flow greater than 30,000 af/year has occurred only 67% of the time (Figure 21). Salinities in the entire middle Texas coast have been increasing over time, most likely due to reduction in inflows (Bugica et al. 2020). Overall, it appears that inflow to the Nueces Estuary will not meet the current attainment standards. There are no standards for Corpus Christi Bay.
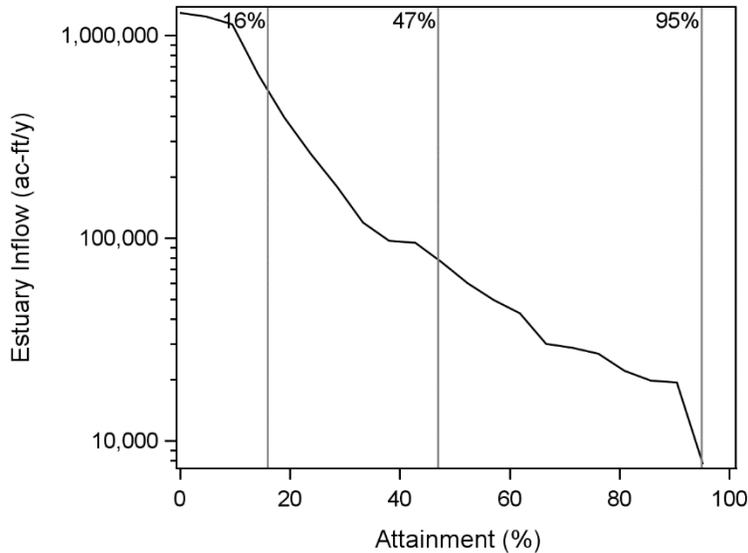
Figure 21. Attainment of annual estuary inflow values for the period 2000 to 2020.

The climate is changing, and it is changing in two ways: temperatures are rising, and extreme events are more common. Sea surface temperatures in Corpus Christi Bay have been rising since the 1970's (Applebaum et al. 2005, Montagna et al. 2011a). One consequence of higher water temperature is lower dissolved oxygen concentrations because the solubility of oxygen in sea water is inversely related to temperature. So, temperature increases are a double-stressor. In addition, higher temperatures also increase evaporation, which can further increase salinity. Droughts are now more severe and occur more frequently (Chen et al. 2021). The 2011 drought was unprecedented (Nielsen-Gammon 2012). It is projected that there will be drier conditions during the latter half of the 21st century than even the most arid centuries of the last 1,000 years that included megadroughts (Nielsen-Gammon et al. 2020). It is obvious that with less rain, there will be less inflow, which will lead to higher salinities in the future. It is now obvious that inflow changes will affect salinity in the future, and this depends on the interactions with climate variability.

Corpus Christi Bay and Circulation

The region is named the Nueces Estuary. An estuary is defined as a semi-enclosed body of water where salt water from the ocean mixes with fresh water from rivers and land (Pritchard 1967).

The Nueces River flows into Nueces Bay, which is the secondary bay. Nueces Bay flows into Corpus Christi Bay, which is the primary bay. The Aransas Pass is the primary connection of Corpus Christi Bay with the Gulf of Mexico. Packery Channel was opened between the Gulf of Mexico and Upper Laguna Madre in 2005 (Palmer et al. 2008), but there is no indication that there is an effect of enhanced circulation between the Gulf of Mexico and Corpus Christi Bay via Packery Channel (Palmer et al. 2013). Estuaries are named for their river sources, thus the name Nueces Estuary.

Circulation in Corpus Christi Bay is driven by freshwater inflow, tidal exchange, wind, frontal passages and Coriolis forces (Ward 1997). Freshwater typically moves along the southern part of Nueces Bay and move into and travels along the southern part of Corpus Christi Bay. Salt water from the Gulf of Mexico primarily enters via Aransas Pass, moves along the northwest along the Corpus Christi Ship Channel, and travels along the northern part of Corpus Christi Bay. The movement of lower salinity water along the southern part and higher salinity water along the northern part of Corpus Christi Bay sets up a gyre that moves in a counter-clockwise direction.

However, circulation patterns and salinity are greatly altered because of man-made structures and practices (including freshwater diversions, seawater withdrawal for cooling purposes, the JFK Causeway, and the Corpus Christi Ship Channel) (Matsumoto et al. 1997). The ship channel has the greatest single effect on water movement and salinity in Corpus Christi Bay. Salinities are increased 1 to 3 psu by the ship channel during dry periods, and 3 psu during wet periods. Circulation in the southeast corner of the bay is much reduced by the channel and there are two loops on either side of the ship channel. This is the physical reason why salinity is different in northern and southern Corpus Christi Bay (Figure 4 - Figure 8).

It is also possible that planned changes to the Corpus Christi Ship Channel could influence circulation and storm surge in the future. For example, the Port of Corpus Christi Authority (PCCA) is permitted to and has started to deepen the Corpus Christi Ship Channel (CCSC) to a depth of -54 feet (MLLW) from the existing depth of -47 feet (MLLW) as well as to widen it in select reaches. The potential for impacts on storm surge water levels and inundation duration patterns, tidal hydraulics, and salinity were recently evaluated (Subedee and Gibeaut 2021). It is predicted that the deeper channel would increase water level in Corpus Christi Bay from 3 to 3.5 inches (8 – 9 cm) and an additional 220 to 492 acres (89 – 199 ha) of low-lying areas would be flooded. While the new channel would cause a slight increase in tidal range by 0.04 to 0.06 feet (1.2 – 1.8 cm), this would be overwhelmed by potential sea level rise effects. Currently, the average tide range increases by 0.02 ft/year (0.6 cm/y) at the Rockport tide gage (Sweet et al. 2017). Over time, this means that sea level rise will have a greater impact on tidal range than the deepened ship channel. With a deeper channel, the monthly average salinity would increase by less than 1% increase in all bays except Aransas Bay where it decreases slightly. The increases in salinity due to the channel deepening projects are most prominent in the upper bay locations of the ship channel and in Nueces Bay.

Corpus Christi Bay is also a neutral estuary where average annual inflow is about equal to average annual evaporation, thus salinities are always high. The long-term average salinity in the entire estuary (i.e., Nueces and Corpus Christ Bays) is about 30 (Van Diggelen and

Montagna 2016). Because of low inflow and a low tidal prism, the freshwater throughflow is low and freshwater replacement time is about 50 months (Ward 1997). The net effect of the neutral hydrology and altered circulation pattern caused by the ship channel is that water movement and mixing in the bay is sluggish. As pointed out by Ward (1997): "it is not well flushed and therefore has a greater tendency to concentrate waterborne substances. . . these flushing considerations suggest that a wasteload will have a magnified effect in the Corpus system because it is so relatively poorly flushed. Since Corpus Christi Bay is potentially more sensitive to wasteloads, prudence and vigilance in its management are necessary.

Effect of Salinity Change on Habitat and Diversity

Ever since the landmarks studies of Gunter (1955, 1961), it has been well known that salinity affects diversity for macroinvertebrate (Van Diggelen and Montagna 2016), epifauna (Zimmerman and Minello 1984), and fish (Gelwick et al. 2001, Froeschke and Froeschke 2011) species. So, it is no surprise that the same relationships are found here because salinity defines estuary habitat (Figure 11 to Figure 20). The difficult question is how much salinity change must occur before species presence/absence, distributions, growth, or reproduction is affected?

Overall, it is obvious that small changes in salinity can alter overall community diversity (Figure 11). The optimal salinity to maintain high diversity in Corpus Christi Bay is between 22 and 24 psu (Table 4), and then diversity decreases as salinity increases (Figure 11). The problem is that the average salinity in the whole Corpus Christi Bay system is 28.5 (Table 3). In fact, the average salinity in the whole system is only about 25.5 in wet years, so on average, the system is already suffering from salinity stress. For Corpus Christi Bay alone, the salinity is much higher, averaging 31.4 from 1987 to 2016 (n = 4317) in the TPWD measurements when bag seine samples were collected (Table 2).

Salinity change affects various species differently. The most sensitive species to salinity change were blue crab, Atlantic croaker, and white shrimp, because the proportion of highly suitable habitat decreased with increasing salinity in all climatic periods (Figure 19 and Figure 20).

Desalination

Drinkable and potable freshwater resources are limited and constrain economic and social development in arid regions. Thus, desalination is emerging to aid semi-arid and arid regions of the world to meet fresh water demands. Seawater desalination is the removal of salts from feed water drawn into a desalination plant from coastal salt water. Presently, treated wastewater accounts for 5%, brackish water for 22% and desalted seawater for 58% of water produced globally (Latteman and Hopner 2008a). Although 24.5 million m^3/day of the worldwide water production is obtained by means of seawater desalination, concerns rise over potential adverse effects on the environment.

The potential environmental impacts of desalination are discharge of brine concentrate and chemicals into the marine ecosystem, the impingement and/or entrainment of organisms due to the intake of large quantities of seawater, emissions of air pollutants such as CO_2 and SO_2, and the energy demand of the processes (Hosseini et al. 2021, Latteman and Hopner 2008a).

Desalination discharges may contain many contaminants and hazardous wastes including heavy metals, anti-fouling agents, and chlorine (Latteman and Hopner 2008a, Dupavillon and Gillanders 2009). Depending on the feedwater salinity, reverse osmosis (RO) plant reject streams usually have a salinity of 60-70 psu and around 50 psu for multi-stage flash distillation (MSF) plants (Lattemann et al. 2008b, Table 9). Therefore, desalination discharges will be an example of a multiple stressor effect. Lower dissolved oxygen will stress organisms, as will the presence of toxic metals or organic compounds. It is common for multiple stressors to have exacerbated effects than any of the individual components have by themselves (Chapman 2018). Acute and chronic stressor effects are enhanced when salinity increases (Hall and Anderson 1995, Ritter and Montagna 1999) or during hydrological disturbances (Stampfli et al. 2013).

Table 9.Typical desalination discharge properties of reverse osmosis (RO) and multi-stage flash distillation (MSF) plants (Lattemann and Hopner 2008b).

Effluent parameter	RO	MSF
Salinity	typically 60 – 70 psu	around 50 psu
Temperature	ambient seawater temperature	+ 5 – 15 °C above ambient
Plume density	negatively buoyant	positively, neutrally or negatively buoyant
Oxygen	decreased as a side-effect of chlorine neutralization (using sodium bisulphite)	very low by physical deaeration and use of oxygen scavengers
Chlorine	neutralized	approx. 10 – 25 % of dosage
Halogenated organics		varying composition and concentrations
Coagulants (Fe^{3+}, Al^{3+})	1 – 30 ppm	not used
Coagulant aids (e.g., polyacrylamide)	0.2 – 4 ppm	not used
Antiscalants (e.g., polymaleic acid)	1 – 2 ppm	1 – 2 ppm
Acid (H_2SO_4)	pH 6 – 7	pH 6 – 7
Antifoaming agents (e.g., polyglycol)	not used	0.1 ppm
Heavy metals (in varying concentrations)	iron, chromium, nickel, molybdenum (from stainless steel)	copper, nickel (from heat exchangers)
Cleaning chemicals	alkaline (pH 11-12) or acidic (pH 2-3) solutions containing detergents (e.g., dodecylsulphate), complexing agents (e.g., EDTA), oxidants (e.g., sodium perborate) and biocides (e.g., formaldehyde)	acidic (pH 2) solution containing corrosion inhibitors such as benzotriazole derivates

The constant concentrate and chemical discharges with high salinity and temperature to the marine environment can be harmful for marine organisms and result in permanent change in species composition, abundance and distribution in discharge sites (Dupavillon and Gillanders 2009). For example, benthic communities such as seagrass beds may be severely affected by high salinity and temperature discharges. Long-term observations of salinity were highly correlated to marine species richness, distribution, and total abundance (Paalme et al. 2020). Depending on mobility, marine species that cannot adapt to high salinity levels often move away from the affected area. Species richness and density can also decrease where salinity is above the optimal level for specific habitats. The increase in the concentrations of salts causes water to leave the cells of marine species which may result in cell dehydration which can produce smaller embryos and eventually result in the death of embryos (Voutchkov 2011). The long-term exposure to saline effluents with low oxygen content can be damaging to marine organisms and result in change in community structure. For example, lower species abundance and diversity is generally observed for salinity above 45 psu (Latteman and Hopner 2008a).

Desalination Activities in the Coastal Bend Region

There are several seawater desalination plant sites in planning in the Corpus Christi Bay region (Figure 22). As the city's population grows and local communities become more developed and water needs increase, desalination is an increasingly important potential water source for the City of Corpus Christi. This is especially true because the region is very likely to be water stressed in the future.
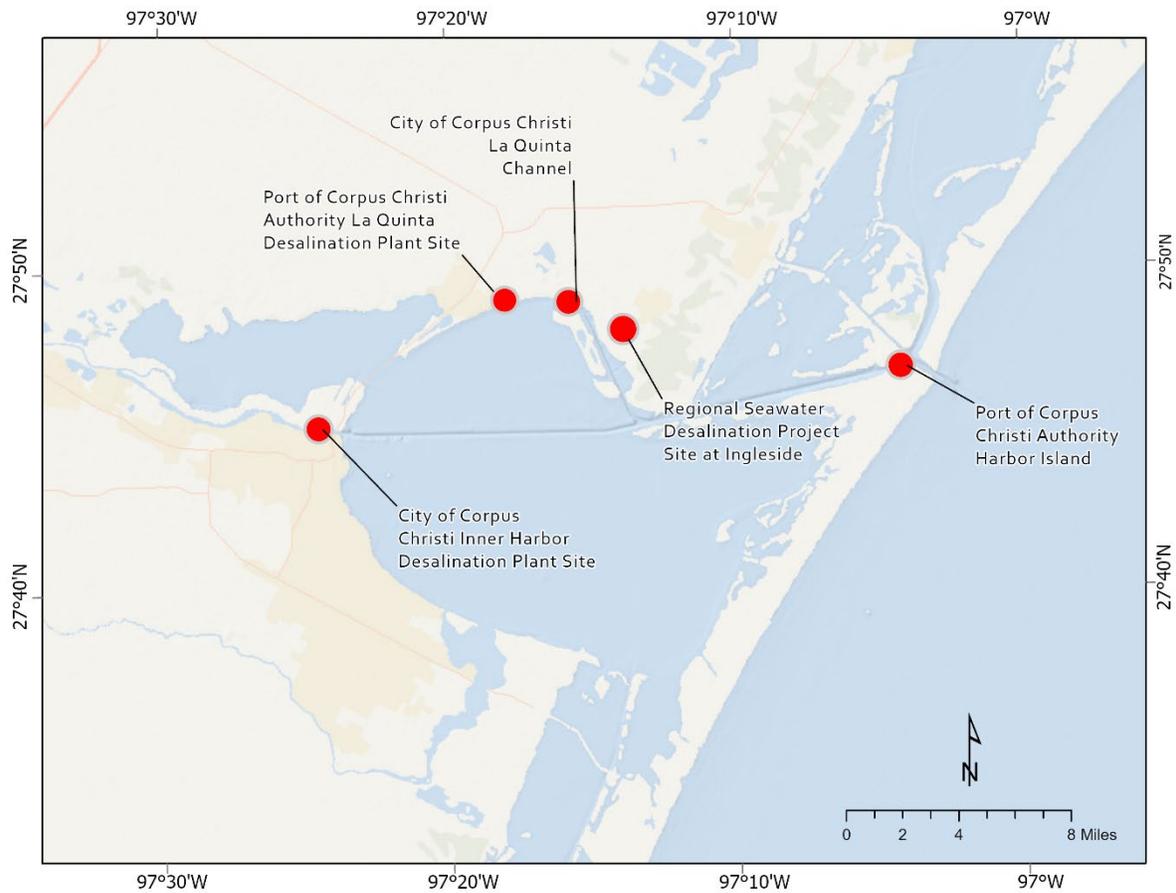
Figure 22. Locations for proposed seawater desalination plants in the Corpus Christi and Nueces region (Crow 2021). In addition, a plant at CC Polymers is proposed for the Inner Harbor.

Conclusion

The Corpus Christi Bay region has high annual average temperatures and salinities, and circulation within the bays of the region is sluggish. This means that the region is sensitive to changes in water borne materials because they are easily concentrated by the high evaporation rates and low flushing rates. Overall estuary community diversity is related to salinity, and as salinity increases past the optimal range, species diversity declines, and abundance of some ecologically and economically important species will decrease. Average salinities are already at levels that could impact species abundance and diversity, and therefore, small increases in salinity could add additional pressure to a system that is already experiencing salinity stress.

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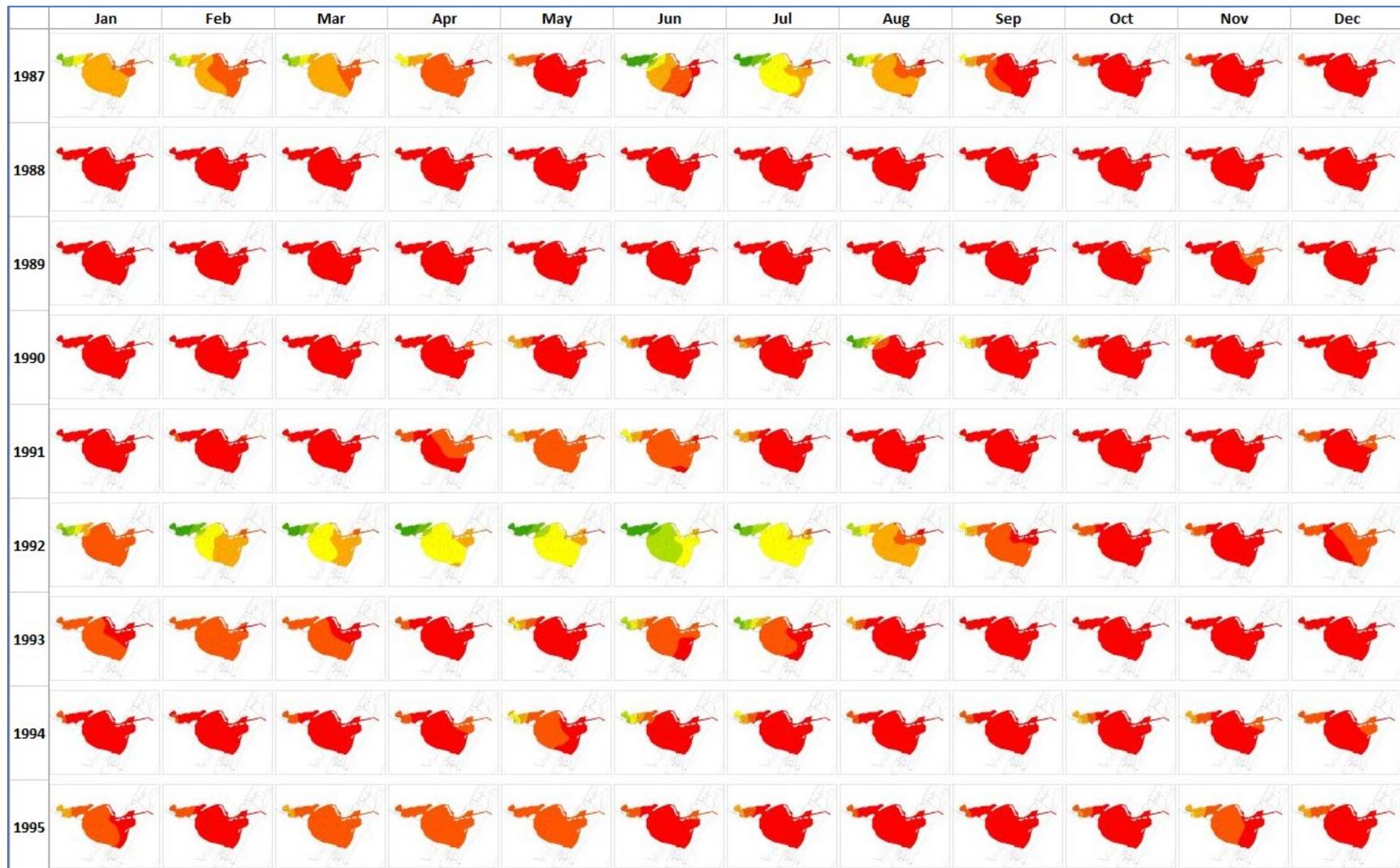
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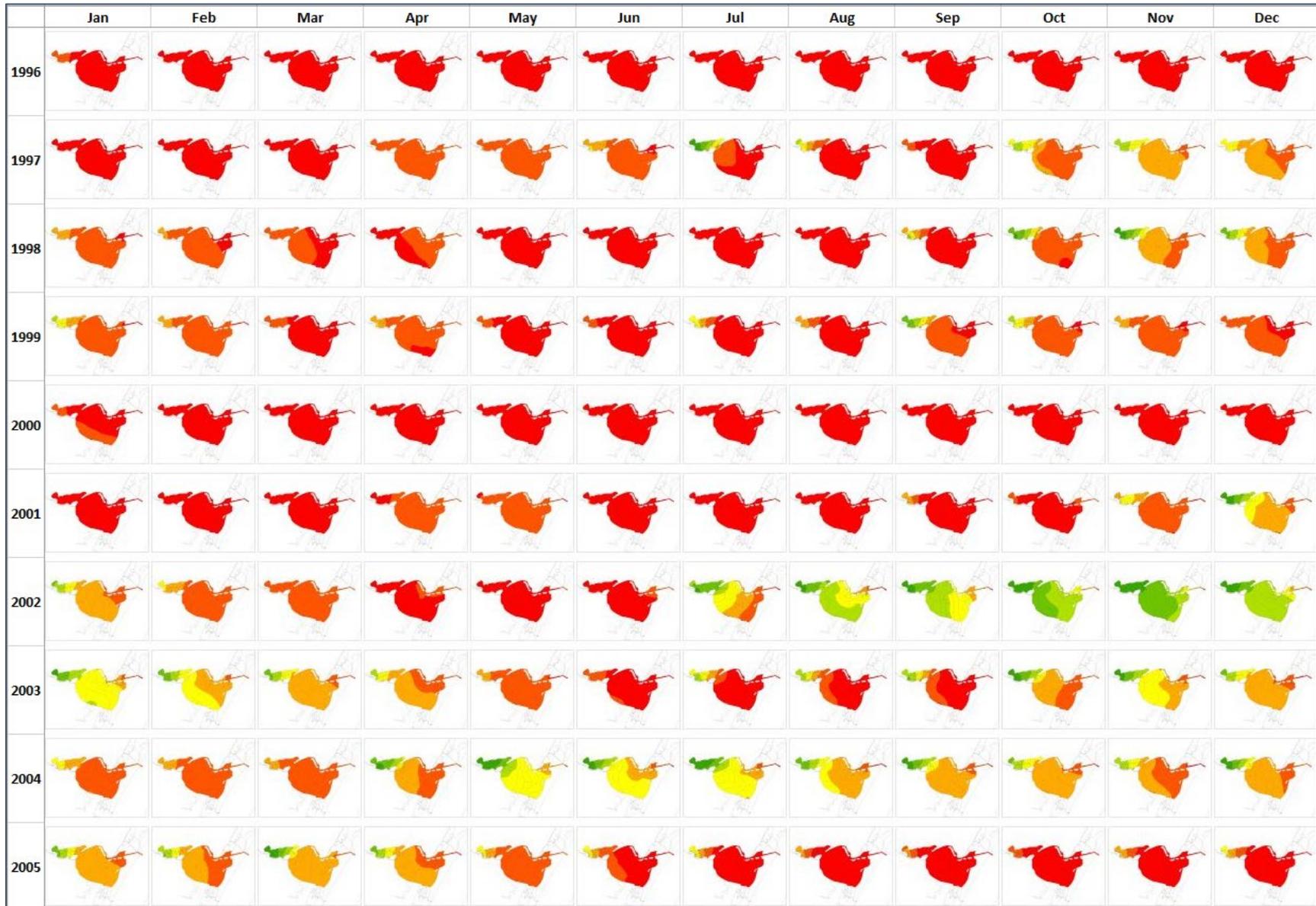
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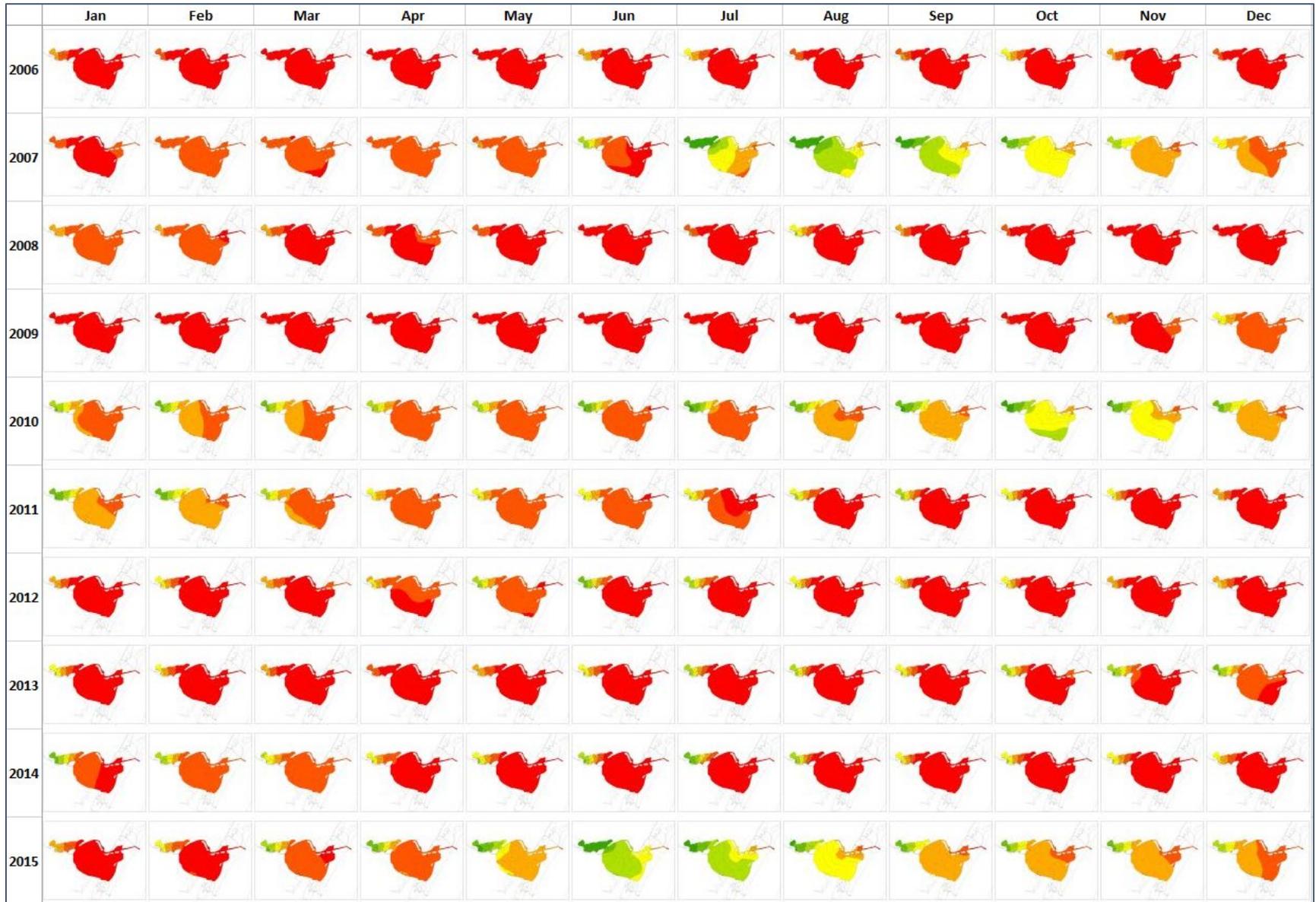# Appendix 1. Spatial Variation of Salinity Patterns Averaged by Month


Legend: 0-5 | 5-10 | 10-15 | 15-20 | 20-25 | 25-30 | 30-35 | >35

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1987												
1988												
1989												
1990												
1991												
1992												
1993												
1994												
1995												

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1996												
1997												
1998												
1999												
2000												
2001												
2002												
2003												
2004												
2005												

Legend: 0-5, 5-10, 10-15, 15-20, 20-25, 25-30, 30-35, >35

Appendix 2. Habitat Suitability Heat Maps

The habitat suitability heat maps presented in Figure 17 and Figure 18 are reproduced here in full-page format to enable higher resolution visualzation of habitat extent across the Corpus Christi Bay region during wet (2007), average (2008), and dry (2009) years. For each species, the patial distribution of habitat suitability, which is defined as the probability of occurrence predicted from the final GAM models, is presented. Color scales for wet and dry years represent the percent change in habitat suitability values from the average year.

Pinfish

51

Atlantic Croaker

2007: Wet

2008: Average

2009: Dry
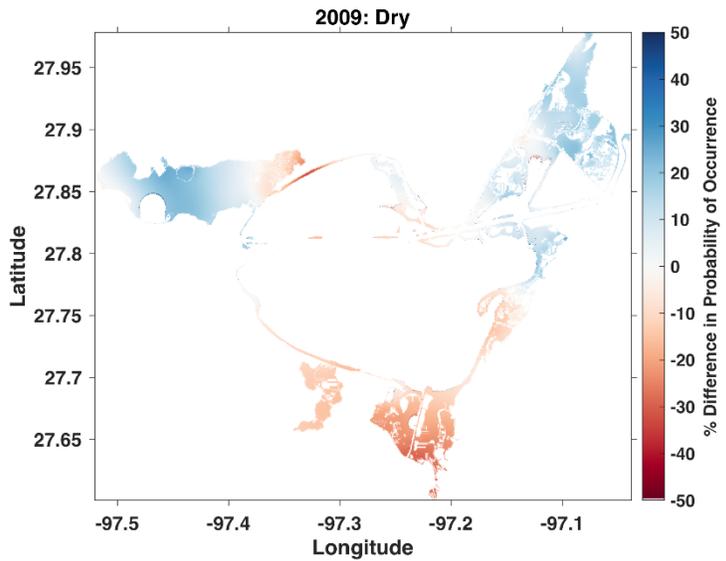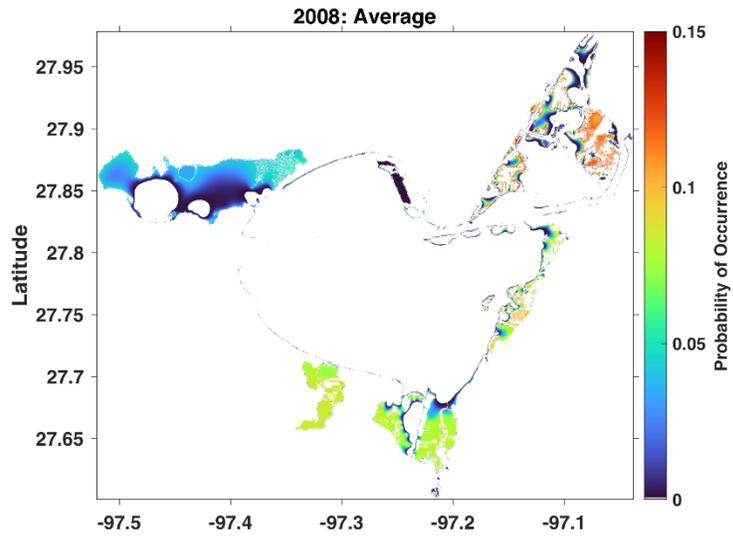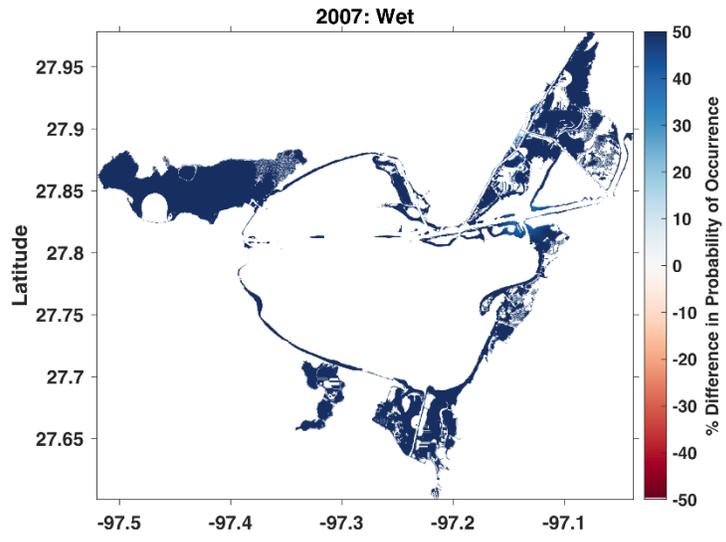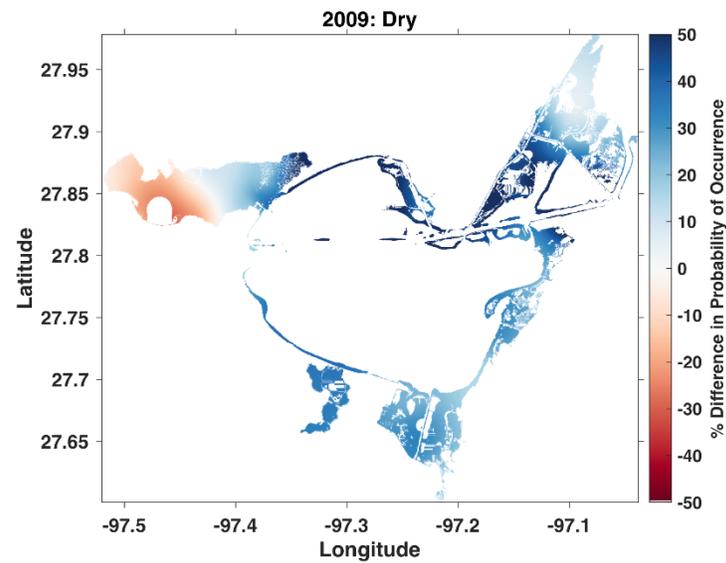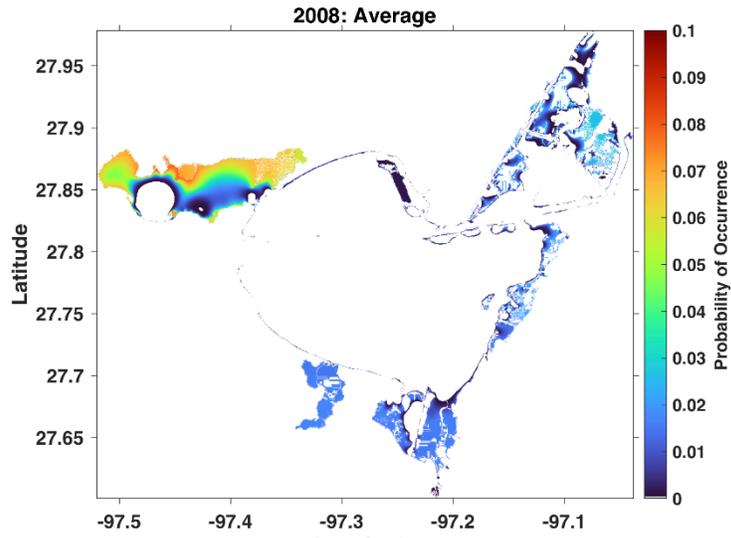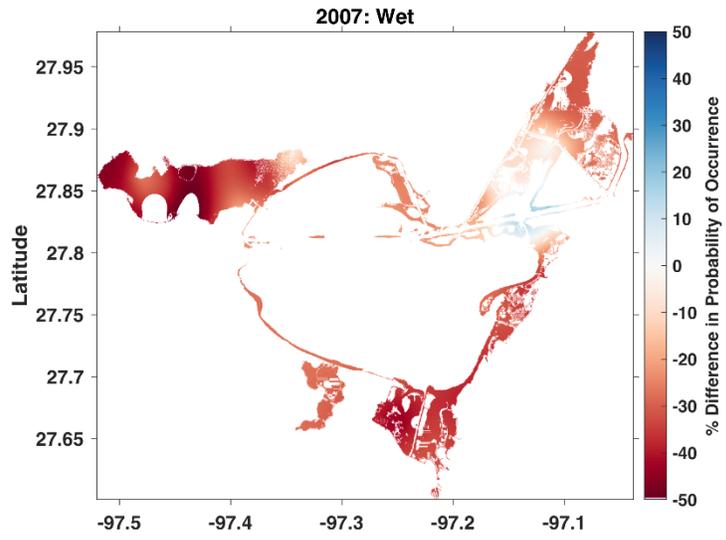
Sheepshead Minnow
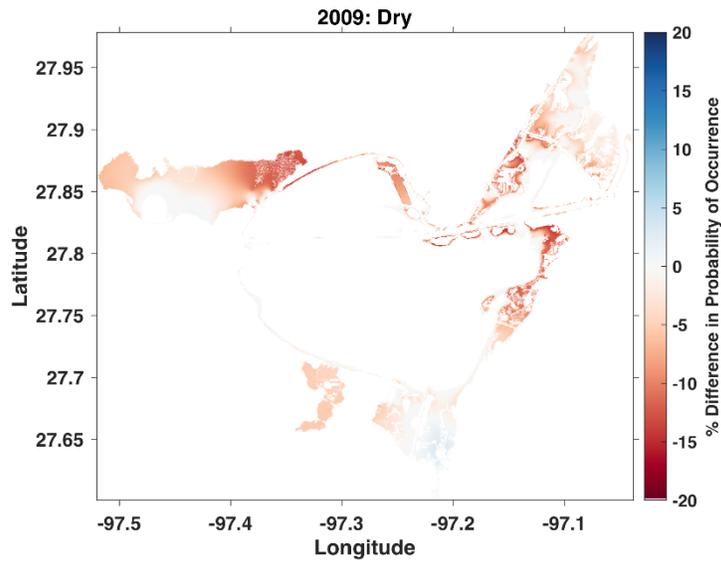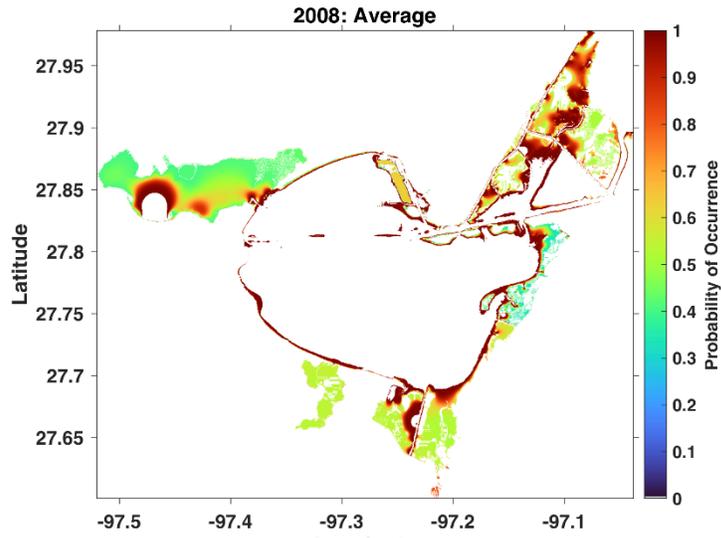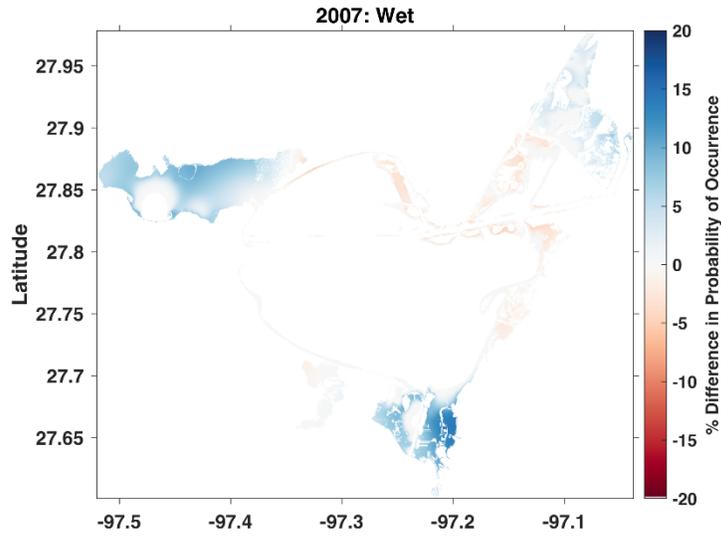
White Shrimp

Brown Shrimp

Blue Crab