1600011941
Final Report

SB3 Work Plan

Defining Bioindicators for Freshwater Inflow Needs Studies Phase 2: Defining a Sound Ecological Environment for Galveston Bay.

Prepared by

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TWDB CONTRACTS

Prepared for

Texas Water Development Board

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TWDB - Contract # 1600011941

PURSUANT TO HOUSE BILL 1 AS APPROVED BY THE 84TH TEXAS LEGISLATURE, THIS STUDY REPORT WAS FUNDED FOR THE PURPOSE OF STUDYING ENVIRONMENTAL FLOW NEEDS FOR TEXAS RIVERS AND ESTUARIES AS PART OF THE ADAPTIVE MANAGEMENT PHASE OF THE SENATE BILL 3 PROCESS FOR ENVIRONMENTAL FLOWS ESTABLISHED BY THE 80TH TEXAS LEGISLATURE. THE VIEWS AND CONCLUSIONS EXPRESSED HEREIN ARE THOSE OF THE AUTHOR(S) AND DO NOT NECESSARILY REFLECT THE VIEWS OF THE TEXAS WATER DEVELOPMENT BOARD.

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August 30, 2018

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List of Abbreviations

AF – Acre feet
AIC – Akaike information criterion
BBEST – Bays and Basin Expert Science Team
CPUE – Catch per unit effort
DISTLM – Distance based linear model
F – Fall
GBEP – Galveston Bay Estuary Program
HARC – Houston Advanced Research Center
LGB – Lower Galveston Bay
nMDS – Non-parametric multidimensional scaling
NOAA – National Oceanic and Atmospheric Administration
NTU – Nephelometric Turbidity Units
PERMANOVA – Permutation based analysis of variance
PRIMER – Plymouth Routines in Multivariate Ecological Research
PSU – Practical Salinity Units
SAC – Science Advisory Committee
SB3 – Senate Bill 3
SIMPER – Similarity percentage analysis
SJR – San Jacinto River
SP – Spring
SU – Summer
SWQM – Surface Water Quality and Monitoring Database
TB - Trinity Bay
TCEQ – Texas Commission on Environmental Quality
TPWD – Texas Parks and Wildlife Department
TPWD – Texas Parks and Wildlife Department
TR – Trinity River
T-SJ BBASC – Trinity, San Jacinto Basin and Bay Area Stakeholder Committee
TSJ-BBEST – Trinity-San Jacinto Bays and Basins Expert Science Team
TWDB – Texas Water Development Board
ULGB – Upper and Lower Galveston Bay
USGS – United States Geological Survey
W – Winter

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EXECUTIVE SUMMARY

Freshwater inflows are necessary for the maintenance of ecosystem health in coastal bays and estuaries. Inflows drive the water (salinity, nutrients, and chlorophyll) and sediment quality, in turn driving the health of biological systems. Freshwater inflows contribute to the fluctuation of these estuarine environmental parameters, all of which are important to the survival and success of the estuarine flora and fauna. Periodic pulses of inflows can influence estuarine systems by enhancing primary productivity, contributing to species biodiversity and supporting energy transfer between trophic levels. Estuarine ecosystem health is fundamentally dependent on freshwater inflows, further supporting the need to find balance between the supply and demand on coastal resources and ecosystem services.

The first component of this study was focused on identifying bioindicator species to characterize "a sound ecological environment" for Galveston Bay. We (report authors and technical advisory committee) used both the Senate Bill 3 (SB3) Science Advisory Committee (SAC 2006, 2009) and the subsequent Texas Commission on Environmental Quality (TCEQ) Chapter 298 (2011). While the technical language may be different, the key elements are similar. For reference, the original SAC definition of a sound ecological environment is one that:

a) *sustains the full complement of native species in perpetuity,*
b) *sustains key habitat features required by these species,*
c) *retains key features of the natural flow regime required by these species to complete their life cycles, and*
d) *sustains key ecosystem processes and services, such as elemental cycling and the productivity of important plant and animal populations*

In TCEQ Chapter 298 (2011) a sound ecological environment is defined as:

"a resilient, functioning ecosystem characterized by intact, natural processes, and a balanced, integrated, and adaptive community of organisms comparable to that of the natural habitat of a region".

The work was performed as part of the adaptive management phase of the Senate Bill 3 process for establishing environmental flow standards. The bioindicator species identified will be used to define the status of Galveston Bay as a healthy estuary, that is, an estuary that provides a sound ecological environment. The biotic community examined in this study was that collected by Texas Parks and Wildlife Division (TPWD) from 1992 to 2015 in 5,226 bag seine sampling events. These netted 217 species of fish and invertebrates, a total catch of 1,044,391 individuals. We found 30 species of fish and invertebrate comprised 97% of the total bag seine catch. Given their overall representation in the collection, spatially and temporally, and that they are all native to Texas, these 30 species are useful as bioindicators. An in-depth analysis revealed that distribution and catch per unit effort (CPUE) for these specific species are significantly correlated to salinity, temperature, dissolved oxygen and turbidity as well as having patterns which are dominated by seasons and locations within Galveston Bay similar to the findings of McFarlane et al., 2015. The Shannon Diversity Index (*H'*), Pielou's Evenness index (*J'*), species richness (*S*) and the total number of individuals (*N*) were calculated on the CPUE data for the top 30 species. These community metrics have strong seasonal and spatial patterns which reflect known lifestyles and habitat use of the fish and invertebrates. While variable, these community metrics were not adversely influenced by periods of drought, flood or other extreme events from 1992-2015. The community metrics reveal relative stability, i.e., no extreme or protracted shifts, consistent with Galveston Bay behaving as a sound ecological environment or healthy bay.

Species distributions and abundances were significantly correlated to salinity and turbidity and displayed patterns dominated spatially and by seasons within Galveston Bay. We found that seasonality was the greatest driver when considering the entire bay, consistent with known life cycles of fish and invertebrates that use estuaries as their habitat (McFarlane et al., 2015; Tolan 2013; Quigg and Steichen 2015; Steichen and Quigg 2018). Fish and invertebrate distribution and abundance were driven by salinity regimes and habitat location (which in this study is considered by bay segment). Gulf Menhaden, Blue Catfish, Atlantic Croaker, Florida grass shrimp are all present in highest abundances when salinities range from 0-20 psu. During times of higher salinity (≥21 psu), Pinfish, Spot, Bay Anchovy and Lesser blue crabs are higher in abundance. Habitat use throughout the life cycles of these animals needs to also be considered when determining if these species can be used as higher salinity bioindicators. Periods of prolonged flooding or low salinities will also reduce habitat suitability for some fish and invertebrates such as when periods of prolonged drought may constrict areas of low salinities to regions of the bay closer to the mouths of the rivers. This in turn, directly affects habitat suitability both in terms of quantity and quality. Those which are mobile can find alternatives; but those which are sessile are likely to be impacted (lower abundance and fecundity).

One of the goals of this study was to determine the freshwater inflows required to maintain the salinity regime necessary to accommodate a "healthy ecosystem" or a "sound ecological environment" within Galveston Bay, that is to say, to "sustain the full complement of native species in perpetuity". In the case of this study, we defined the "full complement of native species" as the dominant fish and invertebrates found in the 5,226 bag seine sampling events conducted from 1992 to 2015 by TPWD. Based on our findings, we conclude that it is reasonable to assert that the inflows into the bay currently provides a "sound ecological environment" to the species captured using this approach. Previous studies have used a similar cohort approach to investigate fisheries in Texas as well as their response to freshwater inflows. Future studies could consider additional records, such as bay trawls, in defining both the complement of native species, and the health of the bay. Although specific details may change, we hypothesize the outcome will be similar to that in the present study. However, more work is needed to confirm or refute this suggestion.

The second part of this study focused on evaluation of the instream flow and freshwater inflows standards for Galveston Bay. The original objective of the study was to determine whether the instream flow and freshwater inflow standards align to support a sound ecological environment in Galveston Bay. However, due to the complex differences in the structure of the two sets of standards (e.g., instream flow standards are comprised of subsistence, base, and pulse flows, but freshwater inflow standards are comprised of seasonal and annual inflow quantities and annual attainment frequencies), it was determined that a comparison analysis was not appropriate. As such, the focus of the study shifted to evaluate the frequency at which the standards were met in the recent record of observed flows. The TCEQ adopted instream flows standards were compared to stream gage data collected by the U.S. Geological Survey (USGS) while the TCEQ adopted freshwater inflow standards were compared to freshwater inflow data compiled by the Texas Water Development Board (TWDB). Our analysis found the Trinity River and San Jacinto River basins *are* receiving the recommended flow volumes and frequencies. Our findings are tentative and provided with caveats as we feel this requires a comprehensive effort with the use of agency models (e.g., TxBLEND, WAM, etc.) and which includes bringing together TCEQ and TWDB and various other stakeholders that was beyond the scope of the current study. This project contributes to several priority activities identified in the Trinity, San Jacinto Basin and Bay Area Work Plan for Adaptive Management (TSJ BBASC 2012), including to test the conclusion that the bioindicators were appropriate for representing the health of Galveston Bay and to consider the addition of new bioindicator species which were previously not recognized.

1. INTRODUCTION

1.1. Bioindicators in estuarine environments

More than 40% of the world's population lives within 100 km of the coast leading to continuous pressure on bays, estuaries and nearshore environments due to increased urban development and growing demands on fisheries resources (IOC/UNESCO, 2011). This growth in coastal populations globally result in increased volumes of freshwater diverted upstream for agriculture and human populations and recycled as returned flows (i.e., effluent, power plants, etc.). The returned flows may contain elevated levels of nutrients as a result of common waste water treatment procedures (Oki and Kanae, 2006) as well as pharmaceuticals and other human by-products. Demands on freshwater inflows in many coastal states around the country and the world, reflect the need to develop suitable indicators and/or metrics of estuarine health.

Freshwater inflows contribute to the fluctuation of estuarine environmental parameters including but not limited to salinity, organic matter, turbidity, nutrient concentrations and sediment loading, all of which are important to the survival and success of the estuarine flora and fauna (Alber, 2002; Copeland, 1966; Dorado et al., 2015; Lester and Gonzalez, 2011; Palmer et al., 2011; Palmer and Montagna, 2013; Roelke et al., 2013). Periodic pulses of freshwater inflows can influence estuarine systems by enhancing primary productivity, contributing to species biodiversity and supporting energy transfer between trophic levels (Flemer and Champ, 2006; Roelke et al., 2013). Estuarine ecosystem health is fundamentally dependent on freshwater inflow further supporting the need to find balance between the supply and demand on coastal resources and ecosystem services (Alber, 2002; Boesch et al., 1984; Longley, 1994; Nixon, 1995; Quigg et al., 2009).

Salinity in the coastal environments is primarily influenced by river inflow and land runoff and is inversely related to freshwater inflows. As freshwater inflows are altered, the estuarine environment faces ecological consequences, some of which include changes in the abundance and distribution of species requiring varying salinity regimes. Decreasing the freshwater pulses to an estuary may result in a concurrent decrease in food and habitat for the resident biota. As freshwater input decreases and salinities increase, species with a higher salt tolerance have the opportunity to encroach on the native habitat compromising function, integrity and sustainability of the natural habitat (Montagna et al., 2013; Flemer and Champ, 2006). Sustainability, a proxy of ecological health, is the capacity of a biological system to maintain diversity and productivity. In this study we are reporting the results of a small subset of the biological community within Galveston Bay, which will offer a glimpse into the biotic diversity and response to freshwater inflows. As with previous studies, fish and invertebrates are often used as bioindicators of estuary health, that is, a sound ecological environment which is supportive of native communities (see e.g., Bortone et al. 2005a, b; Quigg and Steichen 2015; Steichen and Quigg 2018).

1.2. Definitions of a sound ecological environment

In order to identify bioindicator species to characterize “a sound ecological environment” for Galveston Bay, we referred to the definition determined by the Senate Bill 3 (SB3) Science Advisory Committee (SAC 2006, 2009) as our reference and is stated below. The Trinity, San Jacinto Basin and Bay Area Stakeholder Committee (T-SJ BBASC, 2012) requested using this as the “best” definition for assessing the health of Galveston Bay. From the SAC report, the original SAC definition of a *sound ecological environment*, is one that:

(a) sustains the full complement of native species in perpetuity,
(b) sustains key habitat features required by these species,
(c) retains key features of the natural flow regime required by these species to complete their life cycles, and
d) sustains key ecosystem processes and services, such as elemental cycling and the productivity of important plant and animal populations.

Subsequently, the TCEQ Chapter 298 - Environmental Flow Standards for Surface Water SUBCHAPTER B: Trinity and San Jacinto Rivers, and Galveston Bay (hereafter referred to as TCEQ Chapter 298, 2011) defined a sound ecological environment as:

"a resilient, functioning ecosystem characterized by intact, natural processes, and a balanced, integrated, and adaptive community of organisms comparable to that of the natural habitat of a region".

The technical language between the definitions maybe different, but we conclude that the SAC definition components are more or less included under the TCEQ Chapter 298 (2011) definition of a sound ecological environment. Hence, in this study we will be referencing the later definition.

1.3. Use of freshwater resources and increasing population

The conversion of land to support growing populations is a major component of human modification of the environment (Darrow et al., 2017; Montagna et al., 2012). In recent decades, there has been a shift from extensive land use for agriculture, extraction of timber and other natural resources to the rapid expansion of urban areas (development) particularly adjacent to large cities (Wedge and Anderson, 2017). Increases in urban land cover parallels increases in impervious surface areas and subsequently increases water pollution, often as a result of increased runoff which exports fertilizers and pollutants (Wedge and Anderson, 2017; Wilber and Clarke, 2001). Urban-related runoff/storm water is one of the largest contributors to the impairment of river and stream water quality in most states in the US, with high levels of eutrophication reported in 45%

of the estuaries surrounding the Gulf of Mexico (Clement et al., 2001). Resource managers are faced with the trade-off of wisely using freshwater resources while meeting the demands of a rapidly increasing human population.

1.4. Galveston Bay Hydrology

Galveston Bay is a region where freshwater from rain, land runoff, large rivers, and local bayous and saltwater from the Gulf of Mexico meet (Fig. 1). Gulf waters flow into the bay during tidal fluxes through Bolivar Roads (inlet between Galveston Island and the Bolivar Peninsula), San Luis Pass (western end of Galveston Island), and to a lesser degree through Rollover Pass (east end of the Bolivar Peninsula). Usually, most of the freshwater entering the Galveston Bay system flows down two large rivers: The Trinity and San Jacinto rivers. The Trinity River originates in the Dallas-Fort Worth region and contributes to the majority of freshwater inflows (55%) into Galveston Bay (Fig.1). The San Jacinto River flows into Lake Houston and then into the Houston Ship Channel and contributes ~26% (along with Buffalo Bayou) of the freshwater inflows into Galveston Bay (Fig. 1). Runoff from coastal urban watersheds contributes the remaining ~19% of the freshwater inflows to the bay. Its watershed encompasses nearly 37 counties. Human alterations in the bay have likely exerted more profound influence on bay circulation than natural processes (Wilber and Clarke, 2001; Wilber and Clarke, 1998). The Houston Ship Channel has caused the most pervasive change to circulation by greatly increasing the flow of Gulf water into the bay.

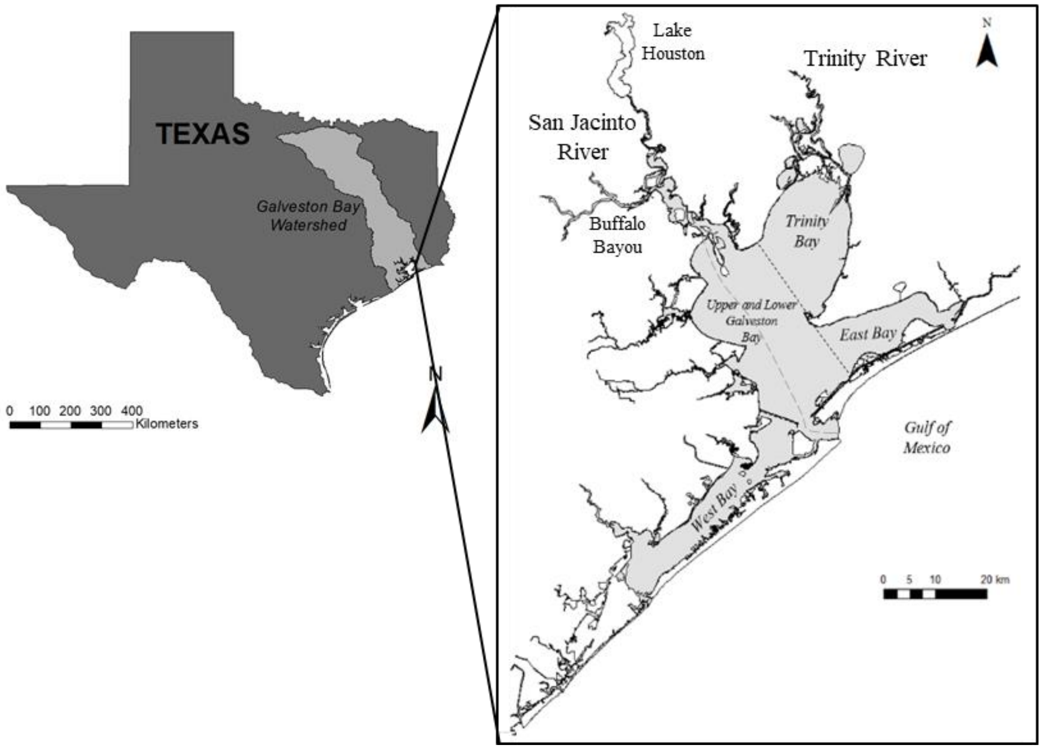


Figure 1 Map of Texas showing the area of the Galveston Bay watershed and the bay segments within the bay including: Trinity, Upper and Lower, East and West Bays. Buffalo Bayou, Lake Houston and Trinity and San Jacinto Rivers are also depicted on the map. The Houston Ship Channel is denoted with the gray long dash line extending from the mouth of the San Jacinto River to the Gulf of Mexico.

2. OBJECTIVE A – DEFINING A SOUND ECOLOGICAL ENVIRONMENT

The first objective of this work includes working towards defining a sound ecological environment for Galveston Bay, identification of bioindicator species suitable for use in freshwater inflow needs studies of Galveston bay as part of the adaptive management phase of the Senate Bill 3 process for establishing environmental flow standards is to be determined.

One of the goals of this objective was to determine the key features of the natural flow regime needed by these species to complete their life cycles; therefore, analyses were conducted to understand how the biotic community changes in relation to changes in freshwater inflows. We analyzed the biotic community within Galveston Bay across a range of abiotic conditions. The time frame for the biotic community analysis in Galveston Bay ranged from 1992 – 2015 and hereafter will be referred to as the “study period”. This study period was selected because it includes extreme drought, extreme flood and average conditions in reference to temperature, precipitation and freshwater inflows. All of the biotic community data was collected via bag seine by the Texas Parks and Wildlife Department (TPWD).

To discover correlations between the biotic community and freshwater inflows, we used the TWDB estimated freshwater inflows (TWDB estimated freshwater inflows) and the salinity that was measured by TPWD at the time and locations of the bag seine collection. The TWDB estimated freshwater inflows volumes are provided as one cumulative number for all of Galveston Bay. We conducted an analysis to determine the correlation between the TWDB estimated freshwater inflows and salinity measured by TPWD during the bag seines collections. In the methods section 2.1 of this report, we will explain how the bag seine species data and water quality parameters, measured at the time and location of each bag seine sampling, and were used in this analysis.

2.1. Methods

2.1.1. Annual TWDB Freshwater Inflow Anomalies

TWDB estimated the surface freshwater inflow (TWDB estimated freshwater inflows) volumes in acre feet (AF) to Galveston Bay by summing the gaged inflows, ungaged inflows (modeled by TWDB), and return flows, while subtracting diversions (Guthrie et al, 2012). The gaged flows were measured by the United States Geological Survey (USGS) stream flow gages located at on the Trinity River at Romayor (USGS 08066500), San Jacinto River (USGS 08072000), Cedar Bayou (USGS 08067500), Brays Bayou (USGS 08075000), Greens Bayou (USGS 08076000), Halls Bayou (USGS 080765000), Hunting Bayou (USGS 08075770), Vince Bayou (USGS 08075730), White Oak Bayou (USGS 08074500), Buffalo Bayou (USGS 08073600), Chocoloate Bayou (USGS 08078000) and Lake Houston (USGS 08072000). The ungaged inflows were estimated using the Texas Rainfall-Runoff model and include the sum of 1) computed runoff, based on precipitation over the watershed, 2) flow diverted from streams by municipal, industrial, agricultural, and other users, and 3) unconsumed flow returned to streams (Matsumoto, 1992; Guthrie et al., 2012b; TWDB, 2015). We calculated TWDB estimated freshwater inflows anomalies annually over the study period of 1992-2015. This study period encompasses months of wet periods (indicated when TWDB estimated freshwater inflows are ≥85th percentile; 2,101 x 10^3 AF mon^{-1}), average flow conditions (TWDB estimated freshwater inflows <85th percentile and >15th percentile; 1051 x 10^3 AF mon^{-1}) and dry periods (TWDB estimated freshwater inflows ≤15th percentile; 203 x 10^3 AF mon^{-1}). The annual average was calculated using the biological year (Dec-Nov) so that a comparison could be made of the TWDB estimated freshwater inflows and the biological communities. The year includes the

December from the previous year to look at an entire winter season. The four biological seasons are defined as: winter (W; Dec (previous year)-Feb), spring (SP; Mar-May), summer (SU; Jun-Aug) and fall (F; Sep-Nov) for each year from January 1992 - November 2015. To calculate the annual anomalies the sum of the TWDB freshwater inflows was calculated for each year of the study period. Then the average of the annual sums was calculated. This overall average of the sums for all years in the study period was subtracted from each years summed TWDB freshwater inflows. This analysis was conducted to better understand the abiotic conditions during our study period. This allows for direct comparison both temporally and spatially between the abiotic parameters and the biota.

2.1.2. Relationship between TWDB estimated freshwater inflows and salinity

An analysis was run to determine how TWDB estimated freshwater inflows are correlated to salinities within Galveston Bay during the study period for this report. While many evaluations have been performed by both TWDB (through TXBLEND) and the TSJ BBEST investigating the relationship between freshwater inflow and salinity this additional analysis was required so that the parameters collected for TWDB estimated freshwater inflows could be directly correlated in various statistical analyses described below (Espey et al. 2009; Guthrie et al., 2012a, 2012b; Lee et al., 2001; Matsumoto et al., 2005). This necessitates redoing such an analysis. Animals respond not to the total flow in anyone month, but to the average flow/salinities they are exposed to (see e.g., Fiol and Kultz, 2007). Hence, we examined average monthly TWDB estimated freshwater inflows rather than total flows.

The TWDB estimated freshwater inflows are reported as a sum of inflow from the Trinity and San Jacinto rivers and surrounding coastal watersheds for all of Galveston Bay for each month. TWDB estimated freshwater inflows summed monthly flow volumes were compared to the salinities that were reported by Texas Parks and Wildlife Department (TPWD) at the time of each bag seine collection. To do this comparison, we averaged the TPWD salinities that were measured in Galveston Bay during each respective month that we looked at TWDB estimated freshwater inflows. In addition to salinity measurements, TPWD measured temperature (°C), dissolved oxygen (mg/L) and turbidity (NTU) during each bag seine. The salinities were averaged across all of Galveston Bay and within each bay segment: Trinity Bay, TB; Upper and Lower Galveston Bay, ULGB; West Bay, WB and East Bay, EB; for each month and for each season (Fig. 1). These bay segments are consistent with those utilized by TPWD in the reporting of the bag seine data and associated abiotic parameters (TPWD, 2012).

The averages for each month and for each season winter (W; Dec (previous year)-Feb), spring (SP; Mar-May), summer (SU; Jun-Aug) and fall (F; Sep-Nov) for each year from January 1992 - November 2015 were calculated from a list of all individual bag seine collection events. The abiotic parameters were averaged spatially within each bay segment and temporally on a monthly and seasonal basis to analytically work with the TPWD random sampling protocol (TPWD, 2012). Once the monthly and seasonal averages were calculated for Galveston Bay and each of the bay segments, they were grouped in a suite of categories including: 0-5 psu, 6-10 psu, 11-15 psu, 16-20 psu, 21-25 psu, 26-30 psu, 31-35 psu and ≥36 (hereafter in this report these categories will be referred to as "salinity categories" (Table 1). These categories were selected because they allowed for increased types of data analysis within PRIMER such as similarity percentages routine (SIMPER) and permutation based analysis of variance (PERMANOVA) to look into the changes within the biotic community. The SIMPER analysis breaks down the Bray-Curtis dissimilarities between all pairs of samples, one from each group selected, into percentage contributions from each species. The results list the species in order of decreasing contribution and the cumulative contribution is also tabulated for all species selected in the analysis (Clarke and Gorley, 2006). This routine allows for the comparison of the biotic community between the selected factor (i.e. year, month, season, bay segment, etc). The salinities across the bay fluctuate directly as a result of freshwater inflow and therefore salinities are changing rapidly in response to fluctuating freshwater inflows. By grouping the salinities into categories, we can present trends between the abiotic factors and the biotic community in a concise manner.

2.1.2. Selection of Biotic Community

This analysis was conducted on fisheries and environmental data collected by TPWD – Coastal Fisheries Division from 1992-2015. TPWD bag seine sampling covered the shoreline (extending from zero out to 15.2m from the coastline) of Galveston Bay. The bag seine gear type and location of collection are intended to catch juveniles and small adults of fish and invertebrate species that inhabit the coastal regions of a waterbody (TPWD, 2012). These juveniles and sub- adult species are more susceptible to fluctuations in the abiotic conditions (Chovanec et al., 2003; Whitfield and Elliot, 2002). Due to this sensitivity, we selected this gear type because the species present will respond to abiotic conditions.

For each bag seine collected (5,226 sampling events), corresponding water quality parameters were measured at the surface (0-15cm) and ~3m from shore (TPWD, 2012). Each month, 20 bag seines were collected across Galveston Bay (240 yr^{-1}) with ten of the bag seines collected during the first half of the month (1^{st}-15^{th}) and the other ten collected during the second half of the month (16^{th}-end of month). TPWD determined the locations of the bag seine sampling by a randomized process. Twenty grids assigned along the shoreline within the bay (1 minute latitude x 1 minute longitude) were further divided into 144 gridlets within each grid (5 seconds latitude x 5 seconds longitude). The bag seines are 18.3m long, 1.8m deep with 19mm stretched nylon mesh in wings (8.3m long with a 1.8m bag) and 13 mm stretched nylon mesh in the bag (TPWD, 2012). A 12.2m limit line is between the two poles to maintain a standardized width during sampling.

The abundance data was then converted to catch per unit effort (CPUE) to allow for a comparison of the bag seines temporally and spatially. Each bag seine covered an area of 0.03 hectare (TPWD, 2012). For each bag seine during the study period, the number of individuals of each species was divided by 0.03 hectare to calculate the number of individuals (of each species) per hectare. Within each bay segment and across the entire bay, the CPUE (# individuals/hectare) was summed monthly (seasonally) and divided by the number of bag seine collections conducted during that respective month (season) to compare bag seine data both spatially (bay segments) and temporally (month/season).

All biotic analyses were conducted on 30 species that accounted for 97% of the total catch within bag seines over the study period of 23 years from 1992-2015. The remaining 3% of the total individuals collected were comprised of 187 other species. These 30 fish and invertebrate species accounted for a majority of the variability and diversity observed during the study period. All results for the biotic community within this report are based on these top 30 species.

2.1.4. Diversity calculations

Diversity indices were calculated on the fish and invertebrate abundances (on the CPUE) per bag seine. Species diversity metrics including the Shannon diversity (*H’;* Eqn. 1), Pielou’s evenness measure (*J’*; Eqns. 2, 3), species richness (*S*) and total number of individuals (*N*) were calculated in Plymouth Routines in Multivariate Ecological Research (PRIMER) to determine the correlations between the biotic and abiotic factors over time (annually and seasonally). Species richness quantifies the number of different species in the corresponding species list of a dataset. Because richness does not take the abundances of the types into account, it is not the same thing as diversity, which does take abundances into account.

Equation 1 Shannon Diversity Index where: *H'* = the Shannon diversity index, P_i = fraction of the entire population made up of species *i*, S = numbers of species encountered, ∑ = sum from species 1 to species *S*

$$H' = -\sum_{i=1}^{R} p_i \ln p_i$$

Equation 2 Pielou's evenness index is derived from the Shannon Diversity index (*H'*) where (*H'* max) is the maximum possible value of H'

$$J' = \frac{H'}{H'_{\mathrm{max}}}$$

Equation 3 The equation for H'_{max} used in Pielou's evenness index where S is the total number of species

$$H'_{\mathrm{max}} = -\sum_{i=1}^{S} \frac{1}{S} \ln \frac{1}{S} = \ln S.$$

2.1.5. Multivariate Statistics - Pretreatment of the data

The data collected by TPWD was reported in abundance per bag seine which was converted to CPUE (# of individuals per hectare). All analyses conducted on the CPUE data did include zero data (times when species were not recorded in a bag seine) to account for bag seines that were conducted but the species were not present. Statistical analyses were conducted in PRIMER v6 with PERMANOVA+ add-on package (Anderson et al., 2008; Clarke and Gorley, 2006). Analyses were conducted on the abundance and environmental data for the study period (1992-2015).

Multivariate statistical analyses have been used to determine the relationship between fish species and environmental parameters in previous studies (Pérez et al., 2013; Montagna et al., 2008). Environmental data including temperature (°C), salinity (psu) and dissolved oxygen (mg L^{-1}) were normally distributed and did not require a transformation. Turbidity (NTU), was not normally distributed and therefore was log(x+1) transformed (Clarke and Warwick 2001). After turbidity was transformed, all environmental data were normalized in PRIMER (to put variables on the same scale for comparison) and then used to build a Euclidean dissimilarity distance matrix (Eqn. 4). To normalize the data, the mean of each variable was subtracted from each sample within that variable and then divided by the standard deviation for that variable (Clarke and Gorley, 2006). The Euclidean distance matrix is calculated using the values produced from the transformation (if conducted) and then subsequent normalization (Eqn. 4).

Equation 4 Euclidean distance calculation where y_{i1} and y_{i2} are the result from the transformation and then subsequent normalization.

$$D_1 = \sqrt{\Sigma_i \, (y_{i1}-y_{i2})^2}$$

Equation 5 Bray Curtis dissimilarity matrix calculation where C_{ij} is the sum of the lesser values for species common between both sites (S_i and S_j)

$$BC_{ij} = 1 - \frac{2C_{ij}}{S_i + S_j}$$

Prior to the statistical analyses, the environmental data were evaluated by draftsman plots to determine collinearity. Tests for collinearity were conducted with no measured collinearity among the environmental parameters (all values <0.95) (Clarke and Ainsworth, 1993). The variables used in this analysis were not collinear and therefore were all included.

The CPUE data (averaged monthly or seasonally across Galveston Bay or within each bay segment depending on analysis) was used to compute a Bray-Curtis (+1 dummy variable to identify the presence of zeros in the biological data) similarity resemblance matrix. The addition of the +1 dummy variable forces two samples with no species present to be counted as 100%

similar rather than be excluded from the analysis. In this analysis, the lack of species has as much importance in the analysis as when species are present. To achieve a monthly average, the CPUEs were averaged across all of Galveston Bay or within each bay segment across each month – year dependent on the analysis. To achieve a seasonal average, the CPUE and water quality parameters were independently averaged across Galveston Bay for each of the four biological seasons: winter (W; Dec (previous year)-Feb), spring (SP; Mar-May), summer (SU; Jun-Aug) and fall (F; Sep-Nov) for each year from January 1992 - November 2015. For intra-bay segment comparisons, the CPUE and environmental parameters were averaged across each bay segment over each season-year (e.g. spring 1992, summer 1993, etc.) or month –year (e.g. January 1992, February 1992, etc.) depending on analysis and will be indicated in each subsequent figure.

2.1.6. Multivariate statistical - analyses

Non-parametric multidimensional scaling (nMDS) plots were used to view the data points in two dimensional ordination space. Points that are located closer together in the plot indicate seasons that have increased similarity in the species community and CPUE compared to those points that are further in distance from each other. The nMDS was constructed based on the Bray Curtis +1 dissimilarity matrix (Eqn. 5) of the species CPUE across all of Galveston Bay from 1992-2015 and included the zeros data to indicate when specific species were not present in a sample. Seasonal average abundance was calculated for each species over the study period and then similarity distances were calculated with the Bray Curtis similarity matrix. Cluster analyses (using group-average linking based on Bray–Curtis similarities) were used to determine how the community changed seasonally. The groupings were determined by running a Cluster analysis in PRIMER to produce a dendogram (Supplemental Figure. 1).

A similarity percentage analysis (SIMPER) was run on the non-transformed CPUE data to explain the similarity and differences in species composition between samples collected during the defined salinity categories which are defined in Table 1 and were defined previously in section 2.1.2. A SIMPER analysis was run to evaluate the variability of the fish and invertebrate communities within estuaries across the bay segments, seasonal variability, and salinity gradient variability within the fish assemblages.

The seasonal differences in environmental parameters were tested for significance using a permutation based analysis of variance (PERMANOVA; Anderson, 2001). The method of permutation of residuals under a reduced model was utilized and the data was partitioned using the Type III sums of squares (Anderson et al., 2008). To determine the significance level of $p < 0.001$, 9999 permutations were run in all analyses.

A distance based linear model (DISTLM) was run on the Bray Curtis dissimilarities to explore the correlations between species CPUE (i.e. response variables) to each of the water quality parameters (i.e. predictor variables) (Anderson et al., 2008). DISTLM performs 'marginal tests' of the biological data against each environmental variable independently. The Best selection procedure was chosen with R^2 criterion was selected to test all possible combinations of variables to find the best overall solution that explains the variation in biological data. DISTLM was utilized to perform a permutation test (9999 permutations) of the null hypothesis that no correlation exists between each indicator species to each of the environmental factors (Anderson et al., 2008). The marginal test produces pseudo-*F* values (the statistic for testing the general null hypothesis of no relationship) analogous to the Fisher's *F*-ratio used in traditional regression with the smaller Akaike criterion (AIC) values indicative of a better model. The alpha significance for PERMANOVA designs and for DISTLM marginal tests was set to $p < 0.05$. The portion of variance within the biotic community that is explained by each respective environmental parameter. Species which display a strong correlation with an environmental parameter have an increased amount of variance explained (i.e. proportion of variance explained) by that respective environmental parameter.

2.2. Results

2.2.1. Temporal variation in the TWDB estimated freshwater inflows

Inter-annual variability in freshwater inflows to Galveston Bay is shown in Fig. 2. During the study period for this report (1992-2015), multiple flood and drought events were recorded along with “average” annual flows. The years with above average freshwater inflows were 1992-1995, 1997-1998, 2001-2002, 2007 and 2015 (Fig. 3a) while years with lower than average freshwater inflows were measured in 1996, 1999-2000, 2005-2006, 2008-2014 (Fig. 3a). An inverse relationship is observed between the TWDB estimated freshwater inflows and the TPWD salinity in Galveston Bay (Figs. 3a and 3b).

The average FWI during the highest inflow months (and volumes) occurred in February (1449 x 10^3 AF), and the lowest FWI occur during July (482 x 10^3 AF) (Fig. 4a). The monthly salinity was also calculated based on the salinity recorded at the time and location of the TPWD bag seine collection (Fig. 4b). The months with salinity at or below the monthly average salinity (18 psu) include Jan (17 psu), Feb (16 psu), Mar (18 psu), Apr (16 psu), May (17 psu), June (18 psu), Nov (18 psu) and Dec (18 psu) (Fig. 4b). The months with higher than average salinity include July (19 psu), Aug (22 psu), Sep (21 psu) and Oct (20 psu) (Fig. 4b).

The average seasonal FWI were highest during the winter (1388 x 10^3 AF) and spring (1299 x 10^3 AF) and lowest FWI were reported in summer (720 x 10^3 AF) and fall (1084 x 10^3 AF) (Fig. 5a). The seasonal salinity averages were lowest in the winter (17 psu) and spring (17 psu) and highest in the summer (19 psu) and fall (20 psu) (Fig. 5b).

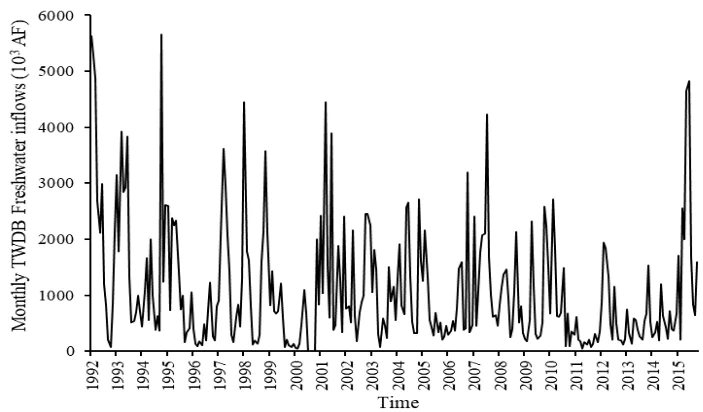


Figure 2 Monthly TWDB estimated freshwater inflows (10^3 AF) throughout the study period (1992 - 2015).

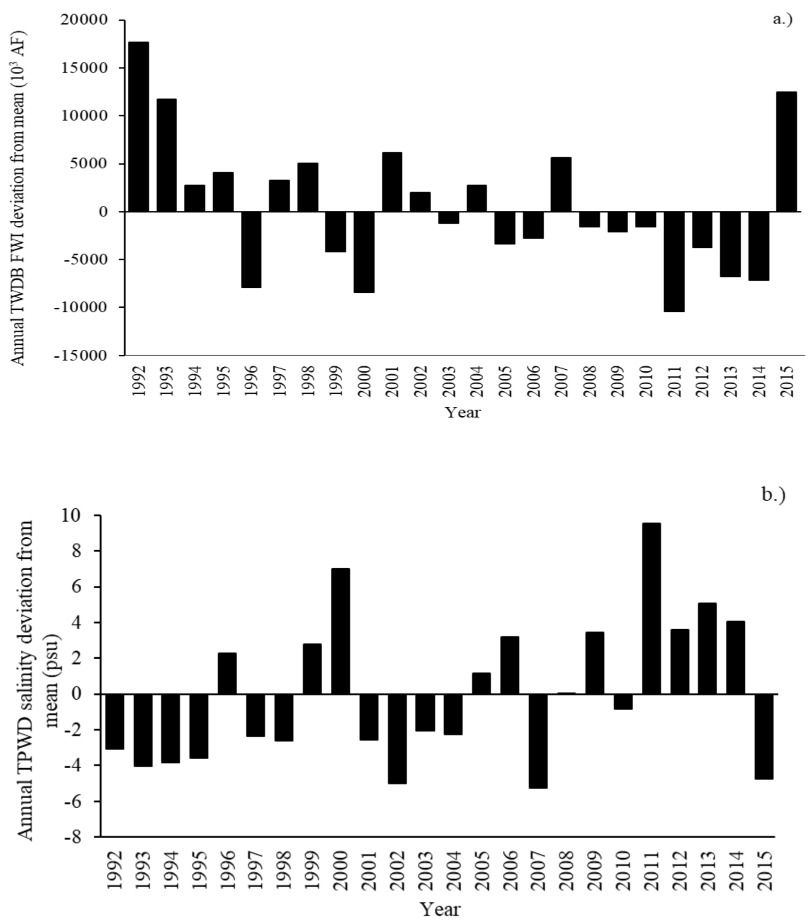
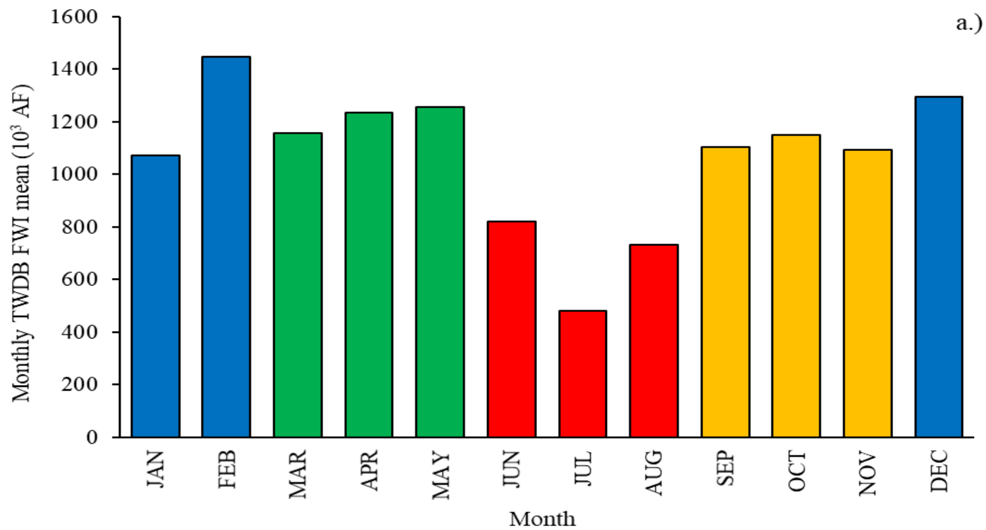


Figure 3 TWDB estimated freshwater inflows (10^3 AF) deviation from the mean (a) and the salinity derivation from the mean (b) recorded at the time of each TPWD bag seine across Galveston Bay. Mean annual inflow for the study period (1992-2015) was calculated by first summing the monthly inflow values within each year and subtracting the mean annual inflow from this sum. Mean annual salinity was calculated by first finding the average annual salinity for each year and subtracting average annual salinity from the average for each year over the study period.



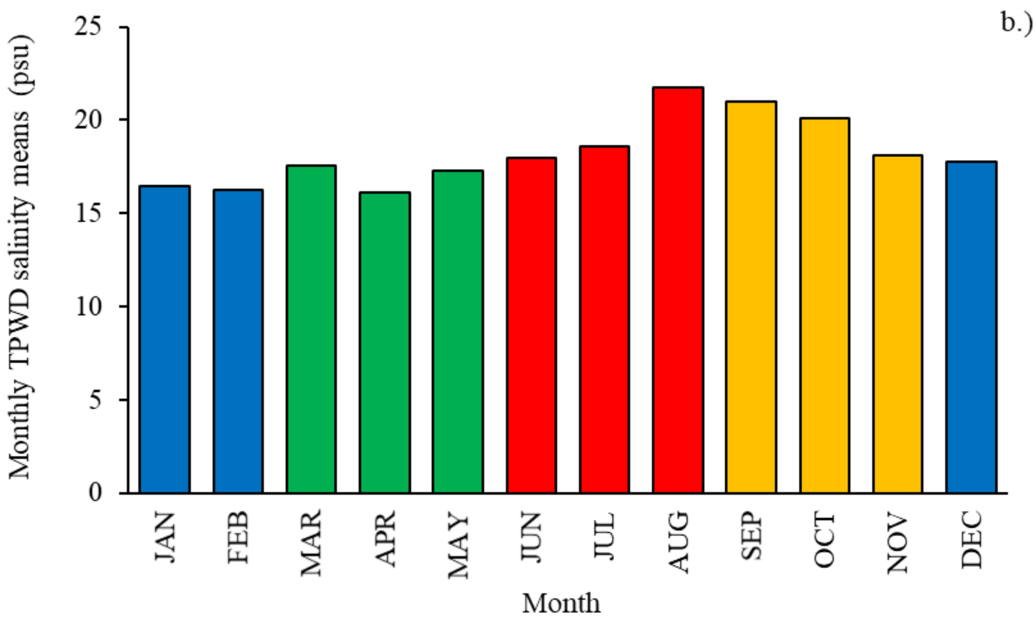


Figure 4 TWDB estimated freshwater inflows monthly flow volumes (10^3 AF) (a) and monthly average of TPWD salinity (psu) (b) measured at the time and location of each bag seine across Galveston Bay. Monthly means were calculated on individual bag seine data collected from 1992-2015. Seasonal definitions are: Winter (blue: Dec-Feb); Spring (green: Mar-May); Summer (red: Jun-Aug); Fall (orange: Sep-Nov).

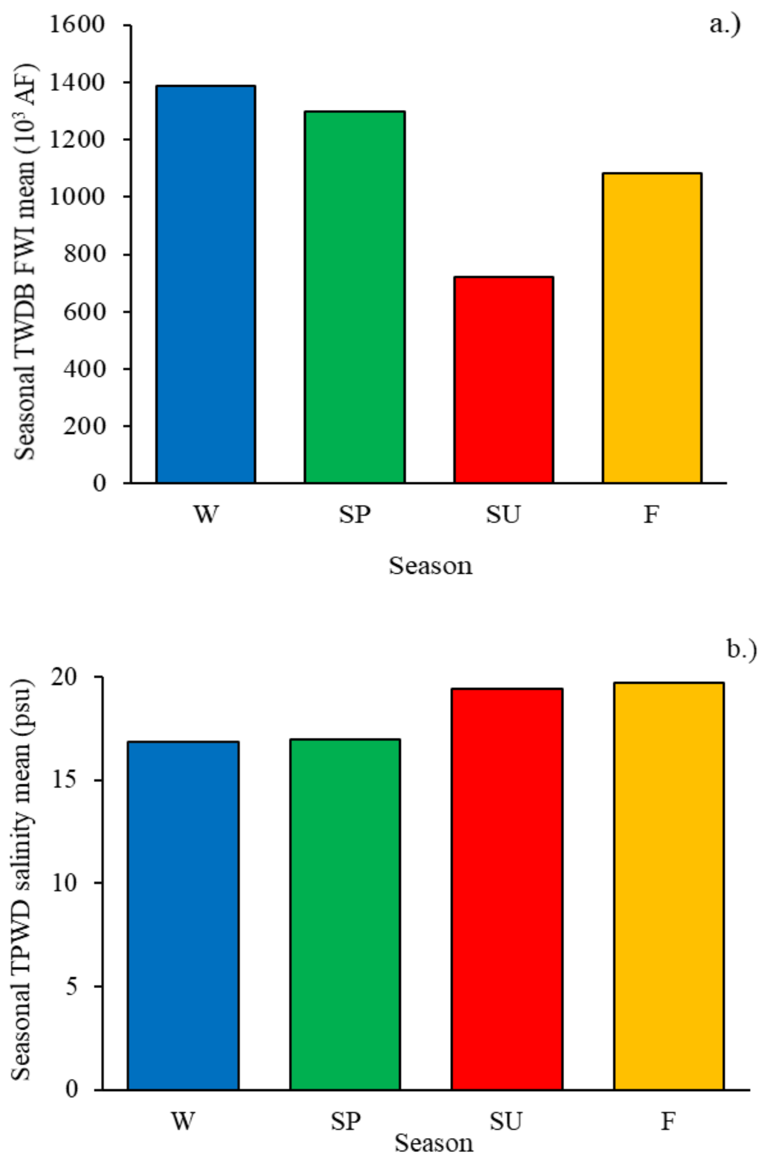


Figure 5 Seasonal means of the TWDB estimated freshwater inflows (10^3 AF) (a) and TPWD salinity at each time and location of the bag seine sampling (b). Seasonal means were calculated on data collected from 1992-2015. Seasonal definitions are: Winter (blue: Dec-Feb); Spring (green: Mar-May); Summer (red: Jun-Aug); Fall (orange: Sep-Nov).

2.2.2. Relationship between TWDB estimated freshwater inflows and salinity

The average salinity was calculated by averaging all reported salinities within each bay segment during each respective month. Then each month of salinity data throughout the study period (1992-2015) was plotted against its corresponding TWDB estimated freshwater inflows for that month (see Fig. 4). This produced 283 data points (number of month's data was collected during the study period). For Galveston Bay as a whole, the TWDB estimated freshwater inflows plotted against the categorized salinities (that is, 5 psu increments) had an $R^2 = 0.92$ (see Fig. 6). When considering Galveston Bay as a whole, freshwater inflow rates of 3471 (±1471 x 10^3 AF) $m^3 s^{-1}$ result in average salinities ranging 0-5 psu while freshwater inflow of 173 (±89 x 10^3 AF) result in the average salinities of 31-35 psu (Fig. 6; Table 1). This revealed a predictable relationship of average salinity within a 5 psu range. Bay-wide salinity could be predicted using this relationship and category approach.

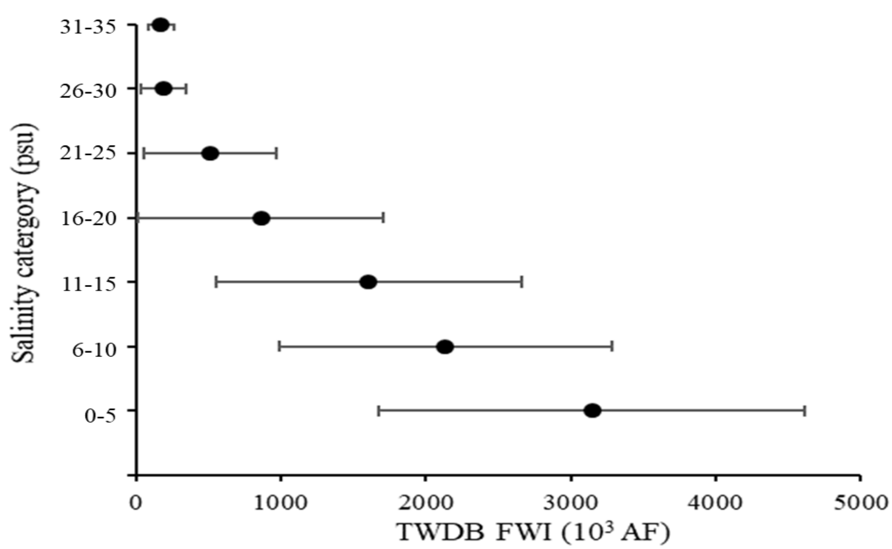


Figure 6 TWDB estimated freshwater inflows (10^3 AF) that were measured during times salinity was measured across Galveston Bay (1992-2015). The number of samples that are included in each data point are indicated (*n*) in Table 2. The error bars on each data point represent the standard deviation in TWDB estimated freshwater inflows when salinities were recorded in each respective category.

Salinity fluctuates as a function of freshwater inflows differently across the Galveston Bay system (Figs. 7-11) so we also examined the salinity and freshwater inflows relationships within each of the bay segments as well. Although we are presenting a comparison of salinity and TWDB estimated freshwater inflows it should be noted that the TWDB estimated freshwater inflows is reported as one value for the entire Galveston Bay per month. We compared the TWDB estimated freshwater inflows value for Galveston Bay against salinities measured within each of the bay segments. We proceed with this analysis acknowledging that the flow into the various regions of the bay is variable. We used 259 TPWD salinity data points for Trinity Bay, 281 for Upper and Lower Galveston Bay, 273 for East Bay and 284 for West Bay (Figs. 7 – 11, Table 1). The Trinity River flows directly into Trinity Bay which is also where overall the lowest salinities were observed (Fig. 8; Table 1). In Trinity Bay, when freshwater inflows reached 1651 (±1167) 10^3 AF, the salinities within Trinity Bay ranged 0-5 psu, and at the lowest FWI rates of 265 (±181) 10^3 AF the salinities ranged 26-30 psu (Fig. 8; Table 1). In Upper and Lower Galveston Bay, the highest FWI of 2910 (±1117) 10^3 AF occurred when salinities were recorded between 0-5 psu and during the lowest FWI of 73 (±0) 10^3 AF salinities were ≥36 psu (Fig. 9; Table 1). In West Bay, the lowest salinities of 6-10 psu were recorded when FWI were reported at 2979 (±958) 10^3 AF and the highest salinities of ≥36 psu occurred when FWI were 154 (±185) 10^3 AF (Fig. 11; Table 1). In East Bay when the FWI were at 2024 (±1384) 10^3 AF the salinities in East Bay were 0-5 psu and the highest salinities of 31-35 psu were recorded when FWI were 169 (±146) 10^3 AF (Fig. 10; Table 1).

Table 1 TWDB estimated freshwater inflows (10^3 AF) average (±standard deviation) and the corresponding number of sampling events that are included in each salinity category (*n*) from 1992-2015 are shown in the Table. Samples are aggregated across Galveston Bay (GB) and for each bay segment including: Trinity Bay (TB), Upper and Lower Galveston Bay (ULGB), West Bay (WB) and East Bay (EB).

	GB		**TB**		**ULGB**		**WB**		**EB**	
Salinity	Avg (±SD)	*n*	Avg (±SD)	*n*	Avg (±SD)	*n*	Avg (±SD)	*n*	Avg (±SD)	*n*
0-5	3147 (±1471)	654	1651 (±1167)	293	2910 (±1117)	94		94	2024 (±1394)	173
6-10	2136 (±1151)	588	925 (±685)	128	1938 (±1113)	152	2979 (±958)	106	1555 (±970)	202
11-15	1604 (±1052)	759	638 (±734)	112	1254 (±1026)	169	2187 (±1234)	232	1030 (±852)	246
16-20	859 (±846)	1029	497 (±518)	88	918 (±922)	246	1612 (±1034)	451	536 (±383)	244
21-25	513 (±457)	981	217 (±156)	32	608 (±569)	211	833 (±850)	606	304 (±273)	132
26-30	189 (±155)	784	265 (±181)	5	310 (±289)	131	611 (±612)	613	221 (±135)	35
31-35	173 (±89)	368		1	211 (±64)	35	414 (±427)	321	169 (±146)	11
≥36		63		0	73 (±0)	4	154 (±185)	59		0

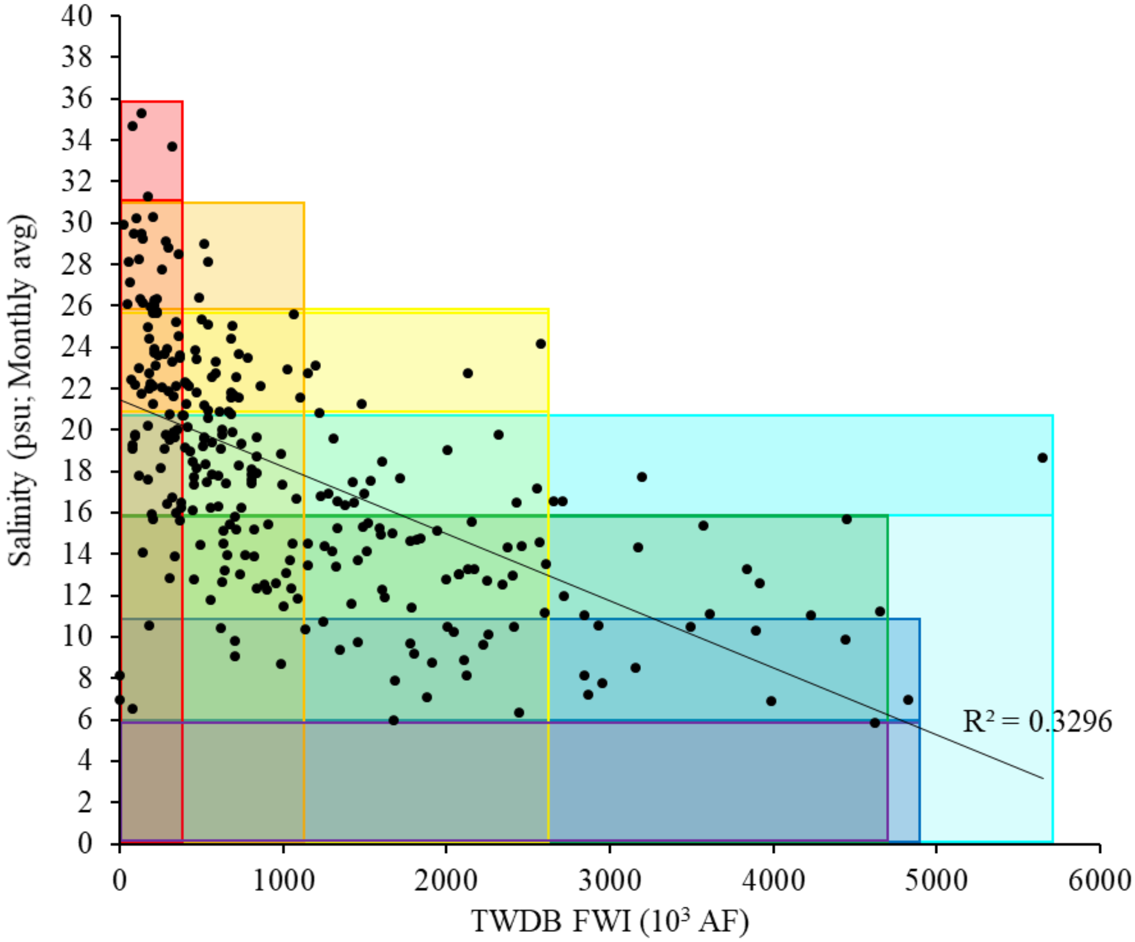


Figure 7 TPWD salinities (monthly average calculated on all bag seines collected in all of Galveston Bay during study period (1992-2015). Each data point corresponds to an average monthly salinity and corresponding TWDB estimated freshwater inflows volume. The colored boxes indicate the TWDB estimated freshwater inflows that were reported when salinities were recorded in each of the respective salinity categories: purple (0-5psu), blue (6-10psu), green (11-15psu), aqua (16-20psu), yellow (21-25psu), orange (26-30psu) and red (31-35psu).

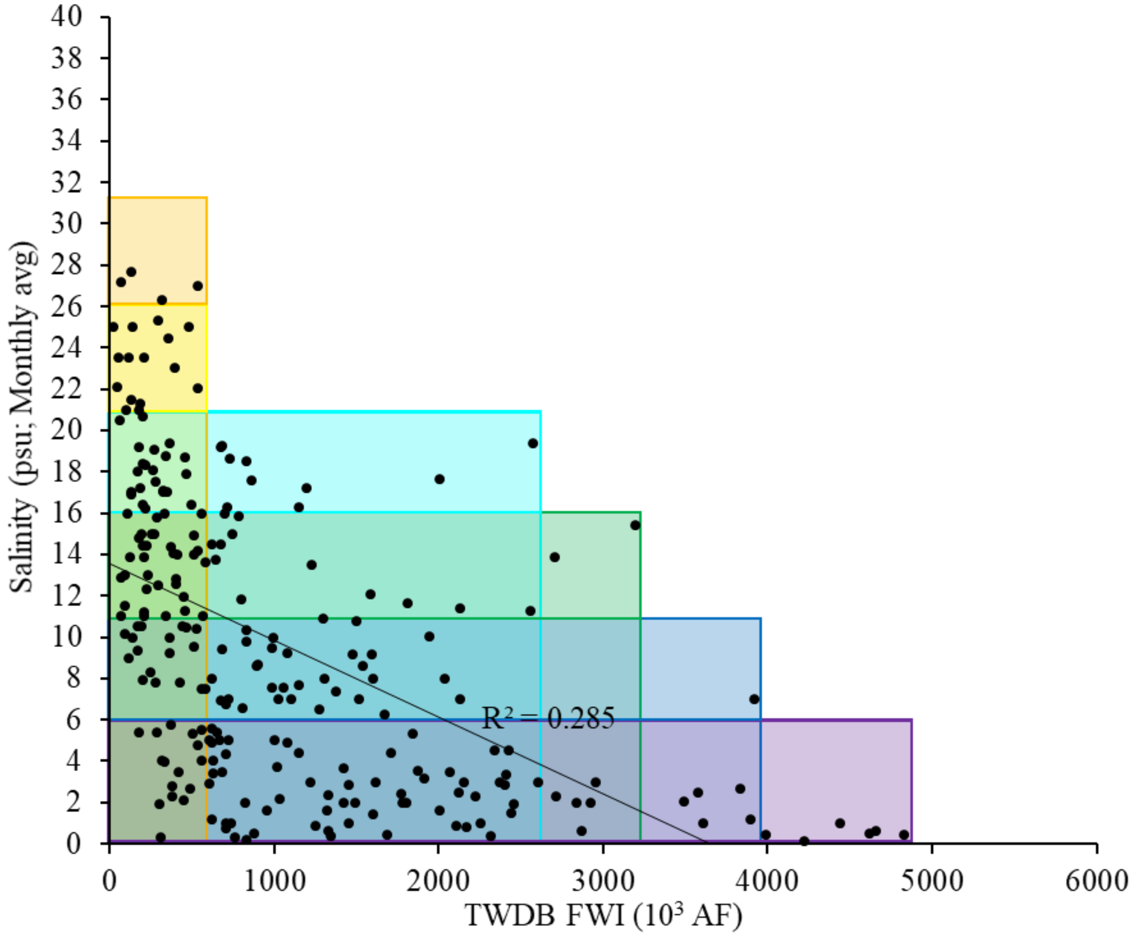


Figure 8 TPWD salinities (monthly average calculated on all bag seines collected in Trinity Bay during study period (1992-2015). Each data point corresponds to an average monthly salinity and corresponding TWDB estimated freshwater inflows volume. The colored boxes indicate the TWDB estimated freshwater inflows that were reported when salinities were recorded in each of the respective salinity categories: purple (0-5psu), blue (6-10psu), green (11-15psu), aqua (16-20psu), yellow (21-25psu) and orange (26-30psu).

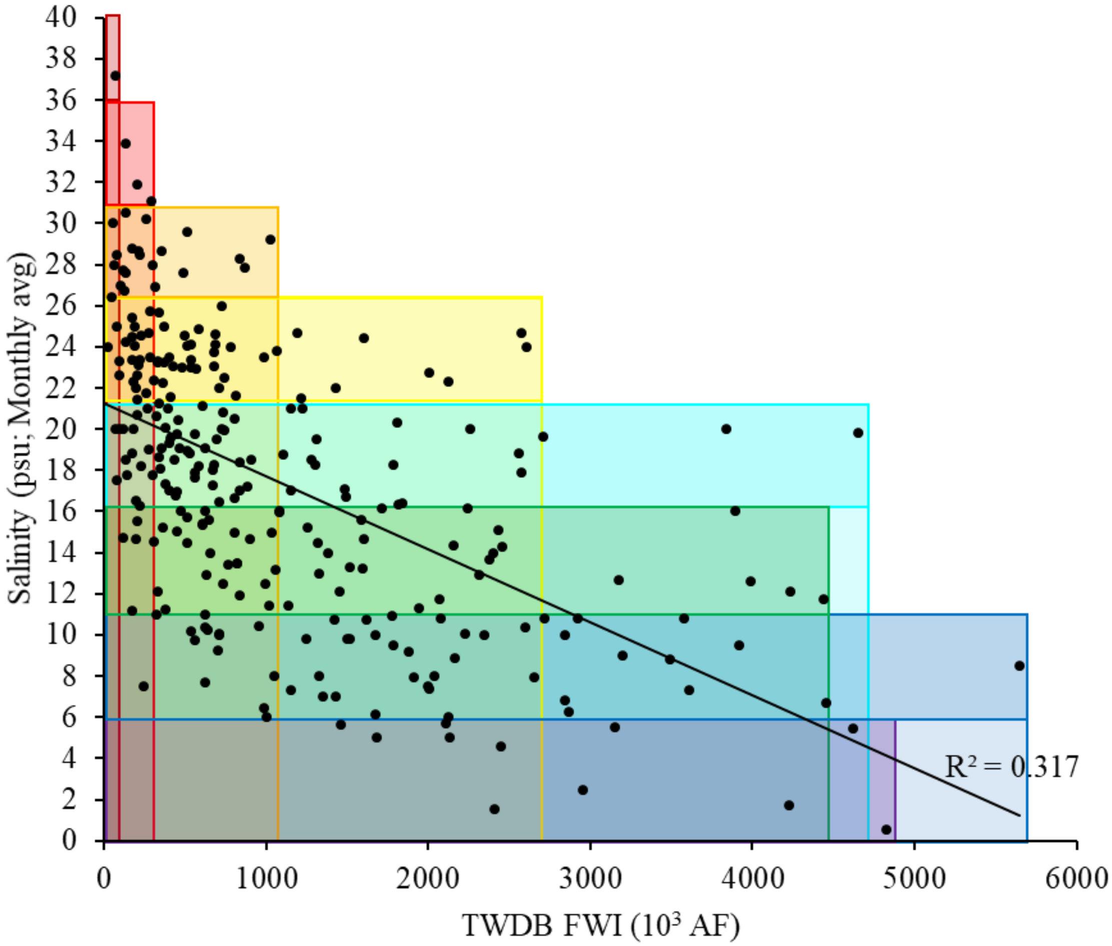


Figure 9 TPWD salinities (monthly average calculated on all bag seines collected in Upper and Lower Galveston Bay during study period (1992-2015). Each data point corresponds to an average monthly salinity and corresponding TWDB estimated freshwater inflows volume. The colored boxes indicate the TWDB estimated freshwater inflows that were reported when salinities were recorded in each of the respective salinity categories: purple (0-5psu), blue (6-10psu), green (11-15psu), aqua (16-20psu), yellow (21-25psu), orange (26-30psu), red (31-35psu) and maroon (36-40).

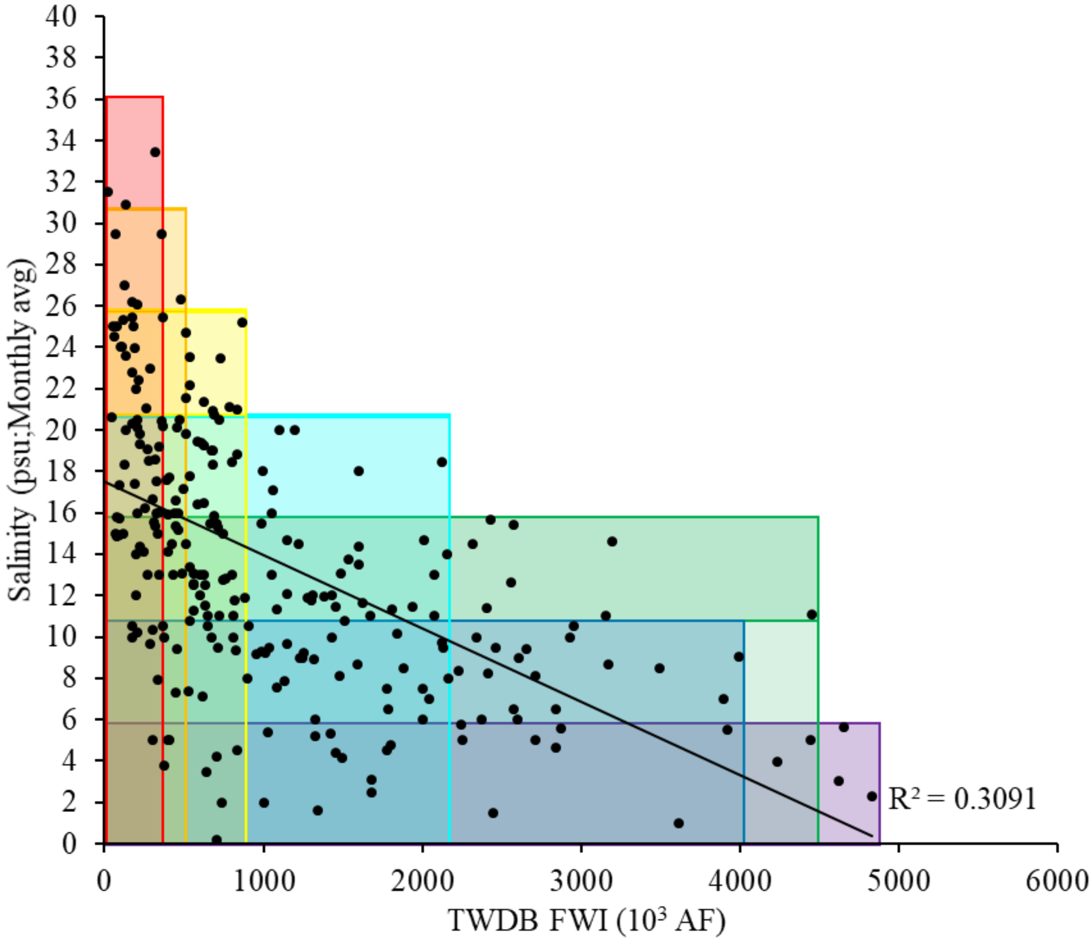


Figure 10 TPWD salinities (monthly average calculated on all bag seines collected in East Bay during study period (1992-2015). Each data point corresponds to an average monthly salinity and corresponding TWDB estimated freshwater inflows volume. The colored boxes indicate the TWDB estimated freshwater inflows that were reported when salinities were recorded in each of the respective salinity categories: purple (0-5psu), blue (6-10psu), green (11-15psu), aqua (16-20psu), yellow (21-25psu), orange (26-30psu) and red (31-35psu).

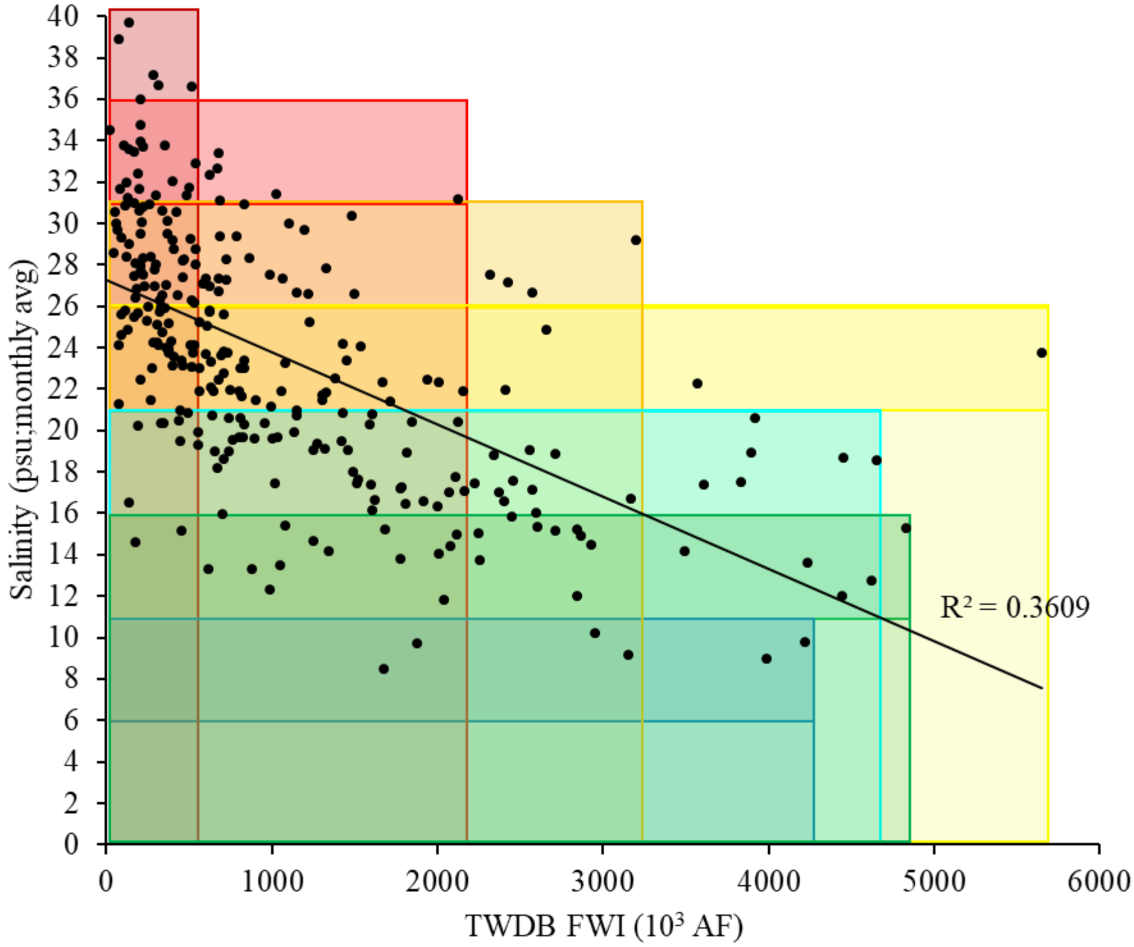


Figure 11 TPWD salinities (monthly average calculated on all bag seines collected in West Bay during study period (1992-2015). Each data point corresponds to an average monthly salinity and corresponding TWDB estimated freshwater inflows volume. The colored boxes indicate the TWDB estimated freshwater inflows that were reported when salinities were recorded in each of the respective salinity categories: blue (6-10psu), green (11-15psu), aqua (16-20psu), yellow (21-25psu), orange (26-30psu), red (31-35psu) and maroon (36-40).

2.2.3. Biotic community

From 1992 to 2015, a total of 5,226 bag seine sampling events occurred which netted 217 species of fish and invertebrates with a total catch of 1,044,391 individuals. Thirty species comprised 97% of the total bag seine catch from 1992-2015 (Table 2). Shown in Table 2, these fish and invertebrates are found within estuaries along the Gulf of Mexico coast and comprise ~90% of the total community observed in all Texas estuaries (Tolan, 2013). The bag seine catch data is being utilized for this study as this includes the juvenile species that will be most sensitive to varying water quality parameters within the bay (Chovanec et al., 2003). While 187 species were not included in this analysis, they represent collectively 3% of the total catch over 23 years. In many cases, these species represent single catch events and on average were collected in less than 1% of the total number of bag seines during the study period (data not shown). A separate analysis could be conducted to analyze the species less frequently represented in the bag seines.

These 30 species in Table 2 are representative of nine taxonomic orders and 18 families (Table 2) and include six invertebrate species and 24 species of finfish. The top ten species collected include: Gulf Menhaden (496,892 individuals), white shrimp (135,688), brown shrimp (94,550), Florida grass shrimp (50,252), Atlantic Croaker (44,270), Spot (34,274), Bay Anchovy (31,065), Pinfish (27,607), White Mullet (16, 273) and Inland Silverside (14,104). Gulf Menhaden make up 47% of the total catch in the bag seines from 1992-2015 (Table 2). When Gulf Menhaden are not considered, the sum of total individuals of the remaining 29 species of the 30 selected species still comprise 97% of the total remaining bag seine catch (Table 2).

Overall in Galveston Bay there were a total of 5,226 bag seine sampling events considered in this analysis from the period of 1992-2015 which included 659 bag seines in Trinity Bay, 1042 in Upper and Lower Galveston Bay, 1043 in East Bay and 2482 in West Bay (Table 3). Across Galveston Bay, 33% of the time when bag seines were collected the salinity was ≤15 psu, 20% of the bag seines were collected when salinities were between 16-20 psu, and 42% of the bag seines were collected when salinity was ≥21 psu (Table 3).

Table 2 Thirty selected species that were collected in the bag seine from 1992-2015. This list of species comprised 97% (1,030,166 individuals) of the total catch (1,045,343 individuals).

Taxonomic Group	Order	Family	Taxonomy	Common Name	# Individuals	Occurrence %	% of total catch
Invertebrates	Decapoda	Portunidae	*Callinectes similis*	Lesser blue crab	3,528	12.01	0.34
			Callinectes sapidus	Blue crab	12,125	49.69	1.16
		Penaeidae	*Farfantepenaeus aztecus*	Brown shrimp	94,545	42.46	9.06
			Farfantepenaeus duorarum	Pink shrimp	182	0.35	0.02
			Litopenaeus setiferus	White shrimp	135,397	39.74	12.98
		Palaemonidae	*Palaemonetes*	Florida grass shrimp	50,032	37.53	4.79
Fish	Clupeiformes	Engraulidae	*Anchoa mitchilli*	Bay anchovy	31,033	31.93	2.97
		Clupeidae	*Brevoortia patronus*	Gulf menhaden	496,728	25.17	47.60
	Siluriformes	Ictaluridae	*Ictalurus furcatus*	Blue catfish	92	0.54	0.01
		Ariidae	*Ariopsis felis*	Hardhead catfish	2,440	11.13	0.23
			Bagre marinus	Gafftopsail catfish	167	1.04	0.02
	Mugiliformes	Mugilidae	*Mugil cephalus*	Striped mullet	10,693	29.55	1.02
			Mugil curema	White mullet	16,722	25.25	1.60
	Atheriniformes	Atherinopsidae	*Menidia beryllina*	Inland silverside	13,935	26.57	1.34
	Cyprinodontiformes	Fundulidae	*Fundulus grandis*	Gulf killifish	3,372	13.03	0.32
			Fundulus similis	Longnose killifish	5,123	14.77	0.49
			Lucania parva	Rainwater killifish	24	0.15	0.00
		Cyprinodontidae	*Cyprinodon variegatus*	Sheepshead minnow	10,733	15.04	1.03
	Syngnathiformes	Syngnathidae	*Syngnathus scovelli*	Gulf pipefish	48	0.54	0.00
	Perciformes	Gerreidae	*Eucinostomus argenteus*	Spotfin mojarra	2,032	8.69	0.19
		Sparidae	*Lagodon rhomboides*	Pinfish	27,607	28.30	2.65
		Sciaenidae	*Cynoscion arenarius*	Sand seatrout	4,556	16.17	0.44
			Cynoscion nebulosus	Spotted seatrout	1,586	10.50	0.15
			Leiostomus xanthurus	Spot	34,265	31.16	3.28
			Menticirrhus americanus	Southern kingfish	2,116	11.15	0.20
			Micropogonias undulatus	Atlantic croaker	43,972	45.51	4.21
			Sciaenops ocellatus	Red drum	2,332	13.33	0.22
		Gobiidae	*Gobiosoma bosc*	Naked goby	216	2.63	0.02
	Pleuronectiformes	Paralichthyidae	*Citharicthys spilopterus*	Bay whiff	2,338	11.20	0.22
			Paralichthys lethostigma	Southern flounder	781	6.96	0.07

Table 3 Number of bag seine sampling events (*n*) within Galveston Bay and in each bay segment from 1992-2015

Salinity Range (psu)	Number of sampling events - bag seine 1992-2015				
	TB	ULGB	EB	WB	GB
0-5	293	94	173	94	654
6-10	128	152	202	106	588
11-15	112	169	246	232	759
16-20	88	246	244	451	1029
21-25	32	211	132	606	981
26-30	5	131	35	613	784
31-35	1	35	11	321	368
36-42	0	4	0	59	63
Total	659	1042	1043	2482	5226

2.2.4. Diversity

The Shannon Diversity Index (*H'*), Pielou's Evenness index (*J'*), species richness (*S*) and total number of individuals (*N*) were calculated on the abundance data for each bag seine (Figs. 12-15). The top 30 species (Table 30) were considered in the community metric analysis. When a zero was present in the data set, it was included as the zeros reflect times when species were not present when a bag seine was conducted.

The Shannon diversity index displays a seasonal trend with lowest averages (±SD) in the winter (0.98 ±0.54) and fall (0.98 ±0.53), increasing in the spring (1.08 ±0.47) and the highest diversity values in the summer (1.22 ±0.48) (Fig. 12). Pielou's evenness index (*J'*) also shows a seasonal trend with the highest values in the winter (0.72 ±0.36) and summer (0.66 ±25) followed by spring (0.61 ±0.25) and fall (0.61 ±0.30) (Fig. 13). The species richness showed a similar seasonal trend to the Shannon diversity index with lowest values observed in the winter (3.55 ±2.48), increasing in the spring (6.43 ±2.913) (Fig. 14). The number of individuals showed a seasonal trend with lowest values observed in the winter (62 ±353), increasing in the fall (124±438) and summer (243 ±1523) with the highest number of individuals in the spring (344 ±1396) (Fig. 15). The error bars reflect the inherent variability in the data set.

A DistLM was run to determine how the variability in the Shannon diversity was explained by the environmental parameters, that is, predictor variables (Table 4). The Shannon diversity had a significant positive relationship with temperature (p<0.001) which explained 14% of the variability in the diversity index (Table 4). Dissolved oxygen also had a significant relationship with the Shannon diversity (p<0.001) but only explained 8% of the variability (Table 4). The turbidity and salinity also had significant relationships with Shannon diversity (p<0.01) and explained 2% and 1% of the variability respectively (Table 4).

Table 4 DistLM results from diversity analysis showing correlation with Shannon diversity index and each of the abiotic parameters measured by TPWD at the time of bag seine collection. SS: Square of sums, prop.: proportion of variance explained.

Variable	$SS_{(trace)}$	Pseudo-F	*p-value*	Prop.
Salinity (psu)	2.63	9.08	0.0032	0.01
Temp (C)	27.10	107.23	0.0001	0.14
Dissolved Oxygen (mg/L)	14.95	55.13	0.0001	0.08
Turbidity (NTU)	3.08	10.64	0.0011	0.02

A principal component analysis (PCA) was run on the environmental data collected at all of the TPWD bag seine collection locations and times. The environmental data put into the PCA was averaged within each season-year across Galveston Bay and each season-year is represented as a data point (diamond; Fig. 16). The PCA (Fig. 16) corresponds to the data points shown in the nMDS (Fig. 17) constructed on the biotic community. The PCA shows that the 48.8% of the variability is explained by temperature and dissolved oxygen along the first principal component (Fig. 16). Along the second principal component 26.5% of the variability is explained by salinity and turbidity (Fig. 16).

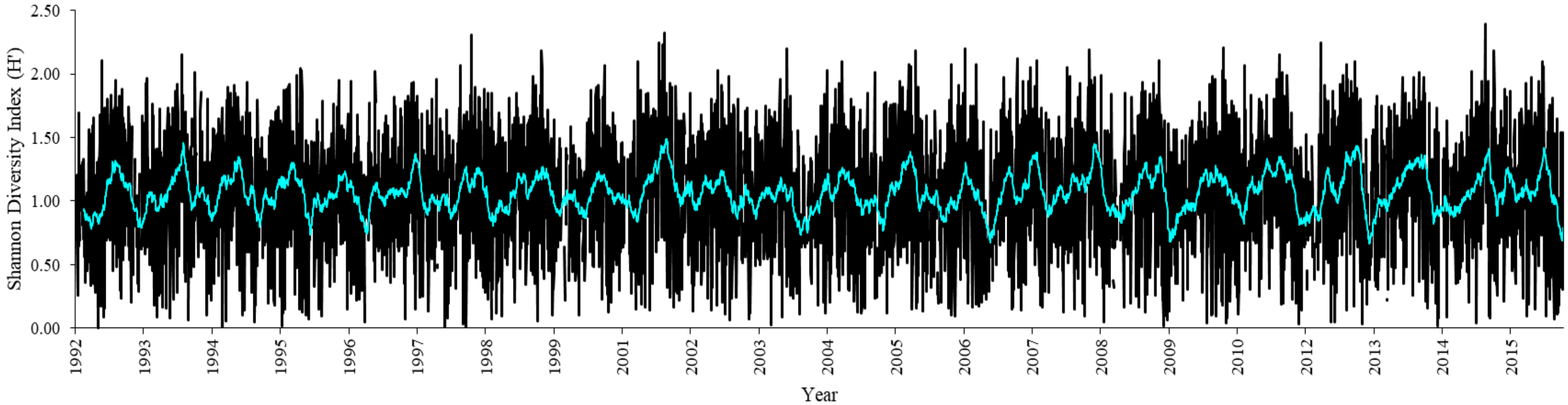


Figure 12 Shannon Diversity of individual sample events for the 30 select species in Table 2. Diversity was calculated on all samples (even when none of the 30 selected species were present) collected in all bay segments during the study period. Shannon diversity (*H'*) is shown in as the black line with 3 month moving average (aqua line) overlain to show trend of data.

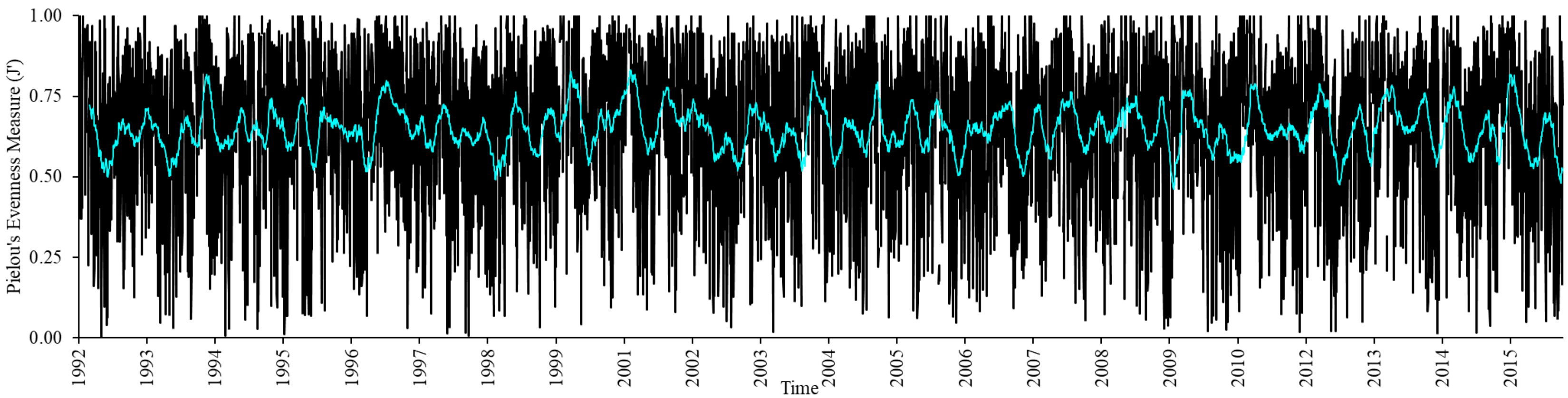


Figure 13 Pielou's evenness index (J') of individual sample events for the 30 select species in Table 2. Diversity was calculated on all samples (even when none of the 30 selected species were present) collected in all bay segments during the study period. Pielou's evenness index (*J'*) is shown in as the black line with 3 month moving average (aqua line) overlain to show trend of data.

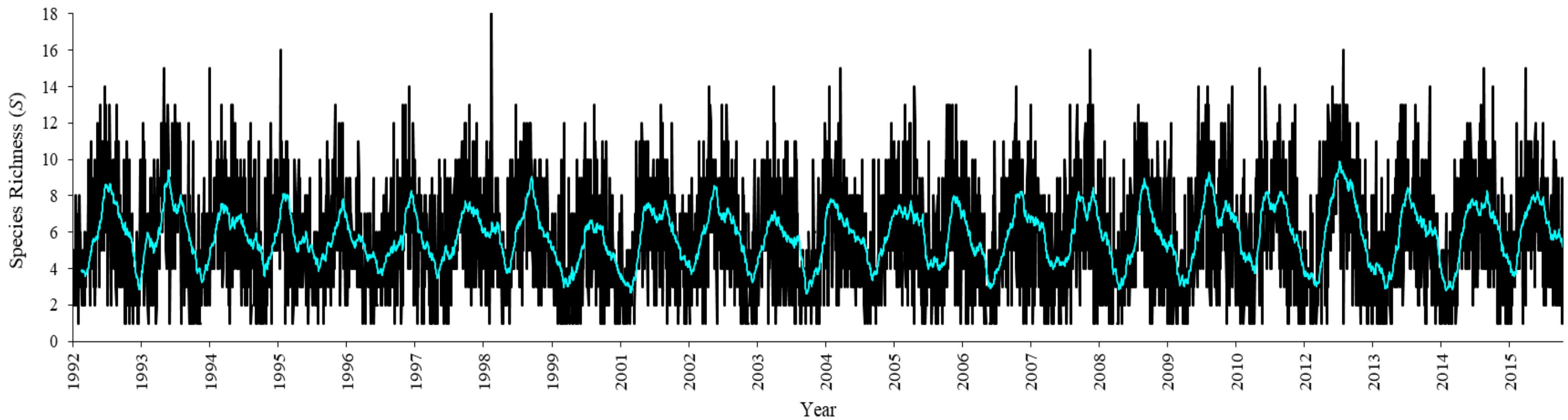


Figure 14 Species richness of individual sample events for the 30 select species in Table 2. Richness was calculated on all samples (even when none of the 30 selected species were present) collected in all bay segments during the study period. Species richness (S) is shown in as the black line with 3 month moving average (aqua line) overlain to show trend of data.

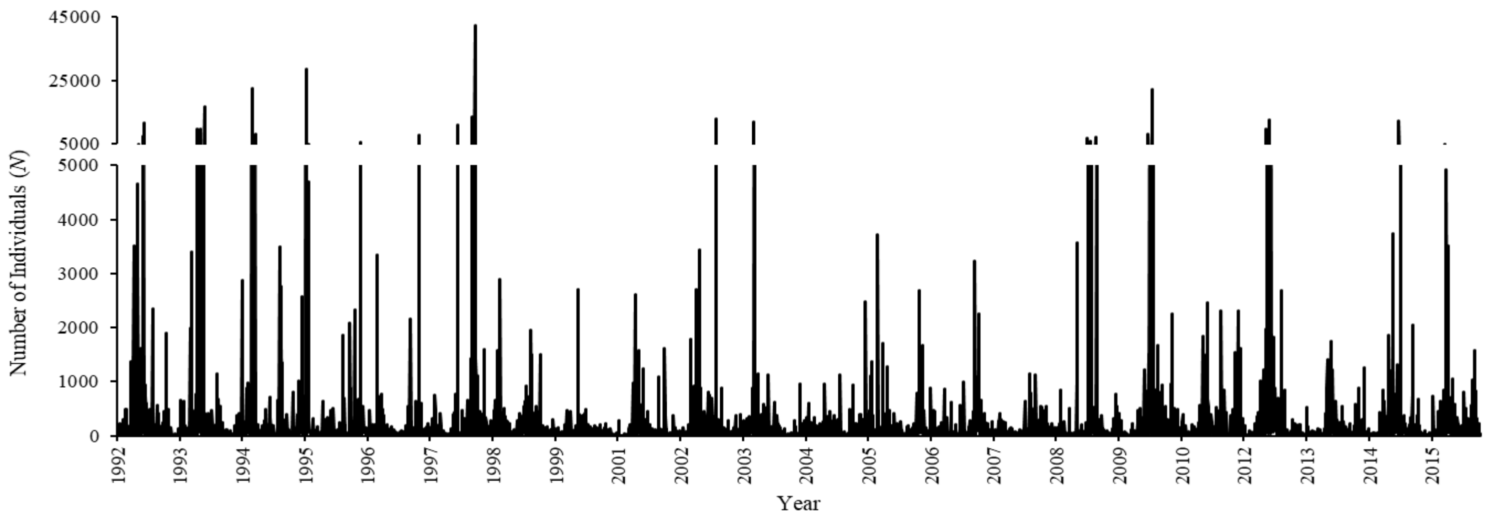


Figure 15 Number of individuals *(N)* of individual sample events for the 30 select species in Table 2. Diversity was calculated on all samples (even when none of the 30 selected species were present) collected in all bay segments during the study period. Number of individuals (*N*) is shown in as the black line with 3 month moving average (aqua line) overlain to show trend of data.

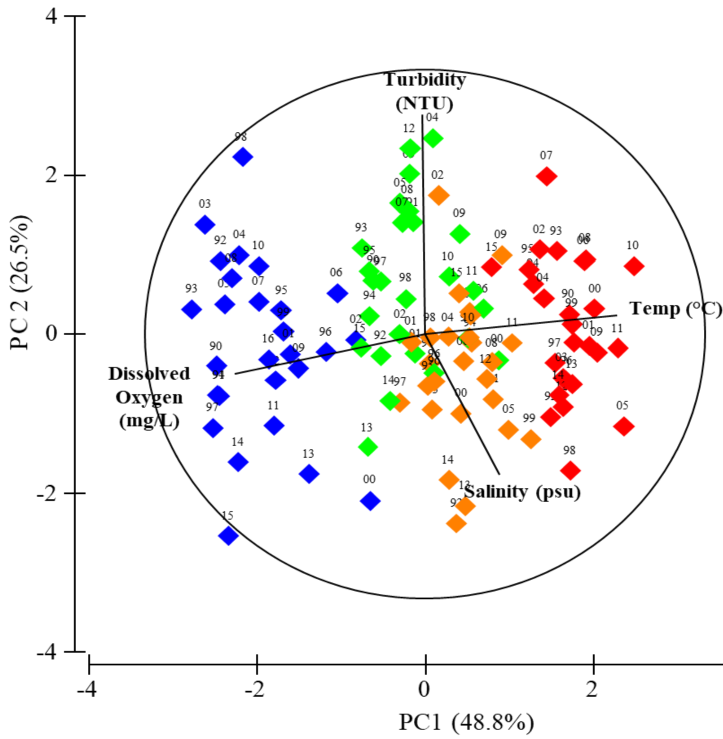


Figure 16 Principal components analysis showing the distribution of data points based on the environmental parameters. Each data point represented a season-year average across Galveston Bay. The years of the sampling event are denoted next to each data point. Seasons are shown in colors: winter (blue), spring (green), summer (red), fall (orange).

The nMDS ordination based on the fish and invertebrate CPUE across Galveston Bay and averaged for each season–year was calculated (Fig. 17). Each data point represents the average CPUE of all 30 selected species for that particular season-year. There was significant variability (p<0.0001) in the biotic community between seasons based on the PERMANOVA analysis after 9999 permutations (Fig. 17). The groupings displayed on the nMDS show the results of the CLUSTER analysis that was run on the biotic community (CPUE). The biotic communities of the samples collected during in the winter, spring summer and fall all grouped together in the CLUSTER analysis with 40% similarity for samples collected within each of those seasons (Fig. 17).

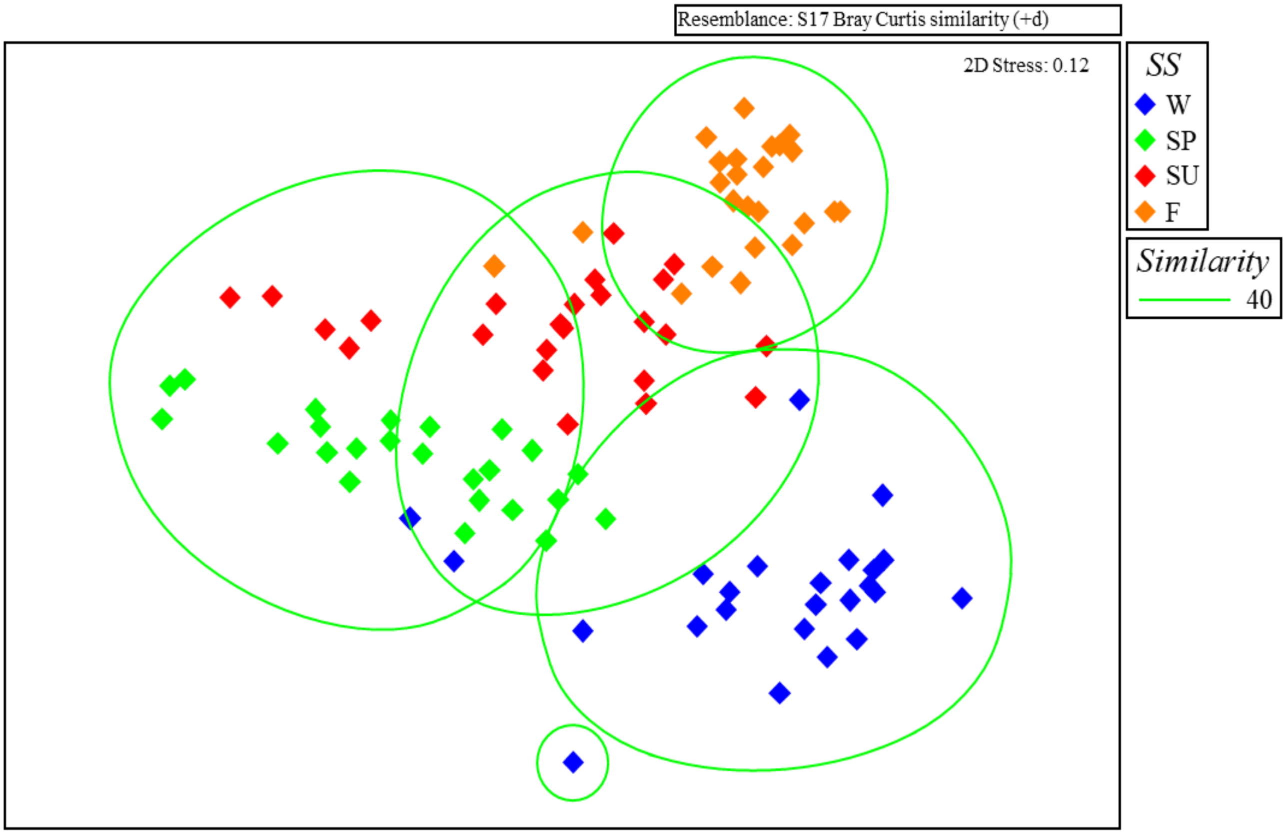


Figure 17 nMDS constructed from the CPUE data of the 30 select species in Table 2. The nMDS constructed on Bray Curtis dissimilarity matrix (+1 dummy variable) that was created with the CPUE data from 1992-2015. The CPUE data was averaged for each season within each year for all of Galveston Bay. The groupings (green line) were defined by the CLUSTER analysis and are indicative of samples grouping with 40% similarity. The year is indicated next to each data point and the colors represent data collected in winter (blue), spring (green), summer (red) and fall (orange).

2.2.5. Relative abundance of 30 select species within a range of salinity categories

A SIMPER (similarity percentage) routine was run to determine the species that were found to be in the highest CPUE in each of the salinity categories previously defined. This analysis was run to work towards the goal of defining the natural biotic community of juveniles and sub-adult species found within Galveston Bay during the various salinity regimes (Figs. 18-22; Tables 5-9). For this part of the analysis, we examined the community within all of Galveston Bay as well as the within each of the bay segments. Each of the bay segments is affected by freshwater inflows differently and therefore to depict variability within the biotic community we analyzed this data using a bay wide and segmented approach (Figs. 18-22; Table 5-9). Twenty one of the 30 species found to make up 97% of the community in Galveston Bay (Tables 2, 5-9) and were found to account for the bulk of the variability measured in the SIMPER analysis including Blue crab, Brown shrimp, White shrimp, Grass shrimp, Bay Anchovy, Gulf Menhaden, Hardhead Catfish, Striped Mullet, White Mullet, Inland Silverside, Gulf Killifish, Longnose Killifish, Sheepshead Minnow, Spotfin Mojarra, Pinfish, Sand Seatrout, Spotted Seatrout, Spot, Southern Kingfish, Atlantic Croaker and Red Drum. The remaining nine species including Lesser blue crab, Pink shrimp, Blue Catfish, Gafftopsail Catfish, Rainwater Killifish, Gulf Pipefish, Naked Goby, Bay Whiff and Southern Flounder contributed to 10% of the total variability and were not shown in these results (Figs. 18-22; Tables 5-9).

In Galveston Bay, there was a relative increase in the invertebrates with increasing salinity whereas the percent contribution of fish species decreased (Fig. 18). Florida grass shrimp had the highest percent contribution (22%) in the lowest salinity category of 0-5 psu followed by Atlantic Croaker (169%), Gulf Menhaden (16%), Blue crab (12%), Striped Mullet (9%) and White shrimp (8%) (Fig. 18; Table 5). In the bag seines collected during times of the highest salinities, (36-42 psu) the Pinfish contributed to 27% of the community variability followed by White shrimp (19%), White Mullet (13%), Atlantic Croaker and Spot (11% each) and Spotfin Mojara (9%) (Fig. 18; Table 5). Overall the Gulf Menhaden, Atlantic Croaker, Blue Crab, Striped Mullet decreased with increasing salinities (Fig. 18; Table 5). As salinities increased the Pinfish, White shrimp, Spotfin Mojara and Inland Silverside increased (Fig. 18; Table 5).

In Trinity Bay, the overall contribution of invertebrates was higher than the fish contribution and the invertebrates increased with increasing salinity while fish variability decreased with increasing salinity (Fig. 19; Table 6). The percent contribution of Florida grass shrimp (27%), Atlantic Croaker (18%), Gulf Menhaden (14%), Blue crab (11%), Striped Mullet (10%) and White Mullet (7%), was comprised a majority of the community at the lowest salinities (0-5 psu). At the highest salinities observed in Trinity Bay (26-30psu), the White shrimp (86%) and Brown shrimp (7%) dominated the community collected in the bag seines (Fig. 19; Table 6). Bay Anchovies were present in salinities ranging 16-26 (Fig. 19; Table 6). Blue crabs declined in relative abundance as salinities increased in Trinity Bay (Fig. 19; Table 6).

In Upper and Lower Galveston Bay, the Florida grass shrimp (19%), Blue crab (18%), Gulf Menhaden (21%) and Atlantic Croaker (18%) and Bay Anchovy (8%) contributed to the variability during low salinity (0-5 psu) conditions (Fig. 20; Table 7). During higher salinity conditions (31- 35 psu), the White shrimp (62%), Bay Anchovy (18%) and White Mullet (7%) and Atlantic Croaker (3%) contributed to a majority of the variability in the biotic community (Fig. 20; Table 7). Atlantic Croaker and Gulf Menhaden steadily decreased in contribution as the salinities increased, but White shrimp and Bay Anchovy increased in contribution as the salinities increased (Fig. 20; Table 7).

In East Bay, the invertebrates increased while the fish species decreased in contribution with increasing salinity (Fig. 21; Table 8). Florida grass shrimp (15%), blue crab (11%), Atlantic Croaker (24%) and Gulf Menhaden (15%) contributed to a majority of the variability in the biotic community during low salinities (0-5 psu) (Fig. 21; Table 8). During higher salinity conditions (26-30 psu) white shrimp contributed to 28%, the Blue crab 19%, Florida grass shrimp 14% and Atlantic croaker 18% of the variability (Fig. 21; Table 8).

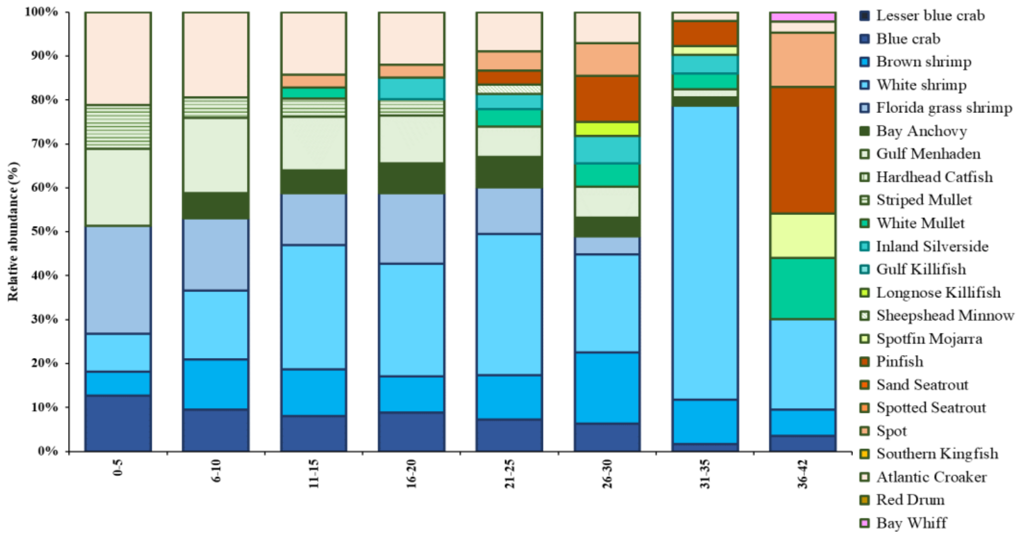


Figure 18 SIMPER results for Galveston Bay showing the most abundant species that make up a majority of the variability in the community (fish and invertebrates). Border color for invertebrates is dark blue and for vertebrates (finfish) is dark green. Color or pattern is variable between taxonomic families. SIMPER analysis was conducted on the CPUE data from individual bag seine data (zeros included).

Table 5 Galveston Bay SIMPER results showing the percent contribution of each species based on the CPUE of each species within each salinity category

Taxonmic Group	Species	Salinity Categories							
		0-5	6-10	11-15	16-20	21-25	26-30	31-35	36-42
Invertebrates	Lesser blue crab								
	Blue crab	11	9	7	8	7	6	2	3
	Brown shrimp	5	10	10	7	9	15	9	5
	White shrimp	8	14	26	23	30	20	61	19
	Florida grass shrimp	22	15	11	14	10	4		
Fish	Bay Anchovy		5	5	6	6	4	2	
	Gulf Menhaden	16	15	11	10	6	6	2	
	Hardhead Catfish								
	Striped Mullet	9	4	4	3				
	White Mullet			2		4	5	3	13
	Inland Silverside				5	3	6	4	
	Gulf Killifish								
	Longnose Killifish						3		
	Sheepshead Minnow					2			
	Spotfin Mojarra							2	9
	Pinfish					3	9	5	26
	Sand Seatrout								
	Spotted Seatrout								
	Spot			3	3	4	7		11
	Southern Kingfish								
	Atlantic Croaker	19	18	13	11	8	6	2	2
	Red Drum								
	Bay Whiff								2

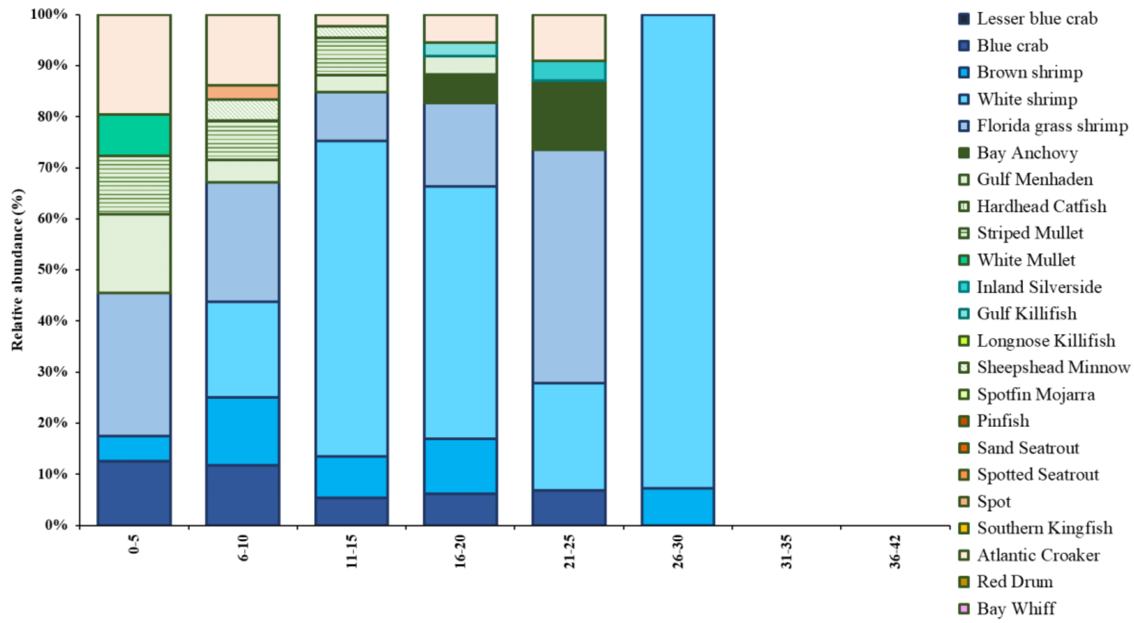


Figure 19 CPUE SIMPER results for Trinity Bay showing the most abundant species that make up 90% of the variability within the community (fish and invertebrates). Border color for invertebrates is dark blue and for vertebrates (finfish) is dark green. Color or pattern is variable between taxonomic families.

Table 6 Trinity Bay SIMPER results showing the percent contribution of each species CPUE within each salinity category.

Taxonmic Group	Species	Salinity Categories							
		0-5	6-10	11-15	16-20	21-25	26-30	31-35	36-42
Invertebrates	Lesser blue crab								
	Blue crab	11	11	5	6	6			
	Brown shrimp	4	12	7	10		7		
	White shrimp		17	57	46	20	86		
	Florida grass shrimp	25	21	9	15	43			
Fish	Bay Anchovy				5	13			
	Gulf Menhaden	14	4	3	3				
	Hardhead Catfish								
	Striped Mullet	10	7	7					
	White Mullet	7							
	Inland Silverside					4			
	Gulf Killifish				2				
	Longnose Killifish								
	Sheepshead Minnow		4	2					
	Spotfin Mojarra								
	Pinfish								
	Sand Seatrout								
	Spotted Seatrout								
	Spot		3						
	Southern Kingfish								
	Atlantic Croaker	18	13	2	5	9			
	Red Drum								
	Bay Whiff								

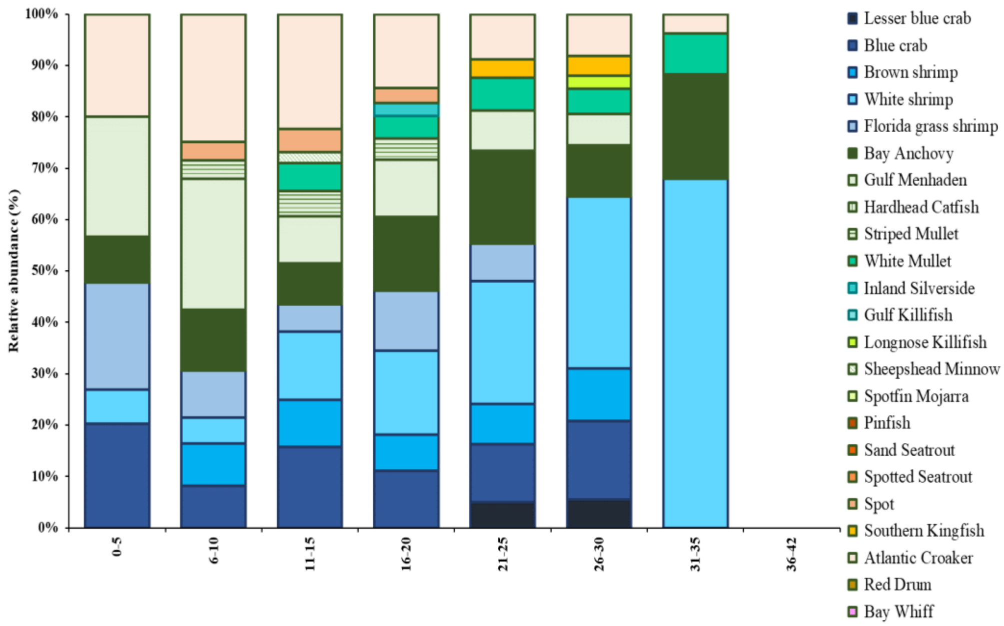


Figure 20 SIMPER results for ULGB showing the most abundant species that make up 90% of the variability within the community (fish and invertebrates). Border color for invertebrates is dark blue and for vertebrates (finfish) is dark green. Color or pattern is variable between taxonomic families. Analysis conducted on CPUE data

Table 7 Upper and Lower Galveston Bay SIMPER results showing the percent contribution of each species CPUE within each salinity category.

Taxonmic Group	Species	Salinity Categories							
		0-5	6-10	11-15	16-20	21-25	26-30	31-35	36-42
Invertebrates	Lesser blue crab					5	5		
	Blue crab	18	8	14	10	10	14		
	Brown shrimp		8	8	6	7	9		
	White shrimp	6	5	12	15	22	31	62	
	Florida grass shrimp	19	8	5	11	7			
Fish	Bay Anchovy	8	11	7	13	16	9	18	
	Gulf Menhaden	21	23	8	10	7	6		
	Hardhead Catfish								
	Striped Mullet		3	4	4				
	White Mullet			5	4	6	5	7	
	Inland Silverside				2				
	Gulf Killifish								
	Longnose Killifish						2		
	Sheepshead Minnow			2					
	Spotfin Mojarra								
	Pinfish								
	Sand Seatrout								
	Spotted Seatrout								
	Spot		3	4	3				
	Southern Kingfish					3	3		
	Atlantic Croaker	18	23	20	13	8	8	3	
	Red Drum								
	Bay Whiff								

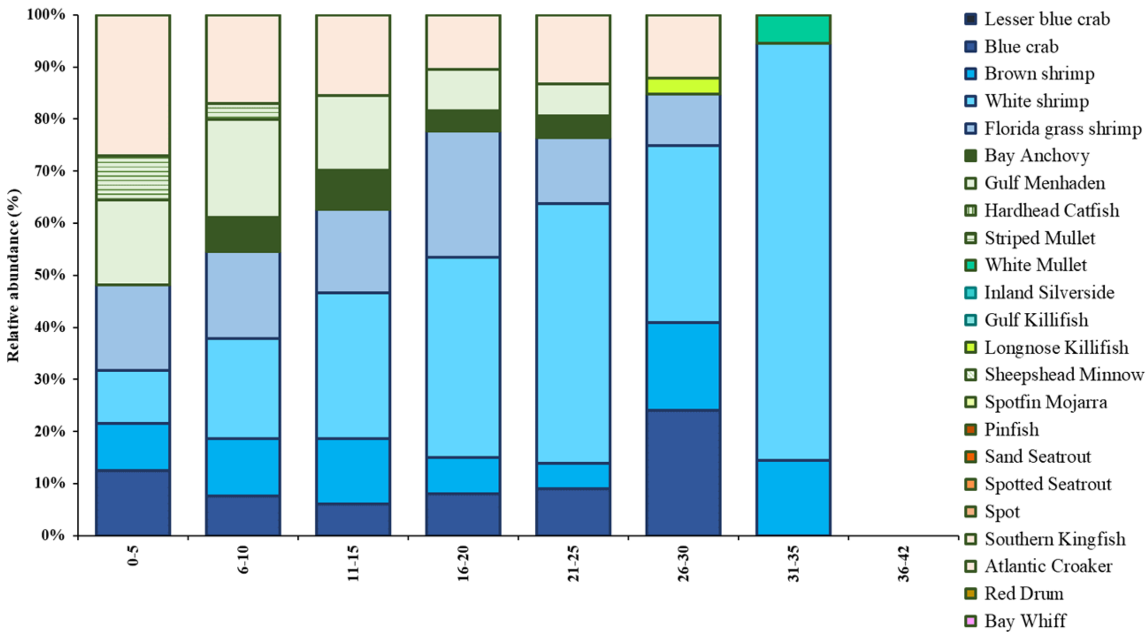


Figure 21 SIMPER results for EB showing the most abundant species that make up 90% of the variability within the community (fish and invertebrates). Border color for invertebrates is dark blue and for vertebrates (finfish) is dark green. Color or pattern is variable between taxonomic families. Run on CPUE data

Table 8 East Bay SIMPER results showing the percent contribution of each species CPUE within each salinity category

Taxonmic Group	Species	Salinity Categories							
		0-5	6-10	11-15	16-20	21-25	26-30	31-35	36-42
Invertebrates	Lesser blue crab								
	Blue crab	11	7	6	7	8	22		
	Brown shrimp	8	10	11	6	4	15	13	
	White shrimp	9	18	25	35	45	31	72	
	Florida grass shrimp	15	15	15	22	11	9		
Fish	Bay Anchovy		6	7	4	4			
	Gulf Menhaden	15	17	13	7	6			
	Hardhead Catfish								
	Striped Mullet	8	3						
	White Mullet							5	
	Inland Silverside								
	Gulf Killifish								
	Longnose Killifish						3		
	Sheepshead Minnow								
	Spotfin Mojarra								
	Pinfish								
	Sand Seatrout								
	Spotted Seatrout								
	Spot								
	Southern Kingfish								
	Atlantic Croaker	24	16	14	10	12	11		
	Red Drum								
	Bay Whiff								

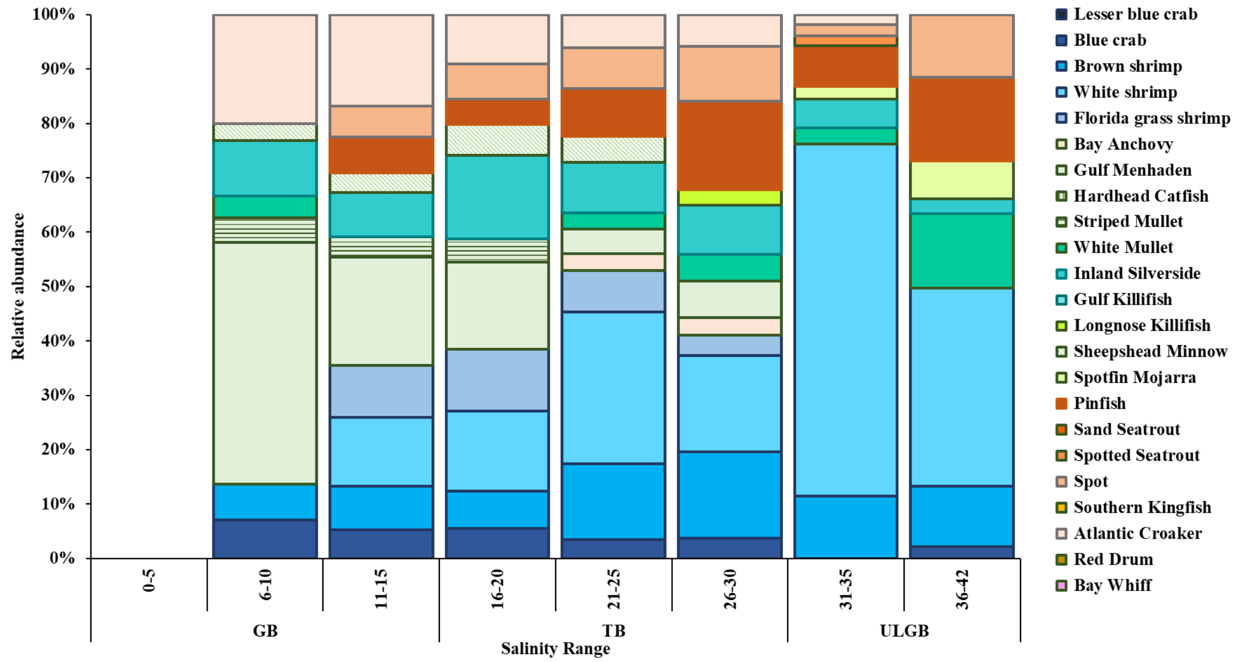


Figure 22 SIMPER results for WB showing the most abundant species that make up 90% of the variability within the community (fish and invertebrates). Border color for invertebrates is dark blue and for vertebrates (finfish) is dark green. Color or pattern is variable between taxonomic families. CPUE data non-transformed data

Table 9 West Bay SIMPER results showing the percent contribution of each species CPUE within each salinity category.

Taxonmic Group	Species	Salinity Categories							
		0-5	6-10	11-15	16-20	21-25	26-30	31-35	36-42
Invertebrates	Lesser blue crab								
	Blue crab		6	5	5	3	3		2
	Brown shrimp		6	7	6	13	14	10	10
	White shrimp			12	13	26	16	58	33
	Florida grass shrimp			9	11	7	3		
Fish	Bay Anchovy					3	3		
	Gulf Menhaden		40	18	15	4	6		
	Hardhead Catfish								
	Striped Mullet		4	3	4				
	White Mullet		4			3	4	3	13
	Inland Silverside		9	7	14	9	8	5	2
	Gulf Killifish								
	Longnose Killifish						3		
	Sheepshead Minnow		3	3	5	4			
	Spotfin Mojarra							2	6
	Pinfish			6	4	8	15	7	14
	Sand Seatrout								
	Spotted Seatrout							2	
	Spot			5	6	7	9	2	11
	Southern Kingfish								
	Atlantic Croaker		18	15	8	6	5	2	
	Red Drum								
	Bay Whiff								

In West Bay, the invertebrates did increase in relative abundance with increased salinities, most notably the number of White shrimp increased to 33% in the 36-42 psu range (Fig. 22; Table 9). At the lower salinities of 6-10 psu the Gulf Menhaden (40%), Atlantic Croaker (18%) and Inland silverside (9%) contribute to a majority of the variability (Fig. 22; Table 9). During times of highest salinity (36-42 psu), the White shrimp (33%), Brown shrimp (10%), Pinfish (14%), White Mullet (13%), Spot (11%) and contribute to the majority of the variability in relative abundance (Fig. 22; Table 9).

2.2.6. CPUE from bag seine within salinity categories

In terms of average CPUE of each of the 30 selected species across all of Galveston Bay, the number of individuals was highest during times of salinity less than 30 psu and lowest average abundance occurred during the highest salinities conditions >31 psu. When considering Galveston Bay as whole, the species with the highest CPUE in the lowest salinity category (0-5 psu) included Gulf Menhaden (5955 individuals /hectare), Florida grass shrimp (715 individuals /hectare), White shrimp (398 individuals /hectare), Atlantic Croaker (417 individuals /hectare) and Brown shrimp (353 individuals /hectare) (Fig. 23; Table 10). During times of highest salinity (36-42 psu) across Galveston Bay, White shrimp (1434) were found in highest CPUE (Fig. 23; Table 10).

In Trinity Bay, CPUE in the bag seines fluctuated across the various salinity regimes and during the lowest salinities Gulf Menhaden (6920 individuals/hectare), Florida grass shrimp (820individuals/hectare), Atlantic Croaker (423 individuals/hectare), White Mullet (389) and Brown shrimp (315 individuals/hectare) had the highest CPUE of the invertebrates collected (Fig. 24; Table 11). During the highest salinities in Trinity Bay (26-30 psu), the overall CPUE was the lowest for the whole community and was dominated by the White shrimp (4981 individuals/hectare) and Brown shrimp (293individuals/hectare) (Fig. 24; Table 11).

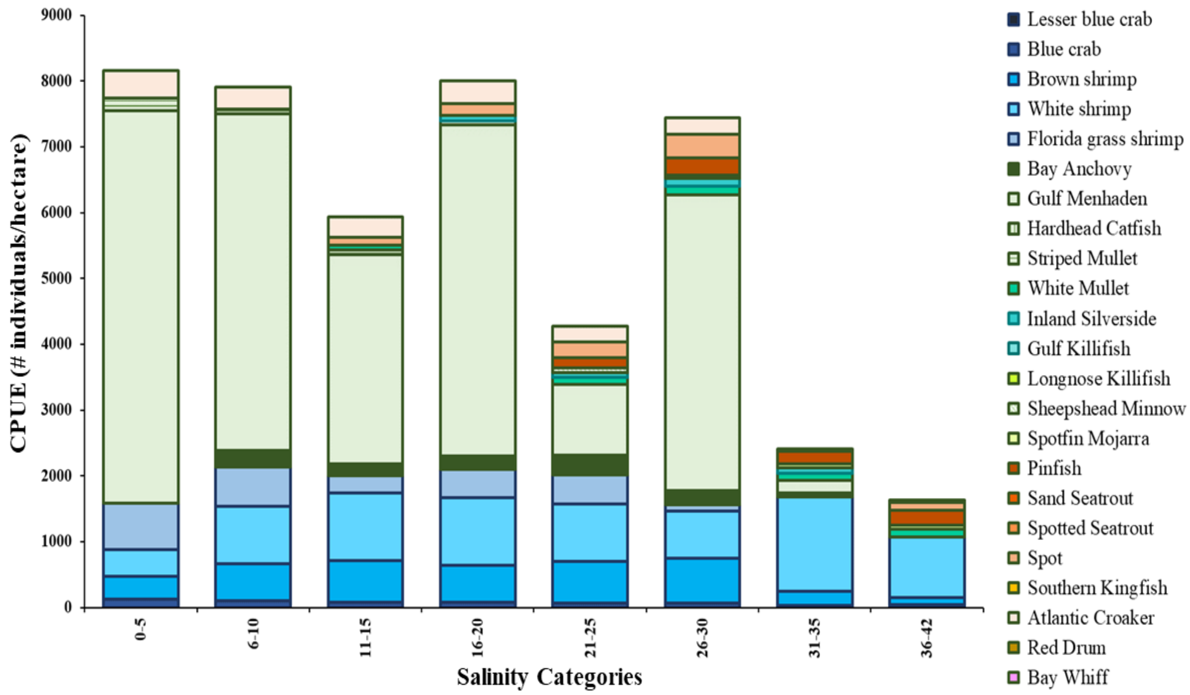


Figure 23 Galveston Bay average CPUE of individuals in each bag seine by salinity group.

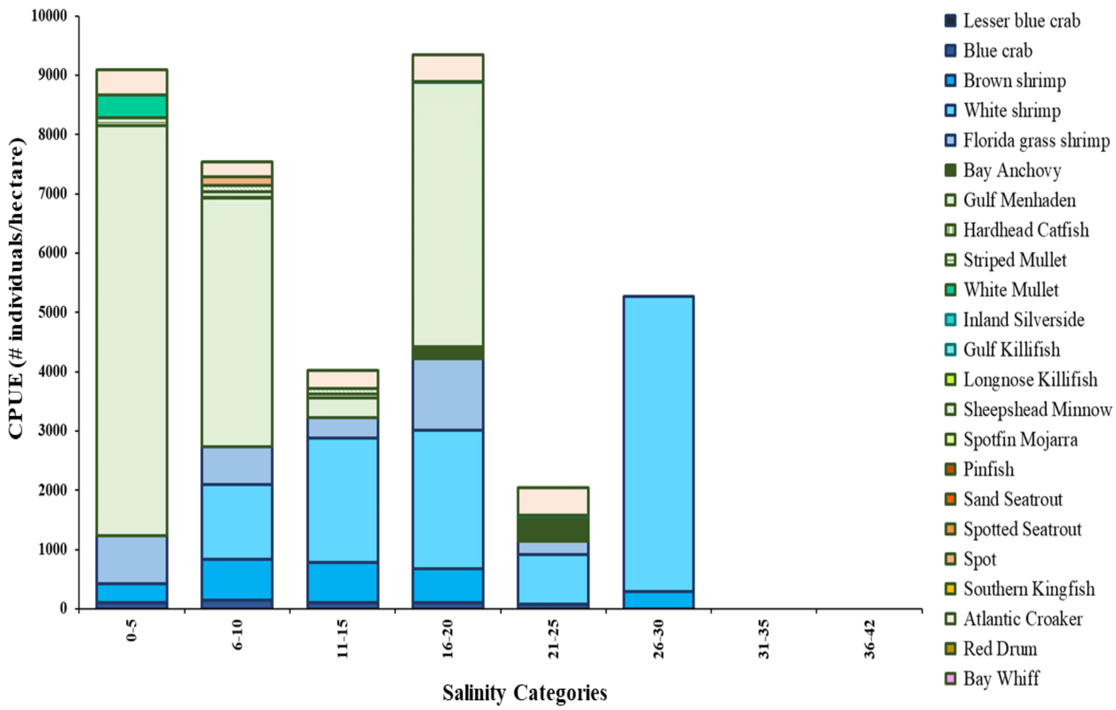


Figure 24 Trinity Bay average CPUE of individuals in each bag seine by salinity group.

Table 10 Galveston Bay species CPUE recorded from bag seines collected within each salinity category.

Taxonmic Group	Species	Salinity Categories							
		0-5	6-10	11-15	16-20	21-25	26-30	31-35	36-42
Invertebrates	Lesser blue crab								
	Blue crab	122	104	79	83	67	70	37	46
	Brown shrimp	353	560	638	558	628	681	209	103
	White shrimp	398	871	1024	1028	873	711	1434	921
	Florida grass shrimp	715	594	261	426	449	98		
Fish	Bay Anchovy		255	183	203	300	217	65	
	Gulf Menhaden	5955	5122	3175	5032	1070	4493	190	
	Hardhead Catfish								
	Striped Mullet	196	70	68	59				
	White Mullet			78		108	129	103	125
	Inland Silverside				84	68	118	88	
	Gulf Killifish								
	Longnose Killifish						55		
	Sheepshead Minnow					71			
	Spotfin Mojarra							50	58
	Pinfish					165	261	192	226
	Sand Seatrout								
	Spotted Seatrout								
	Spot			115	181	237	362		117
	Southern Kingfish								
	Atlantic Croaker	417	330	308	351	232	247	40	25
	Red Drum								
	Bay Whiff								14

Table 11 Trinity Bay species CPUE from bag seines collected within each salinity category.

Taxonmic Group	Species	Salinity Categories							
		0-5	6-10	11-15	16-20	21-25	26-30	31-35	36-42
Invertebrates	Lesser blue crab								
	Blue crab	103	140	106	109	71			
	Brown shrimp	315	693	675	566		293		
	White shrimp		1269	2093	2336	848	4981		
	Florida grass shrimp	820	635	350	1214	217			
Fish	Bay Anchovy				200	424			
	Gulf Menhaden	6920	4189	329	4456				
	Hardhead Catfish								
	Striped Mullet	129	109	68					
	White Mullet	389							
	Inland Silverside					25			
	Gulf Killifish				19				
	Longnose Killifish								
	Sheepshead Minnow		105	102					
	Spotfin Mojarra								
	Pinfish								
	Sand Seatrout								
	Spotted Seatrout								
	Spot		146						
	Southern Kingfish								
	Atlantic Croaker	423	257	301	441	453			
	Red Drum								
	Bay Whiff								

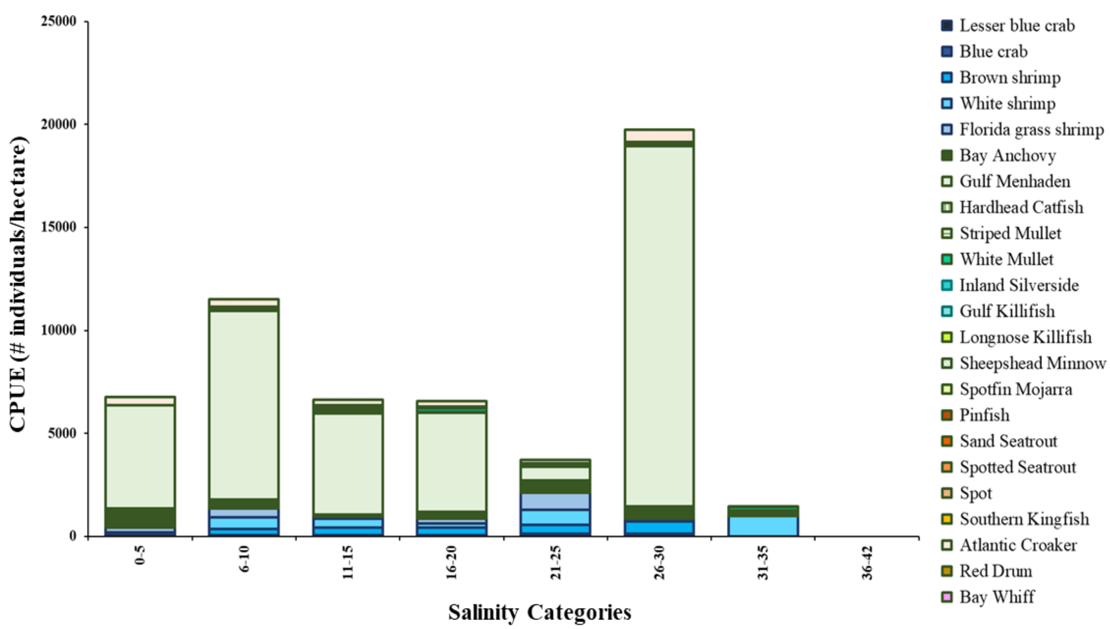


Figure 25 Upper and Lower Galveston bay average CPUE of individuals in each bag seine by salinity group.

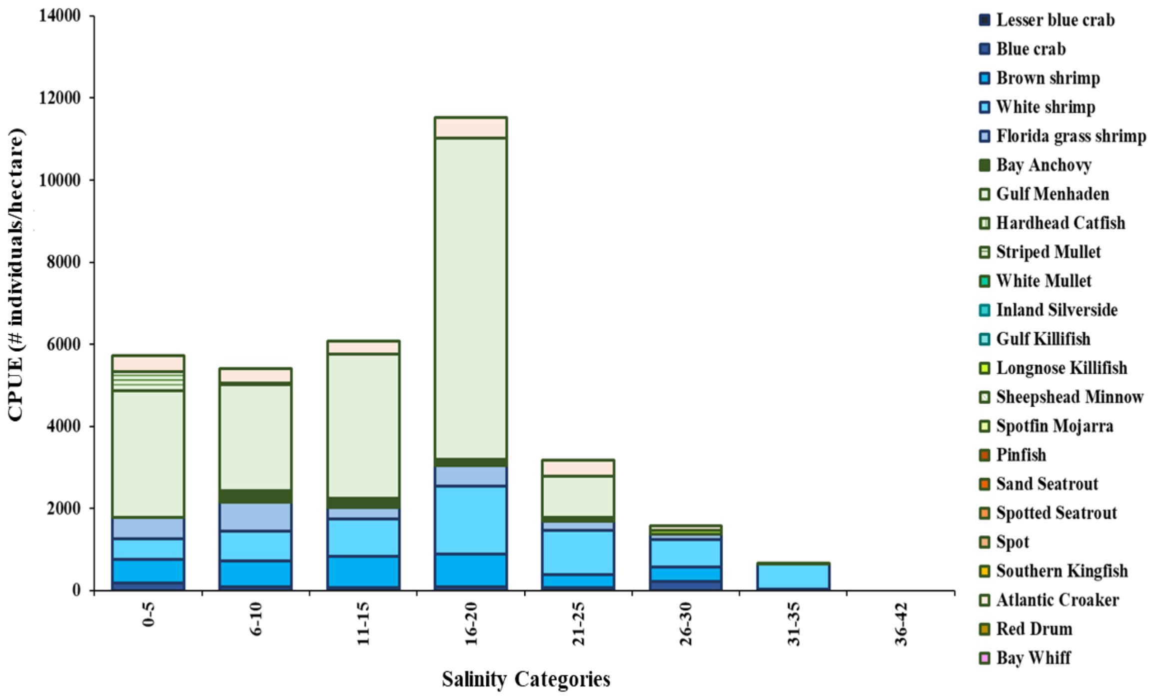


Figure 26 East Bay average CPUE of individuals in each bag seine by salinity group.

Table 12 Upper and Lower Galveston Bay species CPUE recorded from bag seines collected within each salinity category.

Taxonmic Group	Species	Salinity Categories							
		0-5	6-10	11-15	16-20	21-25	26-30	31-35	36-42
Invertebrates	Lesser blue crab					56	95		
	Blue crab	134	73	60	77	73	40		
	Brown shrimp		293	356	335	434	578		
	White shrimp	55	562	433	230	720	135	992	
	Florida grass shrimp	235	420	122	230	826			
Fish	Bay Anchovy	945	451	103	305	601	594	256	
	Gulf Menhaden	4985	9159	4895	4827	657	17507		
	Hardhead Catfish								
	Striped Mullet		60	109	43				
	White Mullet			107	142	120	136	170	
	Inland Silverside				30				
	Gulf Killifish								
	Longnose Killifish						31		
	Sheepshead Minnow			59					
	Spotfin Mojarra								
	Pinfish								
	Sand Seatrout								
	Spotted Seatrout								
	Spot		129	127	85				
	Southern Kingfish					63	51		
	Atlantic Croaker	425	380	270	278	169	572	37	
	Red Drum								
	Bay Whiff								

Table 13 East Bay species CPUE recorded from bag seines collected within each salinity category.

Taxonmic Group	Species	Salinity Categories							
		0-5	6-10	11-15	16-20	21-25	26-30	31-35	36-42
Invertebrates	Lesser blue crab								
	Blue crab	186	95	77	97	71	216		
	Brown shrimp	565	626	750	789	307	355	28	
	White shrimp	508	717	912	1649	1081	675	611	
	Florida grass shrimp	524	715	292	515	226	121		
Fish	Bay Anchovy		272	215	148	99			
	Gulf Menhaden	3090	2585	3522	7830	1002			
	Hardhead Catfish								
	Striped Mullet	455	45						
	White Mullet							26	
	Inland Silverside								
	Gulf Killifish								
	Longnose Killifish						94		
	Sheepshead Minnow								
	Spotfin Mojarra								
	Pinfish								
	Sand Seatrout								
	Spotted Seatrout								
	Spot								
	Southern Kingfish								
	Atlantic Croaker	404	347	314	491	391	121		
	Red Drum								
	Bay Whiff								

In the Upper and Lower Galveston bay segments, the highest overall abundance occurred during the lowest salinity category (26-30 psu) (Fig. 25; Table 12). The species with the highest abundance during the lowest salinities include Gulf Menhaden (4985-17,507 individuals/hectare) and Bay Anchovy (594-945) (Fig. 25; Table 12).

In East Bay, highest CPUE was recorded in salinities 16-20 and the dominant species were Gulf Menhaden (7830 individuals/hectare), White shrimp (11649 individuals/hectare), brown shrimp (789 individuals/hectare), Florida grass shrimp (515 individuals/hectare) and Atlantic Croaker (491 individuals/hectare) (Fig. 26; Table 13). Abundance was highest in the lower salinities <20psu (Fig. 26; Table 13).

In West Bay, the CPUE had an inverse relationship with salinity where the highest CPUE were recorded in the lowest salinity category of 6-10 psu (Fig. 27; Table 14). Fish abundances decreased in West Bay with increasing salinities while invertebrate CPUE slightly increased

(Fig. 27; Table 14). When salinities ranged 6-10 psu, the most abundant species include Gulf Menhaden (12,884 individuals/hectare), White Mullet (1340 individuals/hectare), Atlantic Croaker (444 individuals/hectare), and Brown shrimp (596) (Fig. 27; Table 14). When salinities were highest (36-42 psu) in West Bay the most abundant species include White shrimp (1225 individuals/hectare), brown shrimp (137 individuals/hectare), Pinfish (216 individuals/hectare) White Mullet (144 individuals/hectare) and Spot (137 individuals/hectare) (Fig. 27; Table 14).

To determine how the biotic community changes between years, we ran a SIMPER analysis to show the species that contribute to the variability within each year (Fig. 28; Table 15). This work was conducted to look at the biotic community as a whole between the dry, wet and average flow years (Figs. 2-5). The species that contributed to a majority of the variability every year throughout the study period include Blue crabs, Brown shrimp, White shrimp, Inland Silverside and the Atlantic Croaker (Fig. 28; Table 15). The Southern Kingfish only contributed to the variability during 2000 and the Lesser blue crab only during 2013 (Fig. 28; Table 15). Grass shrimp, Bay Anchovy, Gulf Menhaden, Pinfish and Spot contributed to the community variability ≤20 of the 24 years (Fig. 28; Table 15).

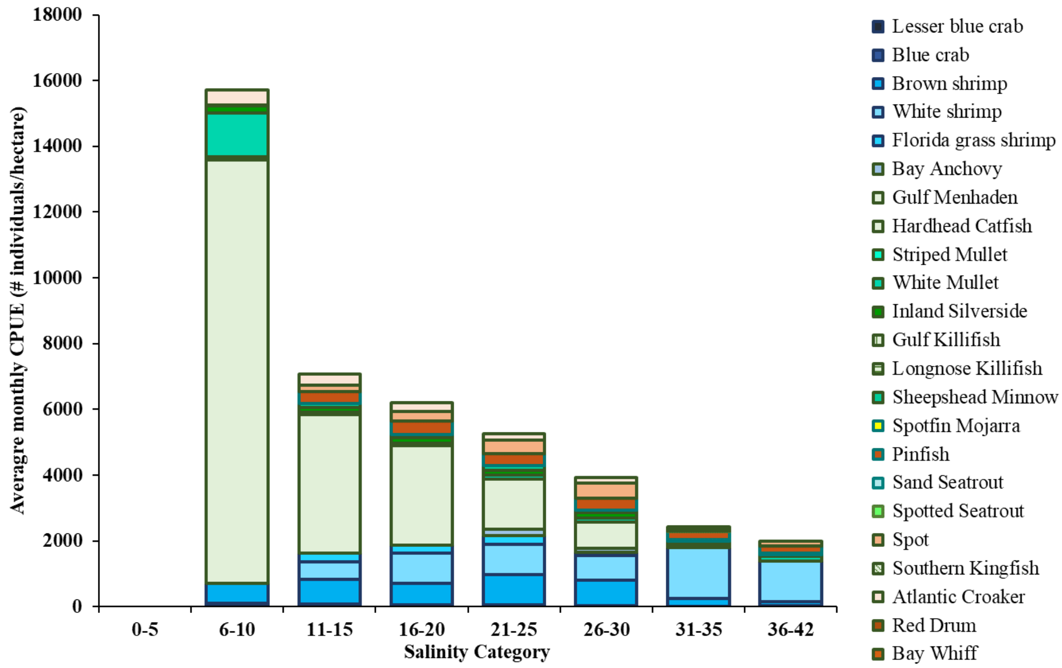


Figure 27 West Bay average CPUE of individuals in each bag seine by salinity group.

Table 14 West Bay species CPUE recorded from bag seines collected within each salinity category.

Taxonmic Group	Species	Salinity Categories							
		0-5	6-10	11-15	16-20	21-25	26-30	31-35	36-42
Invertebrates	Lesser blue crab								
	Blue crab		113	74	65	59	43		25
	Brown shrimp		596	761	646	924	772	239	137
	White shrimp			534	922	919	730	1549	1225
	Florida grass shrimp			268	236	271	115		
Fish	Bay Anchovy					181	125		
	Gulf Menhaden		12884	4194	3017	1519	798		
	Hardhead Catfish								
	Striped Mullet		78	75	77				
	White Mullet		1340			139	121	104	144
	Inland Silverside		208	158	170	143	171	103	43
	Gulf Killifish								
	Longnose Killifish						60		
	Sheepshead Minnow		48	125	91	143			
	Spotfin Mojarra							52	56
	Pinfish			341	413	360	374	226	216
	Sand Seatrout								
	Spotted Seatrout							30	
	Spot			197	298	414	461	76	137
	Southern Kingfish								
	Atlantic Croaker		444	358	278	187	164	43	
	Red Drum								
	Bay Whiff								

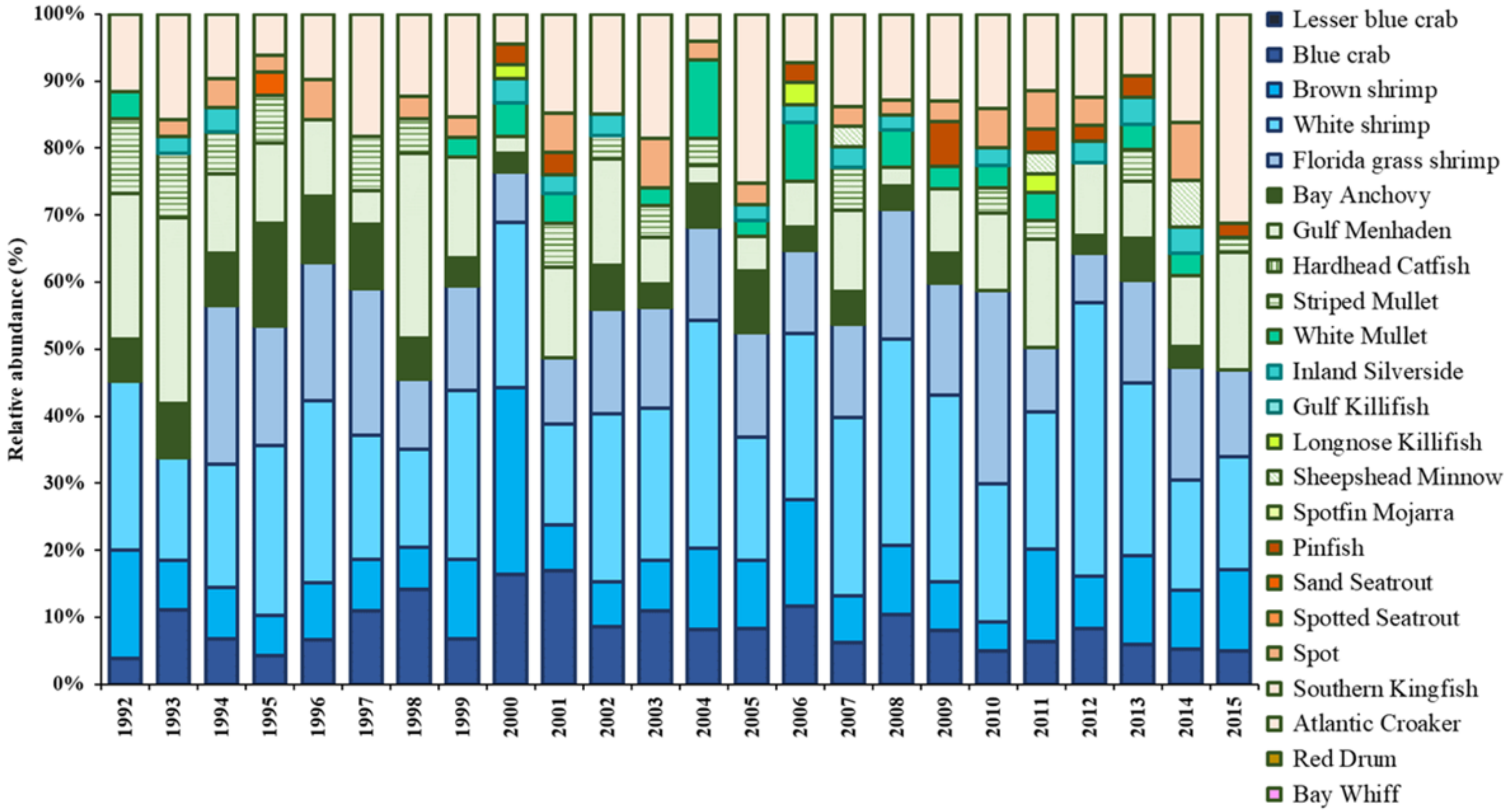


Figure 28 **CPUE SIMPER results showing species that comprise the biotic communities during each year during the study period across Galveston Bay.**

Table 15 Relative CPUE percentages from the SIMPER analysis on the bag seine data collected across Galveston Bay and within each bay segment for each year during the study period.

Taxonomic Group	Common Name	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Invertebrates	Lesser blue crab																								
	Blue crab	4	10	6	4	6	10	13	6	15	16	8	10	7	8	11	6	9	7	5	6	8	5	5	5
	Brown shrimp	15	7	7	5	8	7	6	11	25	6	6	7	11	9	14	6	9	7	4	13	7	12	8	11
	White shrimp	23	14	17	23	24	17	13	23	22	14	23	21	31	17	22	24	28	25	19	19	37	23	15	16
	Florida grass shrimp			22	16	19	20	9	14	7	9	14	14	13	14	11	13	17	15	27	9	7	14	15	12
Fish	Bay Anchovy	6	7	7	14	9	9	6	4	2		6	3	6	8	3	4	3	4			2	6	3	
	Gulf Menhaden	20	25	11	11	10	5	25	14	2	13	14	6	3	5	6	11	2	9	11	15	10	8	10	16
	Hardhead Catfish																								
	Striped Mullet	10	9	6	7		7	5			6	3	4	4			6			3	3		4		2
	White Mullet	4							3	5	4		2	11	2	8		5	3	3	4		3	3	
	Inland Silverside		2	3						3	3	3			2	2	3	2		2		3	4	4	
	Gulf Killifish																								
	Longnose Killifish									2						3					3				
	Sheepshead Minnow																3				3			6	
	Spotfin Mojarra																								
	Pinfish									3	3					3			6		3	2	3		2
	Sand Seatrout				3																				
	Spotted Seatrout																								
	Spot		2	4	2	5		3	3		5		7	3	3		3	2	3	5	5	4		8	
	Southern Kingfish																								
	Atlantic Croaker	10	14	9	6	9	17	11	14	4	14	13	17	4	23	7	13	12	12	13	11	11	8	15	29
	Red Drum																								
	Bay Whiff																								

A SIMPER analysis was run on the biotic community to determine how the community changes between extreme drought (2011) and extreme wet (2015) years (Fig. 29; Table 16). The Spot was present during the drought year of 2011 in Upper and Lower Galveston Bay (288 individuals/hectare) and within East Bay (288 individuals/hectare) and West Bay (493 individuals/hectare) (Fig. 29; Table 16). In all of Galveston Bay, Atlantic Croaker and Gulf Menhaden, White shrimp, Florida grass shrimp were higher in relative abundance during the wet year (2015) (Fig. 29; Table 16). Pinfish were present in a higher relative abundance during both the drought and wet year in West Bay compared to the other bay segments and in general across Galveston Bay (Fig. 29; Table 16).

Seasonal changes were observed in the biotic community as well spatial changes across Galveston Bay. In the winter, the overall CPUE was lowest of all seasons and spring had the highest CPUE (Fig. 30; Table 17). In all of Galveston Bay, Trinity Bay and Upper and Lower Galveston Bay the Gulf Menhaden and Atlantic Croaker had the highest relative abundance during the winter and spring (Fig. 30; Table 22). The Gulf Menhaden were the most abundant species in the spring in all of the bay segments (Fig. 30; Table 17). White shrimp were most abundant in the fall across Galveston Bay and in each bay segment (Fig. 30; Table 17).

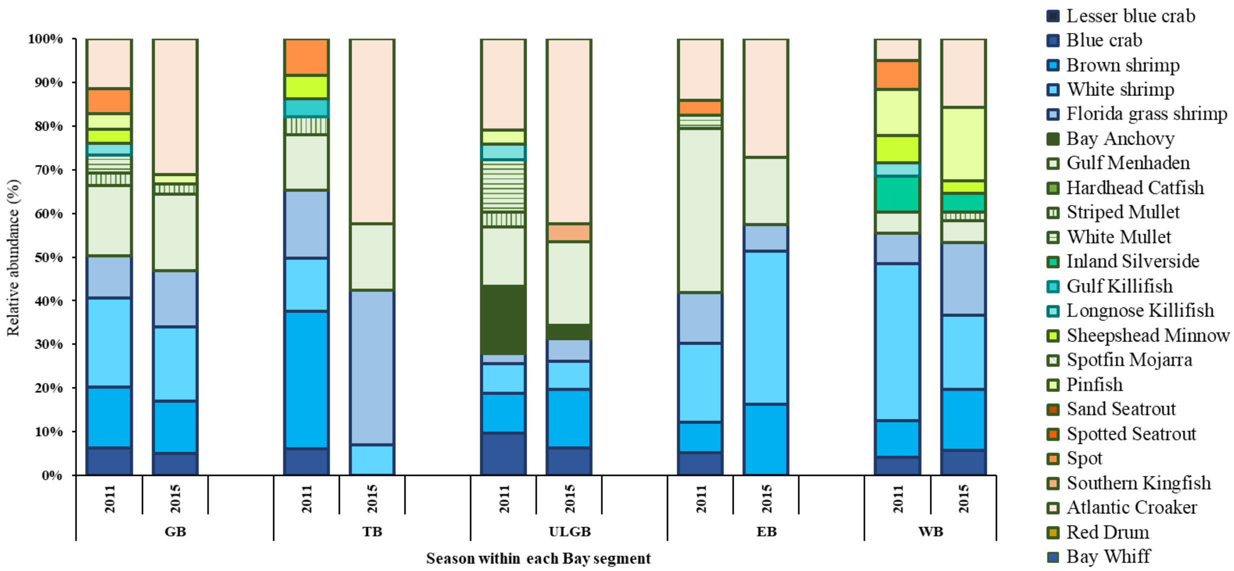


Figure 29 CPUE SIMPER results showing species that comprise the biotic communities during an extreme drought (2011) versus an extreme wet (2015) year for all of Galveston Bay as well as each bay segment.

Table 16 Relative abundance percentages from the SIMPER analysis on the bag seine data collected across Galveston Bay and within each bay segment during the extreme drought (2011) and extreme wet (2015) years.

Taxonomic Group	Common Name	GB		TB		ULGB		EB		WB	
		2011	2015	2011	2015	2011	2015	2011	2015	2011	2015
Invertebrates	Lesser blue crab										
	Blue crab	101	119	214		46	79	90		64	100
	Brown shrimp	600	653	1254		260	387	402	530	539	1057
	White shrimp	1177	1096	1397	2313	188	122	1346	861	1796	1177
	Florida grass shrimp	334	513	367	1360	150	322	717	63	104	344
Fish	Bay Anchovy					802	49				
	Gulf Menhaden	1162	2997	399	1565	324	1110	3271	6963	589	2582
	Hardhead Catfish										
	Striped Mullet	63	40	59		15					51
	White Mullet	115				167		136			
	Inland Silverside									104	84
	Gulf Killifish			26							
	Longnose Killifish	32				32				60	
	Sheepshead Minnow	54		65						79	141
	Spotfin Mojarra										
	Pinfish	123	194			63				332	705
	Sand Seatrout										
	Spotted Seatrout										
	Spot	378		288				288		493	
	Southern Kingfish						53				
	Atlantic Croaker	509	1054		2565	899	722	507	372	221	632
	Red Drum										
	Bay Whiff										

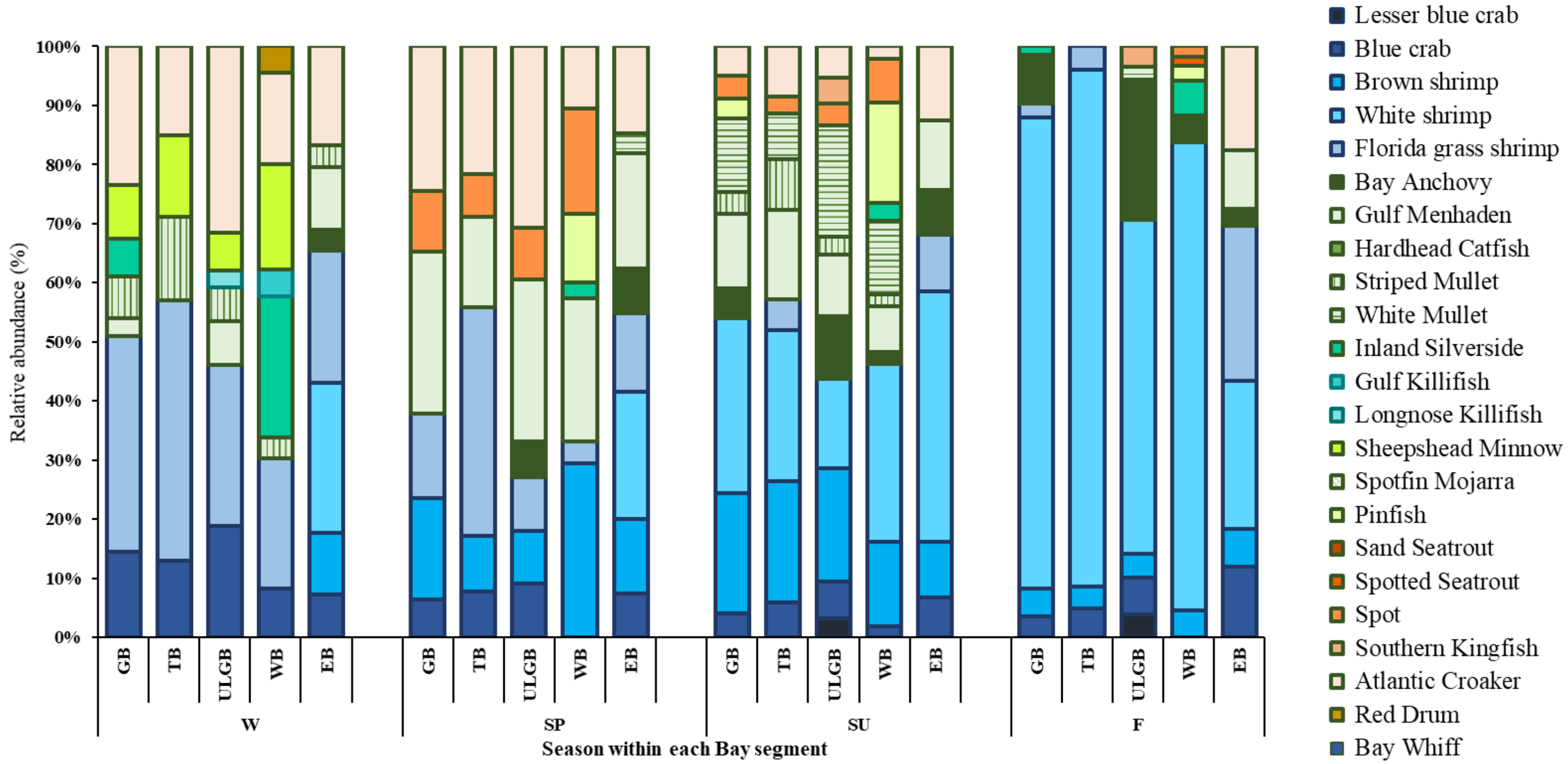


Figure 30 Results of the SIMPER analysis indicating the relative abundance of the fish and invertebrate communities seasonally within each bay segment during the study period.

Table 17 Relative abundance percentages from the SIMPER analysis on the bag seine data collected across Galveston Bay and within each bay segment for each season during the study period.

Taxonmic Group	Common Name	W					SP					SU					F				
		GB	TB	ULGB	WB	EB	GB	TB	ULGB	WB	EB	GB	TB	ULGB	WB	EB	GB	TB	ULGB	WB	EB
Invertebrates	Lesser blue crab													3					3		
	Blue crab	13	12	17	8	7	6	7	8		7	4	5	6	2	6	3	4	6		11
	Brown shrimp					10	15	9	8	27	11	19	19	18	13	8	4	3	4	4	6
	White shrimp					24					19	27	24	14	28	38	72	79	51	72	23
	Florida grass shrimp	33	40	25	20	21	13	37	8	3	12		5			9	2	4			24
Fish	Bay Anchovy					3			6		7	5		10	2	7	7		21	4	3
	Gulf Menhaden	3		7		10	25	15	25	22	18	11	14	10	7	11					9
	Hardhead Catfish																				
	Striped Mullet	6	13	5	3	3						3	8	3	2						
	White Mullet										3	11	7	17	11				2		
	Inland Silverside	6			22					3					3		1			5	
	Gulf Killifish				4																
	Longnose Killifish			3																	
	Sheepshead Minnow	8	12	6	16																
	Spotfin Mojarra																				
	Pinfish									11		3			16					2	
	Sand Seatrout																				
	Spotted Seatrout																			1	
	Spot						9	7	8	16		4	3	3	7					2	
	Southern Kingfish													4					3		
	Atlantic Croaker	21	14	29	14	16	22	21	28	10	13	5	8	5	2	11					16
	Red drum				4																

2.3. Discussion

2.3.1 Biotic community

The goal of this project was to determine the "health of the ecosystem" within Galveston Bay to "*sustain the full complement of native species in perpetuity". *In order to do this analysis, we first had to determine the native or resident community within Galveston Bay. The list of 30 select species which accounted for 97% of the total catch within bag seines over the study period of 23 years from 1992-2015 (Table 2) was used as a representative sampling of the "native species" of the bay. With this list of fish and invertebrate species comprising the vast majority of the juvenile to sub-adult stages of the organisms within the bay over this extensive time period, this subset of species is representative of the organisms comprising the habitats in the coastal environments around Galveston Bay. Tolan (2013) used a similar approach in examining fish communities along the Texas coast. Further, the various community metrics examined support this conclusion (see section 2.2.4). Changes are driven by seasonal oscillations not by extreme events (e.g., drought, flood) over the 23-year study period.

While it is well known that change in abundance of species is dependent upon submerged aquatic habitat, we were not able to perform a habitat quantification as part of our overall analysis. This parameter is not concurrently measured along with the other parameters used in the study (fish and invertebrate counts, water quality) such that we could not use the desired statistical approach. From other studies, we know that when submerged aquatic habitat is measured in Galveston Bay is limited to narrow corridors, which would, if included, reduce the overall scope of the study performed. See additional discussion below.

To better understand the relationship between the abundance of species and salinity within Galveston Bay, several approaches are presented herein. The Shannon Diversity exhibited a seasonal cycle with decreased diversity in the winter and highest diversity during the summers (Figs. 19-21). A DistLM was run to determine which water quality parameter were most correlated with the changes in diversity and the results found temperature, salinity, dissolved oxygen and turbidity (Table 4). The average Shannon diversity of the bag seines was highest during the fall months (H' = 2.40) and lowest in the spring (H' = 2.11) as seen in Fig. 12. The species richness is highest in the summer with an average of 25 different species and lowest in the winter with an average of 16 different species (Fig. 14). The number of individuals is highest in the summer (avg = 42,225) followed by spring (28,450), fall (12,801) and lastly winter (11,039) (Fig. 15).

The nMDS plot also shows the strong seasonal separation of the biotic community across Galveston Bay (Fig. 16). The bag seine gear type was selected because the target organisms include juvenile stage fishes as well as adult invertebrates both of which may be more susceptible to changing environmental conditions (i.e. temperature, salinity, dissolved oxygen) within an estuarine habitat (TPWD, 2012). The community composition as well as abundance contribute to the relationships shown in the nMDS data points (Fig. 16). The biotic community present in the summer samples grouped most closely with those communities recorded during the spring sample time points (Fig. 16). The community in the bag seines that were collected during the fall months grouped more closely with the samples collected in the summer and spring compared to those collected in the winter months (Fig. 16). The biotic community in the summer and spring bag seines grouped together with ≥55% similarity which are the only two seasons that clustered together (Fig. 16; Supplemental Figure 1). The community within the bag seines collected in each season grouped with like season data points with a similarity value of ≥65% (Fig. 16). This seasonal variability shows to be a stronger driver across the community metrics than what is seen between drought and non-drought years (i.e. changing salinity or temperature alone) (data not shown).

Based on the strong seasonal cycles observed, we conclude that Galveston Bay is able to sustain the complement of dominant (top 30) species and has been doing so for decades (study period). SAC (2006, 2009) determined that this was the first criteria towards defining a sound ecological environment. While there are an additional 187 species that were not included in this analysis, they collectively represent only 3% of the total catch over 23 years. While this is nonetheless significant, conducting an analysis is complicated by the various caveats associated with the database. For example, some of these 187 species represent single catch event or perhaps they were collected in less than 1% of the total number of bag seines. Hence, defining the full complement of native species to include these requires an assumption of risk, that is, that all of these are native species and that they play an important role in the ecology and health of the bay. Tolan (2013) used a similar approach in examining fish communities along the Texas coast by ranking the most abundant individuals and using these in his statistical analysis. Tolan (2013) goes into detail about the value of using a subset rather than the entire community.

To further explore the definition of sound ecological environment as it pertains to the biotic community, SAC (2006, 2009) consider that the bay must sustain key habitat features required by these species (b) and sustains key ecosystem processes and services, such as elemental cycling and the productivity of important plant and animal populations (d). These two points are beyond the scope of this study as this data is either not available or difficult to back out of the available data. In addition, SAC (2006, 2009) in their definition of a sound ecological environment proposed that the bay retains key features of the natural flow regime required by these species to complete their life cycles (c) – (the full definition can be found on page 12). This was the focus on much of the effort of this study. We examined the biotic community (30 most abundant fish and invertebrates; Table 2) in relation to salinity across Galveston Bay and within each of the bay segments (Figs. 23-27). We related the biotic community to salinity because this was measured at the time and location of the bag seine and salinity can be used as a proxy for freshwater inflows as was shown in sections 2.2.2.

2.3.2. Galveston Bay

The CPUE of the invertebrates was highest when salinity was <30 psu (Fig. 23; Table 10). When salinities were ≤15, the invertebrate community collected in the bag seines was predominantly Blue crabs, Brown shrimp, White shrimp and Florida grass shrimp (Fig. 23; Table 10). Blue crabs and Florida grass shrimp were most abundant in the winter (lowest salinities) and then decreased into the spring, summer and then fall (highest salinity) (Fig. 30). The brown shrimp were most abundant during the spring followed by summer and then fall and lowest in the winter (Fig. 30). The white shrimp were only present during the summer and fall with highest relative abundances in the fall (Fig. 30). When comparing invertebrate community between the drought year of 2011 to the flood year of 2015 in Trinity Bay, the Brown shrimp were present in higher relative abundance in 2011 and Florida grass shrimp higher in 2015 (Fig. 29; Table 16).

Overall, the CPUE of the fish collected in the bag seine was highest when salinities ranged 0-30 psu (Fig. 23; Table 10). When salinities were ≤15, the biotic community in the bag seines was predominantly comprised of Gulf Menhaden, Atlantic Croaker, Striped Mullet, Spot and Bay Anchovy (Fig. 23; Table 10). Blue Catfish were only present in Galveston Bay when the salinities were ≤15 (Fig. 23; Table 10). At salinities increase ≥16, Pinfish, Inland Silverside, Bay Anchovy, Spotfin Mojarra and Spot increase in CPUE (Fig. 23). At salinities ≥31 Atlantic Croaker and Gulf Menhaden decreased in numbers while Bay Anchovy, White Mullet and Inland Silverside, Spotfin mojarra and Bay Whiff increased in abundance (Fig. 23). The fish community also exhibited seasonal variability across Galveston Bay (Fig. 30). During spring (lower salinities) the Gulf Menhaden, Atlantic Croaker and Spot were relatively high in abundance and in the fall (higher salinities) there was an increase in Spotted Seatrout (Fig. 30). When comparing the drought versus wet year in there was variability in the fish community (Fig. 29; Table 16). The relative abundance of Atlantic Croaker and Gulf Menhaden increased in the wet year (2015) compared to the drought year (2011) while Longnose killifish, Spot and Pinfish increased in relative abundance during the drought year (Fig. 29; Table 16). Inland Silverside were present during the wet year (2015) but not during the drought year (2011) and White Mullet was present during the drought year but not during the wet year (Fig. 29; Table 16). Based on these analyses Gulf Menhaden, Blue Catfish, Atlantic Croaker, Florida grass shrimp are all present in highest abundances when salinities range from 0-20 psu (Fig. 23; Table 10). The Pinfish, Spot and Bay Anchovy are higher in abundance when salinities are ≥16 (Fig.23, 28; Table 10).

2.3.3. Trinity Bay

In Trinity Bay, the invertebrate abundances increased with increasing salinity while the fish abundance decreased (Fig. 24; Table 11). The White shrimp increased with increasing salinity while Florida grass shrimp CPUE was highest in salinity <30 psu (Fig. 24; Table 11). Blue crabs were present when salinities ≤30psu (Fig. 24; Table 11). Seasonal variability was observed in the invertebrate community with Blue crab and Florida grass shrimp present in highest abundance during the winter followed by spring, summer and then fall (Fig. 30). White shrimp was present in highest abundance in the fall followed by summer (Fig. 30). The Brown shrimp were present in highest abundance in the summer followed by spring and then fall (Fig. 30). During the drought year of 2011, the abundance of Brown shrimp was higher than that during the wet year in 2015 while White shrimp and Blue crab showed the opposing trend (Fig. 29).

Gulf Menhaden had the highest abundances recorded in salinities ≤30 psu (Fig. 24; Table 11). Bay anchovies were reported in the salinities between 6-30 psu (Fig. 24; Table 11). Spotted Seatrout were present in the highest abundance when salinities ranged 26-30 psu (Fig. 24; Table 11). Atlantic Croaker and Striped Mullet were present in higher abundances during the winter, spring and summer but not in the fall (Fig. 30). Gulf Menhaden was present in the spring and summer while Spot was present only in the spring and White Mullet only in the summer (Fig. 30). In the fall, when salinities are typically the highest for Trinity Bay the dominant species in the bag seine were Spot and Bay Anchovy (Fig. 30). When comparing the differences in the biotic community between the drought and wet years the Atlantic Croaker was higher in relative abundance in the wet year (Fig. 30). During the drought year the Pinfish and Spot were present but were not recorded during the wet year (Fig.29). Based on these analyses of Trinity Bay, Gulf Menhaden, Atlantic Croaker and white shrimp are present in higher abundances during times of lower salinities (≤20 psu) while Pinfish, Spot and Spotted Seatrout, Bay Anchovy and white shrimp are more abundant during higher salinities (≥21 psu) (Figs. 24, 29, 30).

2.3.4. Upper and Lower Galveston Bay

The invertebrate community made up approximately 50% of the relative abundance of the bag seine catch at all salinity ranges within Upper and Lower Galveston Bay (Fig. 20). White shrimp were only present in bag seines collected at lower salinities (≤25 psu). Seasonally the Florida grass shrimp were highest in relative abundance in the winter and the White shrimp had highest relative abundance in the fall (Fig. 30). The relative abundance of the invertebrates was higher during the drought year compared to the wet year but the species composition was similar (Fig. 29).

Gulf Menhaden were present in bag seines collected during all salinities but were highest in abundance at salinities of 6-10 psu and 26-30 psu (Fig. 25). White mullet made up a large percentage of the relative abundance when salinities were within 16-35 psu (Fig. 20). Seasonally the bay Anchovy showed an increase from winter to spring then summer and fall (Fig. 30). Atlantic Croaker decreased in abundance from winter to spring and then summer and was not present in the fall (Fig. 30). Sheepshead Minnow and Spot were reported during the lower salinity seasons of winter and spring respectively (Fig. 30). During the wet year of 2015 the relative abundance of the fish species was higher compared to the drought year of 2011 (Fig. 29). Atlantic Croaker and Gulf Menhaden were recorded in higher abundance during the wet year (Fig. 29). Based on this analysis in Upper and Lower Galveston Bay, during times of lower salinity the Atlantic Croaker, Gulf Menhaden, Bay Anchovy, Florida grass shrimp and blue crabs were present in the highest relative abundance (Fig. 20). When salinities increased in the Upper and Lower Galveston Bay the abundance of White Mullet, Spot and Bay Anchovy increased (Figs. 20, 25).

2.3.5. East Bay

In East Bay the invertebrate community increased in abundance with increasing salinities up to 20 psu then declined in the 26-30 psu range and then increased again in the higher salinity range of 31-35 psu (Fig. 21; Table 8). The White shrimp showed the largest increase in relative abundance with increasing salinity up to 20 psu (Fig. 21; Table 8). Seasonally the invertebrates displayed similar trends as observed in the other bay segments with increased Florida grass shrimp and Blue crab in the winter and spring (lower salinities) and highest relative abundance of Brown shrimp in the summer and White shrimp in the fall (higher salinities; Fig. 29).

The Gulf Menhaden was reported in higher CPUE in the lower salinity ranges <25 psu (Fig. 31). Atlantic Croaker was present in the bag seines but not in salinities ≥31 psu (Figs. 21, 26). The Sand Seatrout were present in East Bay in the mid-salinity range of 6-20 psu (Fig. 26). Bay anchovies were also present in greater relative abundance in bag seines collected up to 25 psu (Fig. 21). When considering the drought (2011) and wet (2015) years Gulf Menhaden increased in the relative abundance during 2015 (Fig. 29). During the drought year striped and White Mullet contributed to the abundance but not during the wet year (Fig. 29). The bay anchovies had the highest abundance during the fall (highest salinities) and Atlantic Croaker were present in highest abundances in the winter and spring (lower salinities) (Fig. 30). The Gulf Menhaden were present in the spring and summer in East Bay (Fig. 30). Based on these analyses in East Bay, during times of lower salinity the abundance of Atlantic Croaker, Gulf Menhaden, Striped Mullet, Florida grass shrimp and Blue crab increases (Figs. 21, 26, 29-30). When salinities increase in East Bay the abundance of Bay Anchovy and White shrimp (Figs. 21, 26, 29-30).

2.3.6. West Bay

In West Bay the invertebrate community did increase with increasing salinity (Fig. 22, Table 9). The White shrimp, Pinfish, Spot and White Mullet increased with increasing salinities (Figs. 22, 27). The Atlantic Croaker, Gulf Menhaden and Blue crab, Florida grass shrimp decreased in abundance with increasing salinity (Fig. 22, 27). The Sheepshead Minnows were present in the mid to high range of salinities from 11-30 psu (Fig. 22, 27). White shrimp were present in higher relative abundance during the drought year compared to the wet year where blue crabs were present in higher relative abundance (Fig. 29). For seasonal variability the similar trends were observed in the invertebrates similar to what was observed in the other bay segments (Fig. 30). The Blue crab and Florida grass shrimp decreased with increasing salinity while the white shrimp increased in abundance while the White and Brown shrimp increased with increased salinities in West Bay (Fig. 30).

Pinfish showed an increase in relative abundance with increasing salinities at higher salinities in West Bay (Fig. 22). Pinfish, Spot, White Mullet and White shrimp were present in higher relative abundance during the drought year compared to the wet year where Atlantic Croaker, Gulf Menhaden and Blue crab were in higher relative abundance (Fig. 29). Pinfish, Spot and White Mullet were present in higher relative abundance during the drought year compared to the wet year where Atlantic Croaker and Gulf Menhaden were in higher relative abundance (Fig. 29). During the winter season the Sheepshead Minnow, Inland Silverside, Atlantic Croaker and Southern Kingfish were the highest in relative abundance (Fig. 30). In the spring and summer, Spot and Pinfish increased in relative abundance while the Atlantic Croaker decreased (Fig. 30). In the summer the White Mullet increased while the Atlantic Croaker further decreased (Fig. 30). In the fall the Inland Silverside and Bay Anchovy increased and the Spotted

Seatrout were a part of the community (Fig. 30). Based on the analyses conducted in West Bay, the Pinfish are higher in abundance across all salinity regimes while the Gulf Menhaden were decreased in abundance (except for the lowest salinities of 6-10 psu; Fig. 27). Pinfish, Spot, Spotted Seatrout and Inland Silverside were present in greater abundance than in the other bay segments (Fig. 27; Table 14).

3. OBJECTIVE B – FRESHWATER INFLOW EVALUATION

We will work with the TWDB and the best available science to evaluate the freshwater inflow standards for Galveston Bay. In order to do so, we will start with a simple comparison of the instream flow standards adopted by TCEQ for the Trinity and San Jacinto Rivers with the freshwater inflow standards adopted by TCEQ for Galveston Bay. This will be tabulated such that we will be able to visually determine if there is alignment between the two sets of standards, and if the instream flow standards are adequate to maintain a healthy estuary.

3.1. Methods

For this work, we included the TCEQ instream flow standards at all described measurement locations included in Texas Administrative Code Title 30 Environmental Quality PART 1 Texas Commission on Environmental Quality Chapter 298 – Environmental Flow Standards for Surface Water Subchapter B: Trinity and San Jacinto Rivers, and Galveston Bay (http://txrules.elaws.us/rule/title30_chapter298; which will be referenced in this report as TCEQ Subchapter 298 (2011). Environmental flow standards were adopted by TCEQ at described measurement points (which will be referred to herein as instream flow standards) along the Trinity and San Jacinto rivers including: USGS gage 08049500, West Fork Trinity River near Grand Prairie; USGS gage 08057000, Trinity River at Dallas, Texas; USGS gage 08065000, Trinity River near Oakwood, Texas; USGS gage 08066500, Trinity River near Romayor, Texas; USGS gage 08070000 East Fork San Jacinto River near Cleveland, Texas; USGS gage 08068000 West Fork San Jacinto River near Conroe, Texas (Fig. 31; Tables 18, 19). These instream flow standards were compared to the measured USGS river flows at each of the measurement points above to determine the frequency at which the instream flow standards were met over the available period of record for each respective USGS gage.

The TCEQ Bay and Estuary Freshwater Inflow Standards for the Galveston Bay System, comprised of inflow volumes and annual target frequencies were compared to the TWDB estimated freshwater inflows in Galveston Bay (Tables 20, 21). The comparison of TCEQ standards to measured instream flows and freshwater inflows into Galveston Bay will provide insight to the suitability of the standards to protecting the natural flow regime within Galveston Bay.

3.1.1. TCEQ Instream flow standards at selected measurement point's vs measured USGS river discharge at the measurement points.

One of the objectives of this work was to determine if the TCEQ instream flow standards that were set at described measurement points meet the TCEQ Bay and Estuary Freshwater Inflow Standards for the Galveston Bay system. The original objective of the study was to determine whether the instream flow and freshwater inflow standards align to support a sound ecological environment in Galveston Bay. However, due to the complex differences in the structure of the two sets of standards (e.g., instream flow standards are comprised of subsistence, base, and pulse flows, but freshwater inflow standards are comprised of seasonal and annual inflow quantities and annual attainment frequencies), it was determined that a comparison analysis was not appropriate. As such, the focus of the study shifted to evaluate the frequency at which the standards were met in the recent record of observed flows.

The TCEQ adopted instream flows standards were compared to stream gage data collected by the U.S. Geological Survey (USGS) while the TCEQ adopted freshwater inflow standards were compared to freshwater inflow data compiled by the Texas Water Development Board (TWDB). Our analysis found the Trinity River and San Jacinto River basins *are* receiving the recommended flow volumes and frequencies. Our findings are tentative and provided with caveats as we feel this requires a comprehensive effort with the use of agency models (e.g., TxBLEND, WAM, etc.) and which includes bringing together TCEQ and TWDB and various other stakeholders that was beyond the scope of the current study. This project contributes to several priority activities identified in the Trinity, San Jacinto Basin and Bay Area Work Plan for Adaptive Management (TSJ BBASC 2012), including to test the conclusion that the bioindicators were appropriate for representing the health of Galveston Bay and to consider the addition of new bioindicators species which were previously not recognized.

In this report we show the TCEQ instream flow standards for described measurement points that were defined in the TCEQ Subchapter 298 (2011). The USGS measured discharge rates at each of the TCEQ selected measurement points (USGS gages) were plotted against the corresponding TCEQ instream flow standards including the instream trigger flow rate, the instream base flows and the instream subsistence flows for an extended period 1992-2017 (Figs. 32-37). This time frame included times of extreme drought, extreme flooding and average conditions. With the wide range of flow conditions, this time frame is adequate to assess whether the gaged flows meet, exceed, or fall below the TCEQ instream flow standards at the selected measurement points (Figs 32-37).

3.1.2. TCEQ Bay flow standard vs TWDB estimated freshwater inflows.

The TWDB estimated freshwater inflows dataset was used as the basis for comparison to the freshwater inflow standards for Galveston Bay given that the TSJ BBEST evaluated the TWDB estimated freshwater inflowss as the basis for determining total flow from various components to the bay. The work was divided into the main contributing components of Trinity River, San Jacinto River, and surrounding coastal watersheds. The gages alone do not capture significant parts of the watersheds (*e.g.*, ungauged areas, downstream diversions and discharges, etc.). On the San Jacinto River, the gages are located significantly upstream, which do not account for effects of Lake Houston, Buffalo Bayou, Cedar Bayou, and ungauged portions of the contributing watershed. If the gages alone are used, the conclusions could ultimately be misleading.

The TCEQ bay flow standards established for the Trinity and San Jacinto Basins are defined in the TCEQ Chapter 298 (2011). The bay flow standards were compared to the TWDB estimated freshwater inflows to determine if the measured/modeled freshwater inflow into Galveston Bay met the TCEQ standards. We summed the TWDB estimated freshwater inflows seasonally and annually and then calculated the percentage of time that the season and annual inflows were at or exceeded the TCEQ standards for bay flows (TCEQ Subchapter 298, 2011). The percentage of seasons when flow standards were met was calculated by summing the estimated freshwater inflows for each season and then dividing the number of seasons where flow standards were met by the total number of seasons in study period.

Figure 31 Map of USGS gage stations (black star in white balloon) included in the TCEQ instream flow standards. Rivers are shaded in aqua.

3.2. Results

3.2.1. TCEQ Instream standards vs USGS measured inflows

The measured flows at all of the USGS gages used in this analysis are located upstream from Galveston Bay (Figs. 31-37; Tables 18-19). TCEQ instream flow standards in the Trinity River (USGS 08066500) for subsistence flow standards range from 19 cfs in the winter up to 25 cfs in the spring and base flow standards range from 35 cfs in the summer and fall up to 45 cfs in the winter and spring (Table 18). The TCEQ instream flow standards at the Dallas gage on the Trinity range from 15 cfs in the fall up to 37 cfs in the spring for subsistence flow standards and for base flow standards the range is 40 cfs in the summer up to 70 cfs in the spring (Table 18). At the Oakwood gage on the Trinity, the subsistence flow standards range from 75 cfs in the summer up to 160 cfs in the spring and base flow standards range from 250 cfs in the summer up to 450 cfs in the spring (Table 18). TCEQ standards at the Romayor gage on the Trinity river range from 200 cfs in the summer up to 700 cfs in the spring for subsistence flows and the base flows range from 575 cfs in the summer up to 1150 cfs in the spring (Table 18). Along the San Jacinto River at the East Fork gage, the subsistence flows range from 9 cfs in the summer and fall up to 22 cfs in the winter and base flow standards range from 0.51 $m^3 s^{-1}$ in the summer and fall up to 33 cfs in the winter (Table 18). The subsistence flow standards on the San Jacinto River at the West Fork gage range from 10 cfs in the summer and fall u to 24 cfs in the spring and the base flow standards range from 19 cfs in the summer up to 52 cfs in the spring (Table 18).

The measured flows at the West Fork Grand Prairie on the Trinity River (USGS 08049500) ranged from 462 (±31,258) cfs in the fall to 1,119 (±2,411) cfs in the spring (Fig. 32; Table 19). The measured flows at the Dallas gage on the Trinity River (USGS 08057000) ranged from 1,126 (±2,712) cfs in the fall to 2,909 (±6,064) cfs in the spring (Fig. 33; Table 19). The river flows at the Oakwood gage on the Trinity River (USGS 08065000) during the fall were 2728 (±5,637) cfs up to 8,826 (±12,573) cfs during the spring (Fig. 34; Table 19). At the Romayor gage on the Trinity River (USGS 08066500), river discharge ranges from 7804 (±15890) cfs in the fall up to 24,634 (±28,656) cfs during the spring (Fig. 35; Table 19). On the San Jacinto River at the East Fork gage (USGS 08070000) flows range from 263 (±1,253) cfs in the summer up to 684 (±1,394) cfs in the winter (Fig. 36; Table 19). At the West Fork gage (USGS 08068000) the river flows range from 125 (±665) cfs in the summer up to 314 (±702) cfs in the spring (Fig. 37; Table 19).

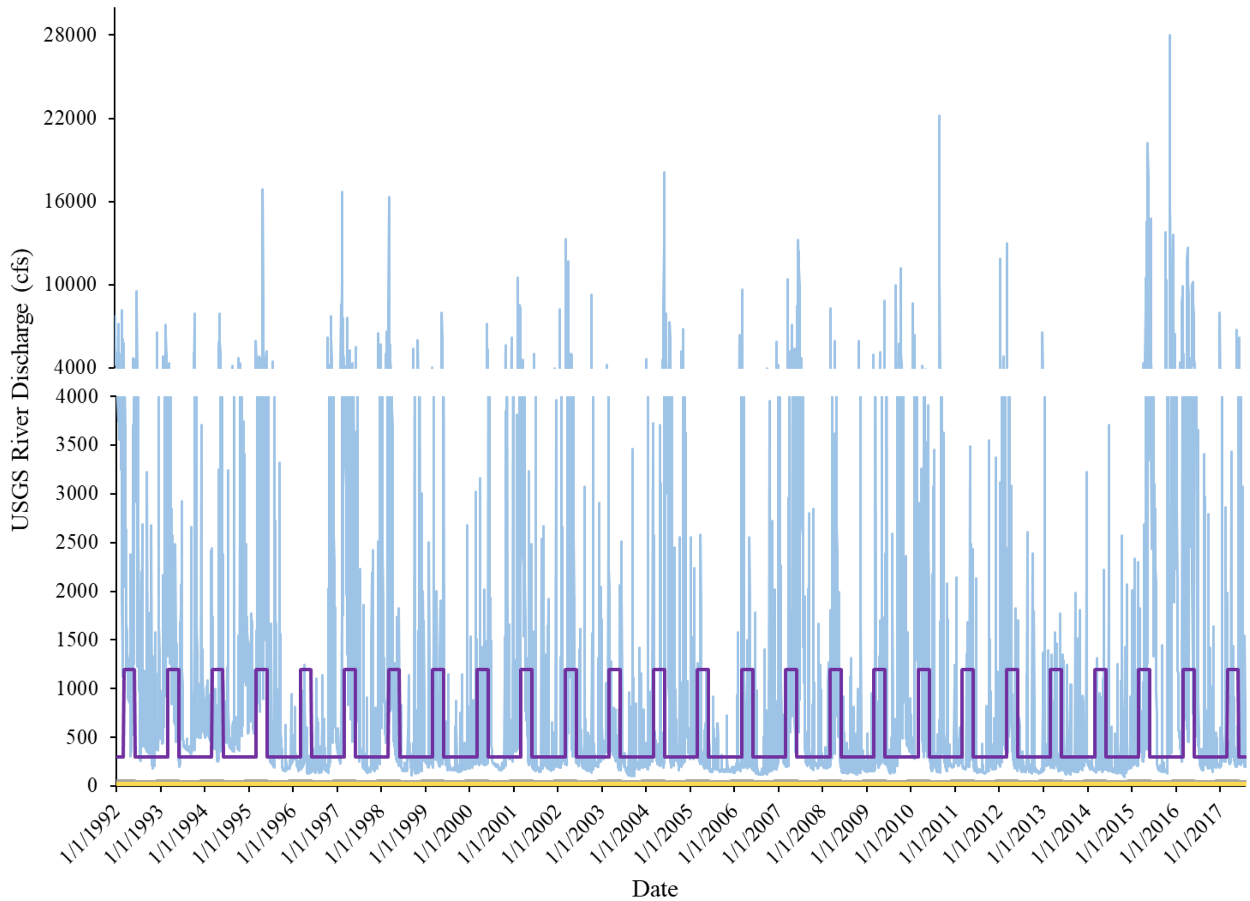


Figure 32 Line graph for the West Fork Grand Prairie Trinity River (USGS Gage 08049500) showing the comparison between actual measured discharge (blue), the instream trigger flows (purple), the instream base flows (gray) and the instream subsistence flows (yellow) from 1992-2017.

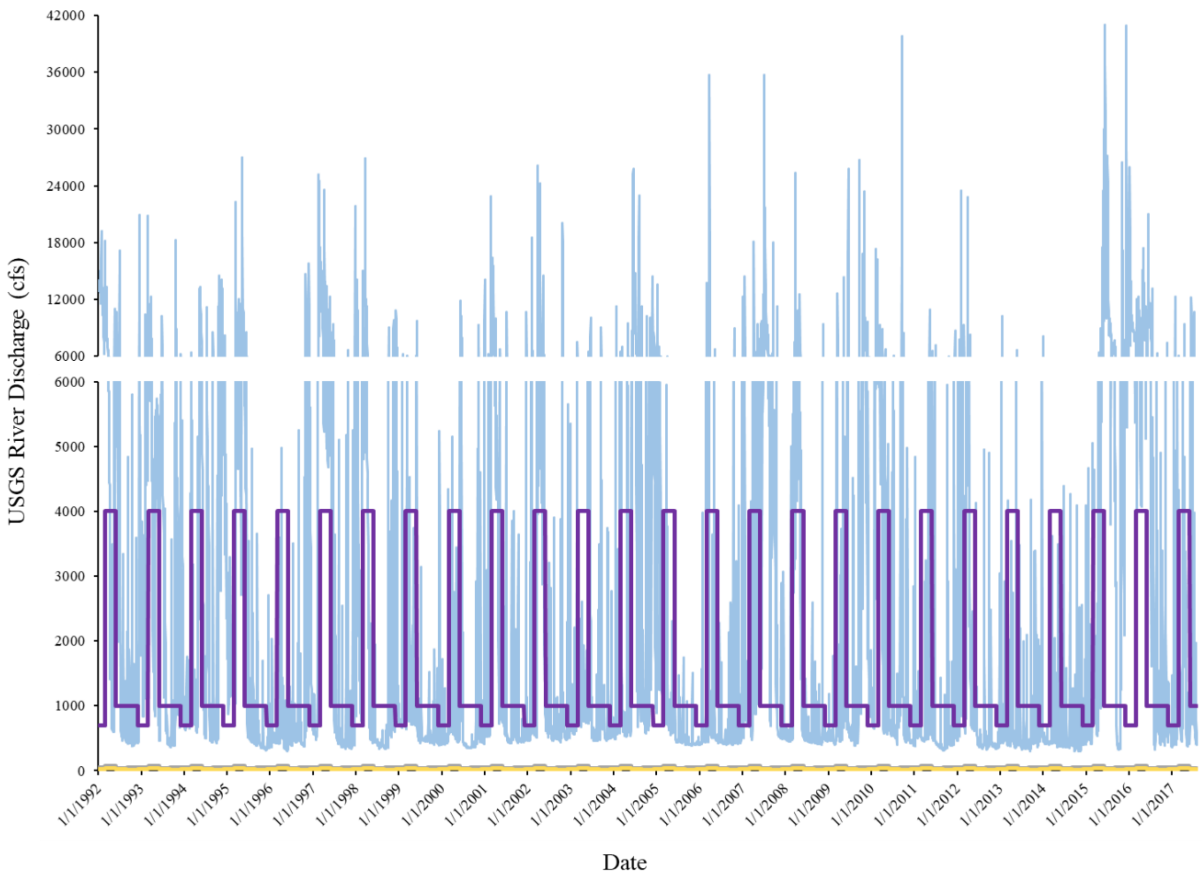


Figure 33 Line graph for the Trinity River at Dallas (USGS Gage 08057000) showing the comparison between actual measured discharge (blue), the instream trigger flows (purple), the instream base flows (gray) and the instream subsistence flows (yellow) from 1992-2017.

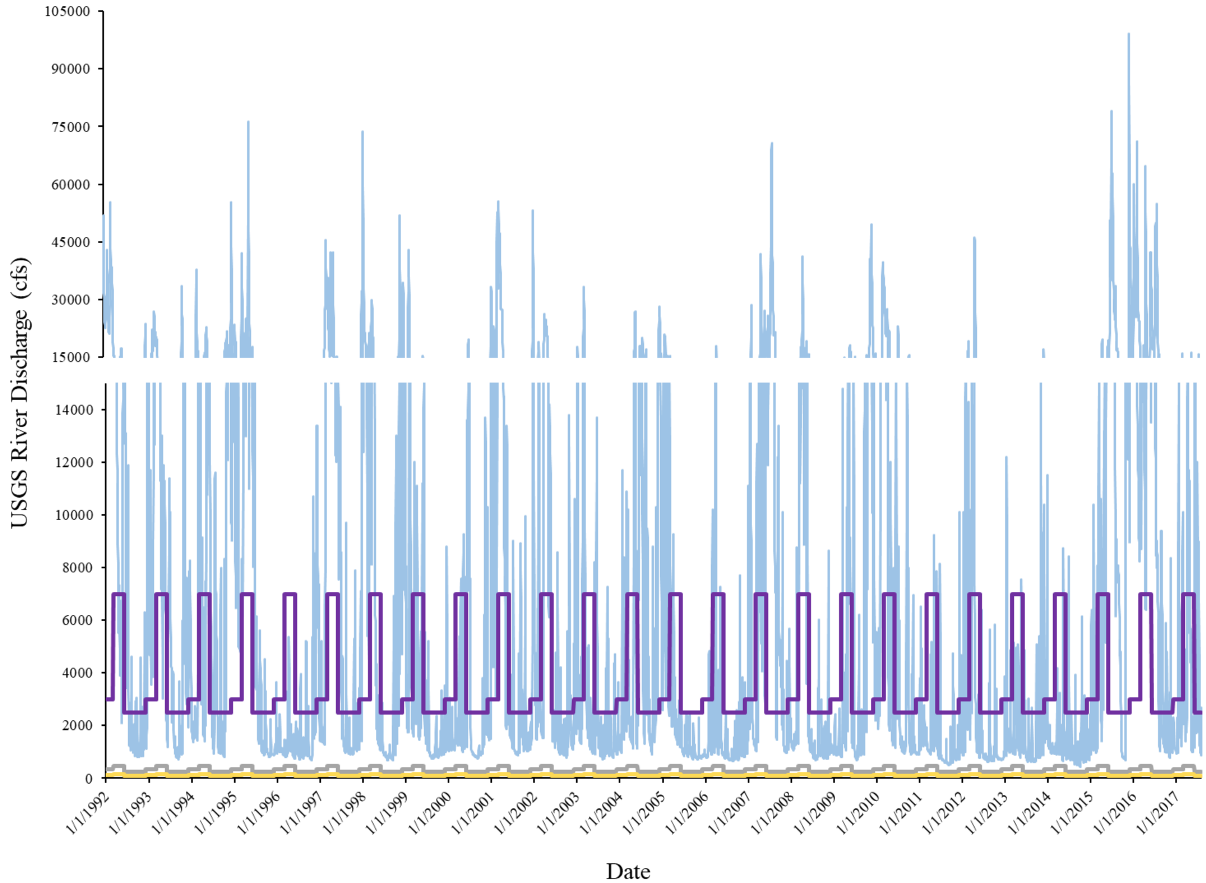


Figure 34 Line graph for the Trinity River at Oakwood (USGS Gage 08065000) showing the comparison between actual measured discharge (blue), the instream trigger flows (purple), the instream base flows (gray) and the instream subsistence flows (yellow) from 1992-2017.

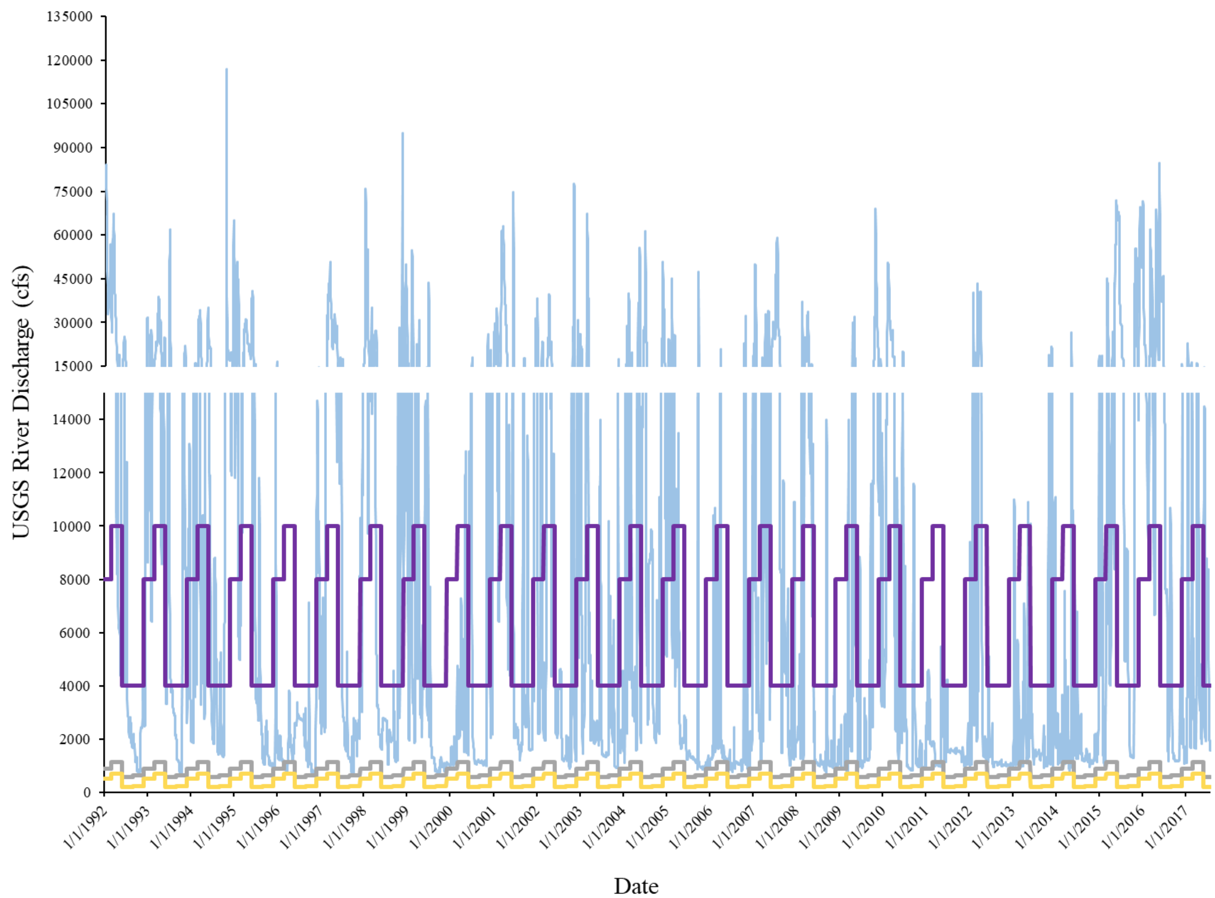


Figure 35 Line graph for the Trinity River at Romayor (USGS Gage 08066500) showing the comparison between actual measured discharge (blue), the instream trigger flows (purple), the instream base flows (gray) and the instream subsistence flows (yellow) from 1992-2017.

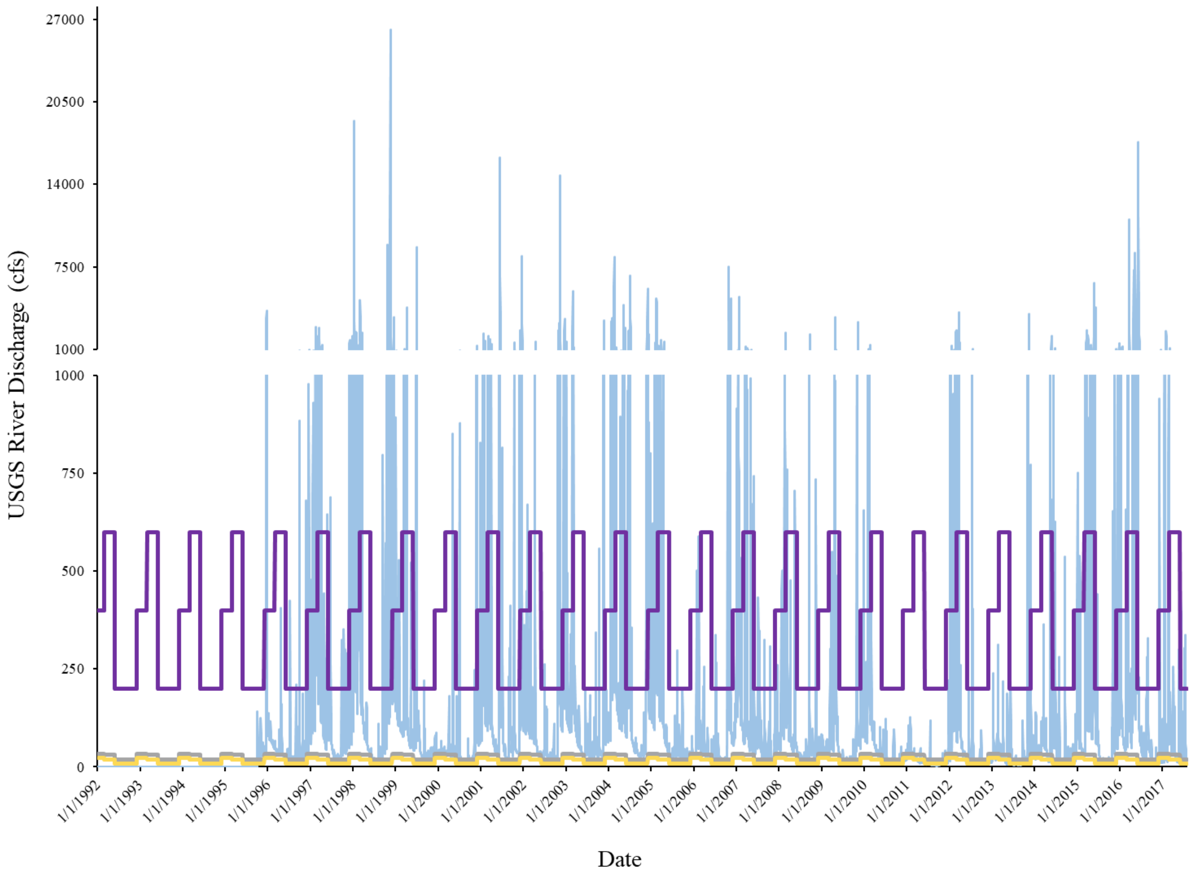


Figure 36 Line graph for San Jacinto at East Fork (USGS Gage 08070000) showing the comparison between actual measured discharge (blue), the instream trigger flows (purple), the instream base flows (gray) and the instream subsistence flows (yellow) from 1992-2017.

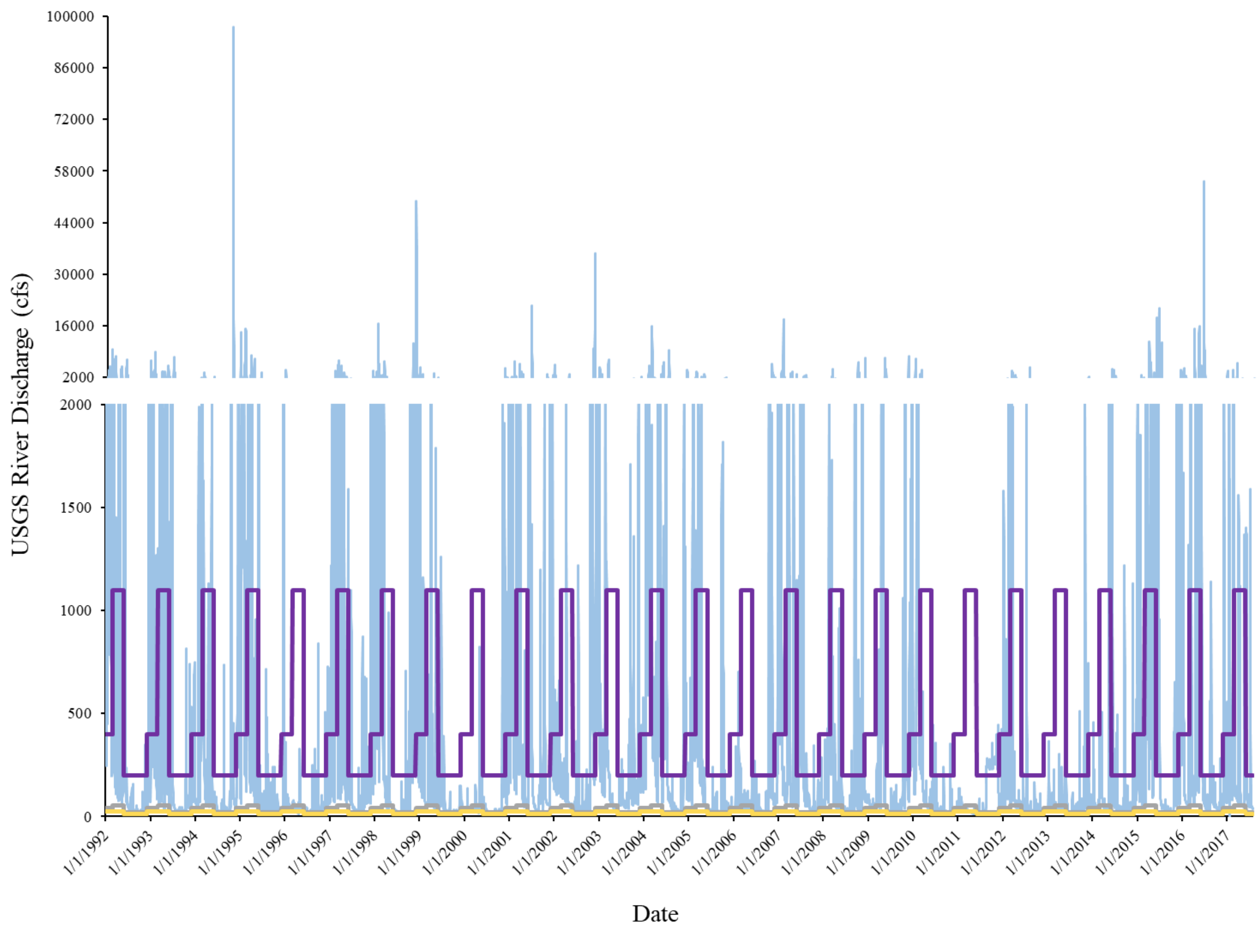


Figure 37 Line graph for the San Jacinto at West Fork (USGS Gage 08068000) showing the comparison between actual measured discharge (blue), the instream trigger flows (purple) the instream base flows (gray) and the instream subsistence flows (yellow) from 1992-2017.

Table 18 TCEQ instream flow standards pulled from TCEQ Chapter 298 (2017).

TCEQ Instream Flow Stds (cfs)	TR at Grand Praire		TR at Dallas		TR at Oakwood	
	USGS 08049500		USGS 08057000		USGS 08065000	
	Subs.	Base	Subs.	Base	Subs.	Base
Winter	19	45	26	50	120	340
Spring	25	45	37	70	160	450
Summer	23	35	22	40	75	250
Fall	21	35	15	50	100	260

TCEQ Instream Flow Stds (cfs)	TR at Romayor		SJR at East Fork		SJR at West Fork	
	USGS 08066500		USGS 08070000		USGS 08068000	
	Subs.	Base	Subs.	Base	Subs.	Base
Winter	495	875	22	33	23	42
Spring	700	1150	18	31	24	52
Summer	200	575	9	18	10	19
Fall	230	625	9	18	10	22

Table 19 USGS river discharge measured at each of the gages included in the TCEQ standards. The period of record at each gage is different and include years as follows: TR at Grand Prairie: 1925-2017; TR at Dallas: 1903-2017; TR at Oakwood: 1923-2017; TR at Romayor: 1924-2017; SJR at East Fork: 1939-2017 and SJR at West Fork: 1924-1997. 199-2017 (no data collected Oct 1987- Sep 1989, Oct 1991 - Sep 1995).

Measured Instream Flows (cfs)	TR at Grand Praire			TR at Dallas			TR at Oakwood		
	USGS 08049500			USGS 08057000			USGS 08065000		
	Mean (±SD)	Min	Max	Mean (±SD)	Min	Max	Mean (±SD)	Min	Max
Winter	574 (±1365)	15	31900	1537 (±3341)	7	60900	5694 (±8913)	98	103000
Spring	1119 (±2411)	11	48900	2909 (±6064)	9	152000	8826 (±12573)	75	153000
Summer	648 (±1629)	5	37100	1691 (±3459)	2	60300	4239 (±7764)	8	72700
Fall	462 (±1258)	5	28000	1126 (±2712)	9	43100	2728 (±5637)	28	99200

Measured Instream Flows (cfs)	TR at Romayor			SJR at East Fork			SJR at West Fork		
	USGS 08066500			USGS 08070000			USGS 08068000		
	Mean (±SD)	Min	Max	Mean (±SD)	Min	Max	Mean (±SD)	Min	Max
Winter	18173 (±22975)	496	166612	684 (±1394)	9	20200	314 (±702)	8	19000
Spring	24634 (±28656)	672	218182	701.36 (±2153)	12	58300	293 (±883)	6	30400
Summer	12342 (±20611)	206	186843	263 (±1253)	6	29400	125 (±665)	3	31900
Fall	7804 (±15890)	246	232066	382 (±2391)	5	97200	175 (±1050)	3	43200

Table 20 TCEQ Bay flow standards for Galveston Bay

TCEQ Bay flow standards										
Basin	Annual Inflow Quantity (AF)	Annual Target Frequency	Winter Inflow Quantity (AF)	Winter Target Frequency	Spring Inflow Quantity (AF)	Spring Target Frequency	Summer Inflow Quantity (AF)	Summer Target Frequency	Fall Inflow Quantity (AF)	Fall Target Frequency
Trinity	2,816,532	50%	500,000	40%	1,300,000	40%	245,000	40%	N/A	N/A
	2,245,644	60%	250,000	50%	750,000	50%	180,000	50%	N/A	N/A
	1,357,133	75%	160,000	60%	500,000	60%	75,000	60%	N/A	N/A
San Jacinto	1,460,424	50%	450,000	40%	500,000	40%	220,000	40%	200,000	40%
	1,164,408	60%	278,000	50%	290,000	50%	100,000	50%	150,000	50%
	703,699	75%	123,000	60%	155,000	60%	75,000	60%	90,000	60%

Table 21 Percentage of time the bay flow standards were met based on the TWDB estimated freshwater inflows between the years of 1941-2016. The average annual sum of TWDB estimated freshwater inflows are included for years where freshwater inflows were greater than or equal to the TCEQ standard for basin inflow.

TCEQ Bay flow standards - Trininty and San Jacinto Basins combined											
Standard		Measured		Standard		Measured		Standard		Measured	
Annual Inflow Quantity (AF)	Annual Target Frequency	% time standard was met or exceeded	Annual avg inflow when flow above TCEQ std (AF)	Winter Inflow Quantity (AF)	Winter Target Frequency	% time standard was met or exceeded	Winter avg inflow when flow above TCEQ std (AF)	Spring Inflow Quantity (AF)	Spring Target Frequency	% time standard was met or exceeded	Spring avg inflow when flow above TCEQ std (AF)
4,276,956	50%	88%	12,212,899	950,000	40%	89%	3,274,078	1,800,000	40%	72%	4,661,804
3,410,052	60%	92%	11,861,053	528,000	50%	97%	3,076,035	1,040,000	50%	88%	4,076,443
2,060,832	75%	97%	11,372,288	283,000	60%	100%	3,006,337	655,000	60%	96%	3,804,168

TCEQ Bay flow standards - Trininty and San Jacinto Basins combined							
Standard		Measured		Standard		Measured	
Summer Inflow Quantity (AF)	Summer Target Frequency	% time standard was met or exceeded	Summer avg inflow when flow above TCEQ std (AF)	Fall Inflow Quantity (af)	Fall Target Frequency	% time standard was met or exceeded	Fall avg inflow when flow above TCEQ std (AF)
465,000	40%	93%	2,513,899	200,000	40%	97%	2,126,804
280,000	50%	99%	2,401,379	150,000	50%	99%	2,100,840
150,000	60%	100%	2,372,904	90,000	60%	100%	2,075,085

3.2.2. TCEQ Bay flow standards vs TWDB estimated freshwater inflows

The TCEQ standards are shown in Tables 20-21 along with the percent of time that these standards were actually met for the time period of 1941-2016. This time period was chosen because it covers the entire of data set of TWDB estimated freshwater inflows available. In Galveston Bay (including in both the Trinity and San Jacinto Basins), the highest annual inflow quantity standard (4,276,956 AF) was met in 88% of the years between 1941-2016, the mid-range annual inflow target of 3,410,052 AF was met in 92% of the years and the lowest annual inflow quantity of 2,060832 AF was met in 97% of the years (n = 40) (Tables 20-21).

Seasonal bay flow standard targets were also met for the Trinity and San Jacinto basins combined (Table 20-21). The highest and lowest target flows for the winter (950,000 AF and 283,000 AF respectively) were achieved 89% and 100% of the time and the standard requires that target be met 40% and 60% of the time respectively (Table 21). The spring high flow volume annual target frequency was met or exceeded 72% of the time and the frequency standard is 40% (Table 21). In the summer the high inflow volume standard was achieved 93% of the time and in the fall it was met 97% of the years (Table 21).

3.3. Discussion

3.2.1. TCEQ Instream standards versus measured flows for Galveston Bay

In an effort to examine the environmental flow standards for the Trinity and San Jacinto Rivers, their associated tributaries, and Galveston Bay, we used the TCEQ Chapter 298 (2011). This report reiterates the TCEQ flow standards with the schedule of flow quantities that contain subsistence flow, base flow, and one level of high flow pulses at defined measurement points. TWDB estimated freshwater inflows (including minimum flow levels) and the river discharge measured by USGS at specific measurement points (gages) vary by season and by year since the amount of precipitation varies; this also impacts the number of pulses protected.

3.2.2. Instream flow standards

In this study one of our tasks was to determine if the instream flow standards are sufficient for freshwater needs to the bay. To achieve this goal, we set out to compare the measured flow at the six USGS gages that had been established as measurement locations in the TCEQ Subchapter 298 (2011) along the Trinity and San Jacinto Rivers (Fig. 31, Table 18). These standards are set to inform water permit holders of when they are allowed to pull water from the rivers according to their permits (TCEQ, 2011). At each of the six gages (see Fig. 31), we compared the measured flow to the flow that is required for water right permit holders to pull from the rivers (Figs. 32-37; Tables. 18-19). This analysis showed that the TCEQ instream standards are set below the measured flows on the Trinity River at the West Fork, Dallas and Oakwood gages (Figs. 13-15). Flow at all six gages were primarily at base or trigger flow volumes (Tables. 18-19). At the West fork of the Trinity River gage, over the course of this study period, 57% of the days between January 1, 1992 and December 31, 2015 (8765 days) were above the level of base flow and 39% of the days measured flows were above the trigger level for a pulse flow (Supplemental Figure 2). At the Dallas and Oakwood gages on the Trinity River we see similar flows during the study period with 64% of the day's flows were above base flow but below trigger flow and 36% of the time the flows were high enough to trigger a pulse (Supplemental Figure 2). Further down the Trinity River at the Romayor gage the flows are above base flow 64% of the time, above trigger flow 34% of the time, between subsistence and base flow 2% of the time and between low flow and subsistence flow <1% of the time (Supplemental Figure 2). On the San Jacinto River at the gage on the West Fork flows were above trigger volume only 22% of the time, above base flows 60% of the time, above subsistence flow 16% and above low 2% of the time (Supplemental Figure 2). On the East Fork of the river the flows were only above trigger flow for a pulse 10% of the time, 60% of the days the flow was above the base flow (but below trigger flow for a pulse), 14% of the time flow was at the subsistence level and 7% of the time flows were above low flow but below subsistence level (Supplemental Figure 2; Heat map). Overall, the flow levels were low during times of drought in 1996, 2000, 2011-2014 and the end of 2015 (Supplemental Figure 2). Although we only presented data here from 1992-2015, similar trends were observed dating back to 1939 for all six gages (data not shown in report but available upon request).

The goal of this work was to determine if the instream flow standards will protect the natural flow regime into Galveston Bay. To do this we had to determine how the instream flow standards compare to the measured flows at each of the described measurement points indicated in TCEQ Subchapter 298 (2011) (Figs. 32-37). These graphs indicated the rate of river discharge compared to the standards that need to be met for water right holders to pull the water allowed in their permit. On the San Jacinto River, the USGS measured river discharge does fall below than instream flow standards for subsistence flow and base flow (Figs. 36-37) during low flow periods. On the Trinity River at all measurement sites the low flows are typically above the base and subsistence flows (Figs. 32-35). The natural flow regime is much higher than that of the instream flow standards (Figs. 32-37).

3.2.3. Bay flow standards (environmental flow)

The second task we were charged with in conducting this study was to determine if the TCEQ instream flow standards are sufficient flow volumes to satisfy the environmental flows set for the Trinity and San Jacinto Basin within Galveston Bay. The way that we approached the bay flow standards (without running a WAM or other model simulation which was beyond scope of the current study) was to compare the TWDB estimated freshwater inflows to the standards set in place for the Trinity and San Jacinto Basins. Based on meetings with the technical guidance committee, this task will require further effort in the form of running a WAM and other simulation models. The TCEQ instream flow standards set limits to when water right permit holders are allowed to pull their allotted freshwater from the rivers at a particular location. If the flow conditions are at or above the required flow limit then water rights holders can pull their allotted volumes of water from the river. The TCEQ instream flow standards are evaluated differently than the bay flow standards (i.e. environmental flow). The bay flow standards are evaluated before a new permit is granted, while instream flows are evaluated on an operational basis. Complex modeling efforts would be needed to be conducted to determine the flow rate (including the water volumes being removed from the rivers by water permit holders) and if these rates would be sufficient to meet the environmental flow standards for the basins within Galveston Bay. In this scope of work, we were tasked with conducting a comparison study but running the WAM is considered outside the scope of this project.

4. CONCLUSIONS

In order to characterize “a sound ecological environment” for Galveston Bay, we returned to the definition determined by the Senate Bill 3 (SB3) Science Advisory Committee (SAC 2006, 2009) and the refinement, but not change, of that definition by the TCEQ in 2011 (TCEQ Chapter 298, 2011). There were two objectives of this study. First, we worked towards defining a sound ecological environment for Galveston Bay or healthy estuary using bioindicator species which could then be used as part of an adaptive management strategy. This part of the study contributes to several priority activities identified in the Trinity, San Jacinto Basin and Bay Area Work Plan for Adaptive Management (TSJ BBASC 2012), including to test the conclusion that the bioindicators were appropriate for representing the health of Galveston Bay and to consider the addition of new species which were previously not recognized. Espey et al. (2009) identified the following species as potential bioindicators:

Table 22 List of indicator species by habitat type from Espey et al (2009)

Indicator Type	Species	Examined in current study
Habitat indicator	*Vallisneria americana* (Wild celery)	no
Low salinity indicator	*Rangia cuneata* (Atlantic rangia)	no
	Brevoortia patronus (Gulf Menhaden)	yes
	Ictalurus furcatus (Blue Catfish)	yes
High salinity indicators	*Squilla empusa* (Mantis shrimp)	no
	Lagodon rhomboids (Pinfish)	yes
Oyster health indicators	*Perkinsus marinus* (Dermo) *Stramonita haemastoma* (Oyster drill) *Crassostrea virginica* (Eastern oyster)	no

Previous work examined the validity of these bioindicators (see Quigg and Steichen, 2015; Steichen and Quigg, 2018). In the current study, we examined three species from the Espey et al. (2009) report plus an additional 27 species of fish and invertebrates as potential bioindicators (Table 2). While Espey et al. (2009) focused on bioindicators for specific purposes (habitat, salinity, oyster health), the current effort was more targeted towards determining if bioindicators could provide information on the health of the bay, that is to say, if it is a sound ecological environment. Various approaches were considered in an effort to do so.

We used standard community metric(s) to quantify the complement of native species which accounted for 97% of the catches in bag seines. The Shannon Diversity Index (*H'*), Pielou's Evenness index (*J'*), species richness (*S*) and the total number of individuals (*N*) were calculated on the CPUE data for each bag seine collected in Galveston Bay. In terms of the influence of freshwater inflows on the community, we did not investigate this per se as it was beyond the scope of the current project. Rather we examined salinity, which is often a proxy for inflows, in both the entire bay as well as bay segments as a factor for the 30 species identified. An in-depth analysis revealed that these species distributions and abundances are significantly correlated to salinity and turbidity as well as having patterns which are dominated by seasons and locations within Galveston Bay. We found that seasonality was the greatest driver of variability when considering the entire bay, consistent with known life cycles of fish and invertebrates that use estuaries as their habitat (this study, McFarlane et al., 2015; Tolan 2013; Quigg and Steichen 2015; Steichen and Quigg 2018). While variable, these community metrics were not adversely influenced by periods of drought, flood or other extreme events from 1992-2015. This suggests the bay and its communities are resilient to natural perturbations and further supports the notion that the bay is indeed a sound ecological environment given both the SACs and TCEQ definitions (SACS 2006, 2009; TCEQ Chapter 298, 2011).

Future work should include an analysis of the remaining 3% of the individuals collected in the bag seines and perhaps also consider individuals collected in bay trawls and using other mechanisms. This would allow us to test the notion that the analysis herein includes a representative assemblage of the natural community which we are using to infer that there is indeed a sound ecological environment in Galveston Bay. This was not performed as part of the current study as there are no tools available (to our knowledge) which allows the simultaneous comparison of such diverse data sets on the same scales. There are many studies on bioindicators, many of which provide the challenges and advantages of using bioindicators as a proxy for a sound ecological environment; see the book by Bortone et al. (2005) for the most recent in-depth review of this area.

We worked with TWDB to evaluate the TCEQ freshwater inflow standards for Galveston Bay as well as the TCEQ instream flow standards. The approach used was to compare observed flows to the instream flow standards and freshwater inflow standards to the TWDB estimated freshwater inflows. This is a difficult task because the instream flow standards adopted by TCEQ for the Trinity and San Jacinto Rivers with the freshwater inflow standards adopted by TCEQ for Galveston Bay were developed using very different procedures, criteria, metric, assumptions, etc.

The original objective of the study was to determine whether the instream flow and freshwater inflow standards align to support a sound ecological environment in Galveston Bay. However, due to the complex differences in the structure of the two sets of standards (e.g., instream flow standards are comprised of subsistence, base, and pulse flows, but freshwater inflow standards are comprised of seasonal and annual inflow quantities and annual attainment frequencies), it was determined that a comparison analysis was not appropriate. As such, the focus of the study shifted to evaluate the frequency at which the standards were met in the recent record of observed flows. The TCEQ adopted instream flows standards were compared to stream gage data collected by the U.S. Geological Survey (USGS) while the TCEQ adopted freshwater inflow standards were compared to freshwater inflow data compiled by the Texas Water Development Board (TWDB). Our analysis found the Trinity River and San Jacinto River basins are receiving the recommended flow volumes and frequencies. Our findings are tentative and provided with caveats as we feel this requires a comprehensive effort with the use of agency models (e.g., TxBLEND, WAM, etc.) and which includes bringing together TCEQ and TWDB and various other stakeholders that was beyond the scope of the current study. This project contributes to several priority activities identified in the Trinity, San Jacinto Basin and Bay Area Work Plan for Adaptive Management (TSJ BBASC 2012), including to test the conclusion that the bioindicators were appropriate for representing the health of Galveston Bay and to consider the addition of new bioindicators species which were previously not recognized. We took a simplified approach compared to TxBLEND and WAM to address the question of whether the TCEQ freshwater inflow standards and instream flows have been met over the period of record.

In the case of this study, we defined the “full complement of native species” as the dominant fish and invertebrates found in the 5,226 bag seine sampling events conducted from 1992 to 2015 by TPWD. Based on our findings, we conclude that it is reasonable to assert that the inflows into the bay currently provides a “sound ecological environment” to the species captured using this approach. Previous studies have used a similar cohort approach to investigate fisheries in Texas as well as their response to freshwater inflows. Future studies could consider additional records, such as bay trawls, in defining both the complement of native species, and the health of the bay. While the specific details may change, we hypothesize the outcome will be similar to that in the present study. However, more work is needed to confirm or refute this suggestion.

5. REFERENCES

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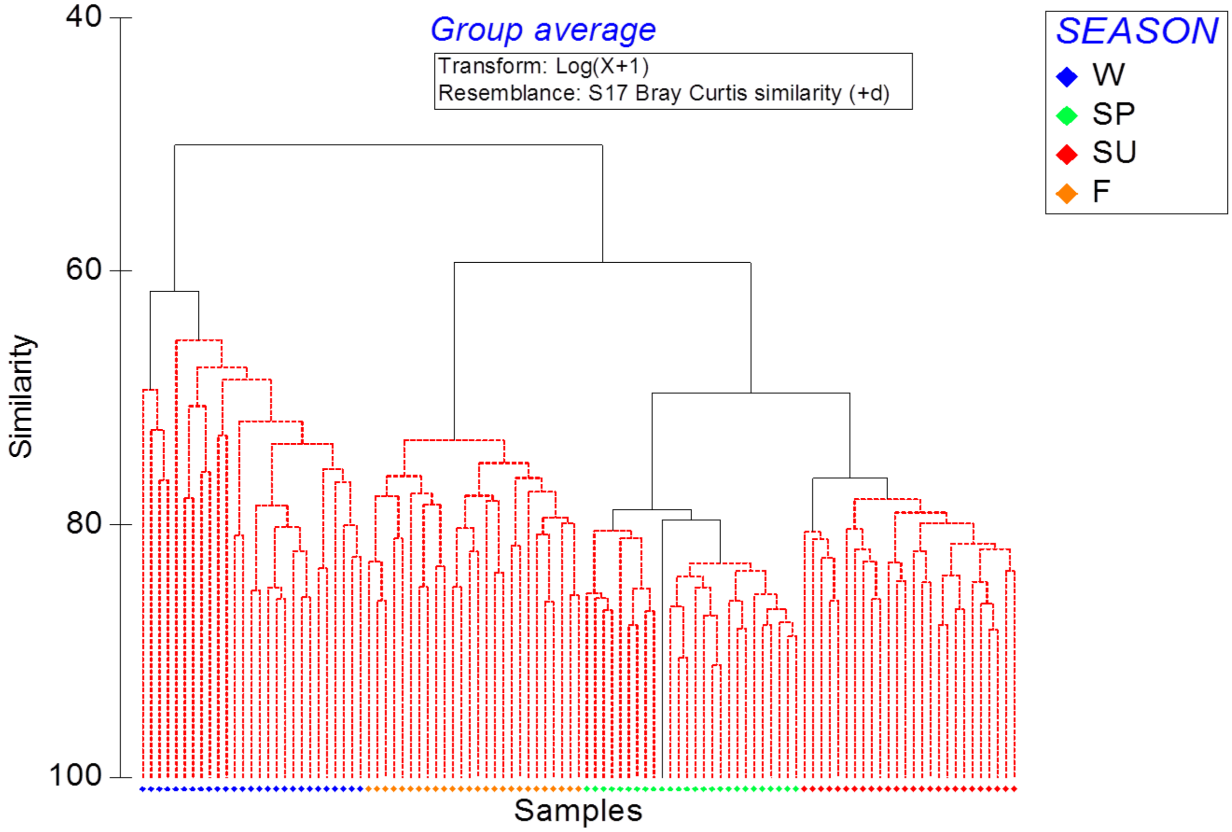
6. SUPPLEMENTAL FIGURES



Supplemental Figure 1 CLUSTER analysis of the biotic community based on Bray Curtis similarity matrix.

Supplemental Figure 2 Please request Excel spreadsheet (separate file) of heat map showing measured flow at each of the six USGS gages. Flow is color coded based on the instream standard values: Trigger flow for a pulse (dark blue), base flow (light blue), subsistence flow (orange), low flow (red), data not available (gray).