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Long-Term Benthic Data: Adaptive Management of Three Basins

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Using Comparative Long-term Benthic Data for Adaptive Management of Freshwater Inflow to Three Basins

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4 Executive Summary

The goal of this project is to extend the long-term dataset of benthos (i.e., bottom-dwelling) species and community data collected from Lavaca and Matagorda Bays (Lavaca-Colorado Estuary), San Antonio Bay (Guadalupe Estuary), and Nueces and Corpus Christi Bays (Nueces Estuary) by analyzing archived samples. Benthic organisms are ideal bioindicators of freshwater inflow effects on bays and estuaries because they are fixed in space and integrate ephemeral processes in the over-lying water column over long periods of time. Benthic studies, some of which has been funded by the Texas Water Development Board (TWDB), have demonstrated that long-term hydrological cycles—which affect freshwater inflow and water quality—also regulate benthic abundance, productivity, diversity, and community structure. The TWDB has supported water and sediment sample collections since 1987 in the mid-coastal bay systems (Lavaca-Colorado Estuary, Guadalupe Estuary, and Nueces Estuary), but over the years there have been insufficient funds to complete the analysis of collected samples. This study extended those initial efforts to document benthic conditions by analyzing 975 archived samples from all three bay systems (648 from Lavaca-Colorado Estuary, 36 from Guadalupe Estuary, and 291 from Nueces Estuary).

The bay systems have different long-term characteristic fauna that reflects the long-term average salinity conditions in each bay system. The Lavaca-Colorado Estuary has on average about 37% more inflow than the Guadalupe Estuary, and 11 times more than the Nueces Estuary. San Antonio Bay is small and limited exchange with the Gulf of Mexico, therefore it has lower long-term average salinity than Lavaca Bay. The San Antonio Bay community has a higher contribution of mollusks, which are freshwater indicators, than Lavaca Bay, and much higher than Nueces Bay. Within the estuary systems, the secondary bays have distinct communities compared to the primary bays. This is because secondary bays are closer to freshwater inflow sources and are more oligohaline and/or brackish in nature than primary bays, which are more marine influenced.

The period analyzed included the effects of a flood caused by Hurricane Harvey, which made landfall on August 25, 2017, in San Antonio Bay. When taking a short-term view, i.e., analyzing data from three quarters prior and three quarters after the hurricane induced flood, it appears as if the benthos were devastated by the flood and then recovered slowly. However, long-term analysis led to a different conclusion. The data from 2004 to 2017 was analyzed using an exponential smoothing model (a form of time series analysis) to forecast the response in the 12 months following the storm. There was a seasonal cycle where abundances decline every fall and increase every spring, and the responses due to the storm were at the edge, but within the bounds of error. The seasonality and responses within error bounds indicates that benthos were resistant to disturbances, and the recovery within nine months indicates that benthos are also resilient to flood disturbance.

Bioindicators of freshwater inflow effects include four dominant species: the polychaete species, *Mediomastus ambiseta* and *Streblospio benedicti*, the bivalve *Mulinia lateralis* , and the amphipod *Ampelisca abdita*. Each of these species were found mostly in secondary bays and had higher abundances in bays with similar salinities.

The time-series of benthic data is critical information for the Senate Bill 3 environmental flows adaptive management process, because of the relationship between salinity and community structure. Within each bay system, salinity can be used to identify the freshwater inflow needs to maintain a “sound ecological environment” as indicated by benthos. Thus, this provides a rich, multi-decade, dataset from which it is possible to evaluate the effectiveness of current freshwater inflow standards in three basin-bay systems along the mid-Texas coast. However, the inflow standards are based on hydrological statistical characteristics and are complex based on three characteristics: the climatic period, season, and geographical locations. Thus, to use biotic information to evaluate the environmental flow standards, it is also necessary to model how flow effects salinity over space and time.

5 Introduction

Since the early 1970's, the TWDB freshwater inflow studies focused on the major bay systems of the Texas coast. These bay systems, which are influenced primarily by river inflow, are now subject to greater scrutiny due to recent legislative changes. In recognition of the importance of environmental flows, the 80th Texas Legislature enacted Senate Bill 3 (SB3, 2007), which calls for consideration of the ecological soundness of riverine, bay and estuary systems, and riparian lands in the water permitting process. This required the Texas Commission on Environmental Quality (TCEQ) to set environmental flow standards for bays and estuaries, based on recommendations provided by Basin and Bay Expert Science Teams (BBESTs) and Basin and Bay Area Stakeholders Committees (BBASCs). The BBASCs are also responsible for overseeing an adaptive management process to evaluate the effectiveness of environmental flow standards. Benthic indicators (including oysters, clams, crab, and shrimp) were used by five of the seven BBESTs during the SB3 process to create inflow regime recommendations.

Benthos are excellent indicators of sediment quality, because they are relatively long-lived, fixed in place, integrate variations in the overlying water column over time, and are forage for commercial and recreational fish species. Further, the analysis of the biodiversity and community structure of benthos provide powerful metrics to detect changes among sensitive species, which decrease in number or die out, versus tolerant species, which survive or thrive, during prolonged unfavorable conditions. Thus, analysis of estuarine benthic diversity data can be used to evaluate effectiveness of currently adopted inflow regimes. Furthermore, while a modeling analysis is not being performed here, an evaluation of the effectiveness of the adopted freshwater inflow standards in supporting the complete estuarine food web could be undertaken by incorporating the archived benthic data with water column data and Texas Parks and Wildlife Department (TPWD) Coastal Fisheries data.

While each Texas estuary is distinct, they share similar geographical features (Figure 1). Estuaries form at the mouth of a river where freshwater from the river flows into a secondary bay. The secondary bays are connected to primary bays, which are open to the Gulf of Mexico and are influenced by tides. Thus, within each estuary there is a salinity gradient from lower salinity secondary bays to higher salinity primary bays. Marsh and oyster habitat is typical of low and mid salinity zones, while seagrass is typical of high salinity zones. Although each estuary shares common geographical attributes with one another, these habitats offer a spatial comparison, because salinity within each bay varies from the river to the Gulf of Mexico due to freshwater inflow influence with distance from the river.

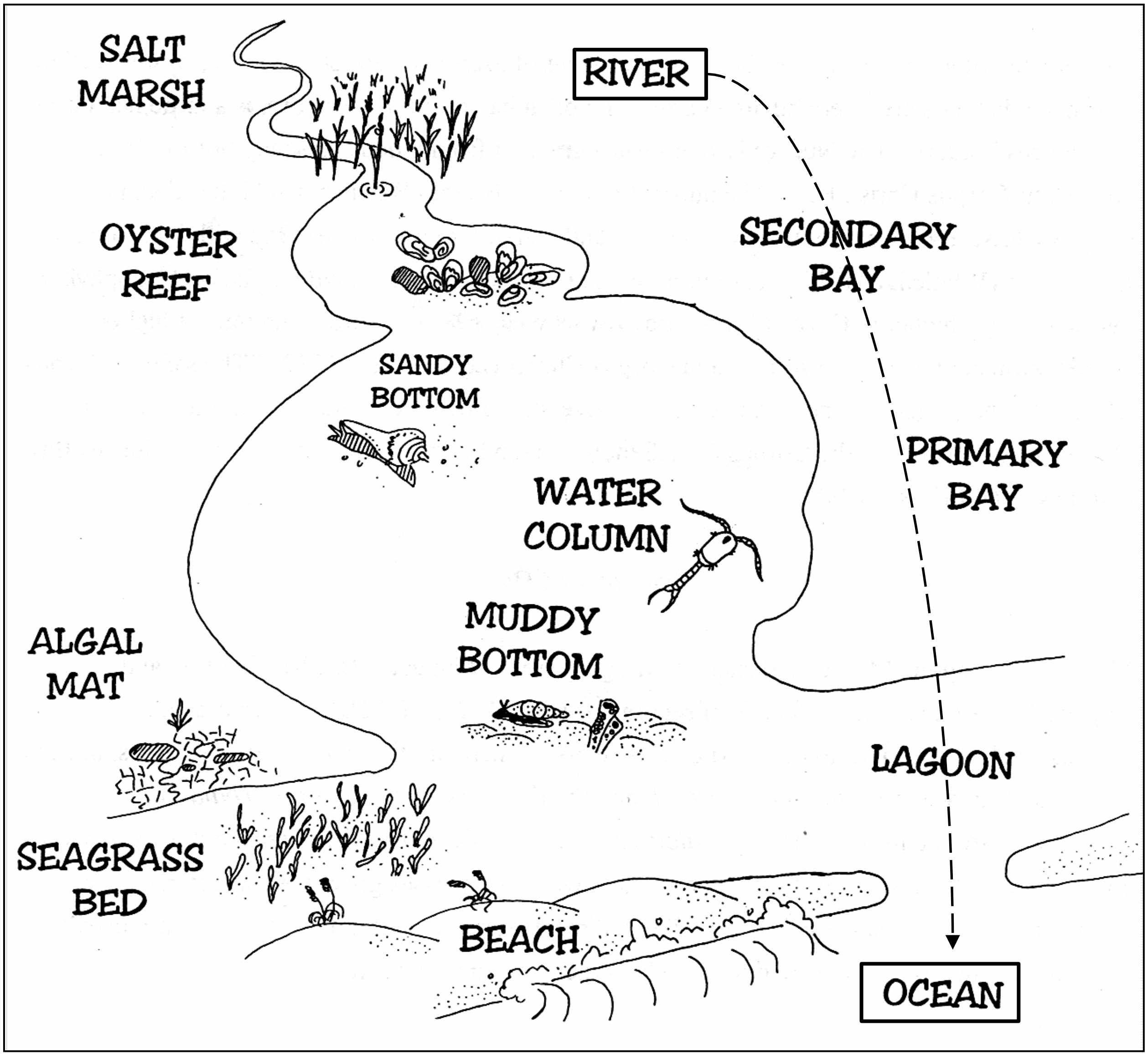
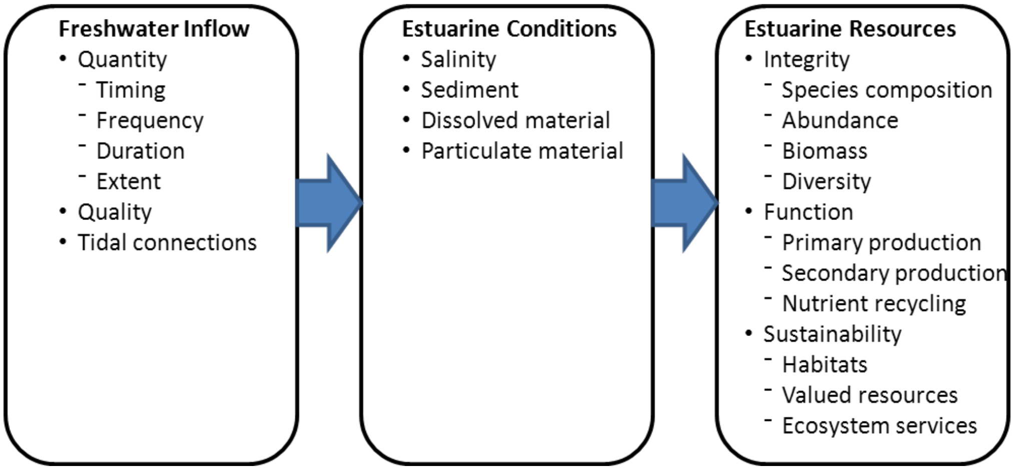


Figure 1. Geographical and habitat features typical of a Texas estuary (Montagna et al. 1996).

The long-term benthic studies sponsored by the TWDB have helped change the fundamental understanding of how freshwater inflow affects living marine resources (Montagna 2021). Originally, the paradigm was based on a simple conceptual model of "*grow = flow*" where inflow was expected to have a *direct* impact on population size. It is now recognized that freshwater inflow has very important *indirect* effects (*i.e.*, inflow drives water quality conditions, and water quality drives habitat quality). The idea was first formalized into a management strategy by Alber (2002). The Alber conceptual model was based on a quantitative model of the cumulative impacts on ecosystem processes as a function of changes in freshwater, sediment, and nutrient inflows created by Sklar and

Browder (1998). This indirect approach or paradigm was adopted by the statewide Science Advisory Committee (SAC 2009). The SAC was created by Texas Senate Bill 3 to provide guidance to all the environmental flow science and stakeholder teams responsible for making inflow recommendations to the TCEQ. The conceptual model developed by these earlier efforts was refined based on benthic studies by Palmer *et al.* (2011) and Montagna *et al.* (2013) and named the Domino Theory (Figure 2). In fact, benthic studies conducted in Texas estuaries have demonstrated that long-term hydrological cycles, which affects freshwater inflow also drives water quality (Montagna *et al.* 2013, Palmer *et al.* 2009, 2011, Paudel and Montagna 2014); and regulates benthic abundance (Pollack et al. 2011), productivity (Montagna and Li 2010, Kim and Montagna 2012), diversity (Montagna *et al.* 2002, Van Diggelen and Montagna 2016), and community structure (Montagna and Kalke 1992, 1995, Ritter *et al.* 2005).



Freshwater Inflow
- Quantity
  - Timing
  - Frequency
  - Duration
  - Extent
- Quality
- Tidal connections

Estuarine Conditions
- Salinity
- Sediment
- Dissolved material
- Particulate material

Estuarine Resources
- Integrity
  - Species composition
  - Abundance
  - Biomass
  - Diversity
- Function
  - Primary production
  - Secondary production
  - Nutrient recycling
- Sustainability
  - Habitats
  - Valued resources
  - Ecosystem services

Figure 2. Conceptual model of the Domino Theory of inflow effects on estuary biological resources (from Montagna et al. 2013).

5.1 Objectives

This study had one objective (*i.e.*, task): to analyze archived benthic samples and use the data to evaluate the adequacy of the freshwater inflow standards adopted for the three basins as part of the Senate Bill 3 adaptive management process.

<u>Lavaca-Colorado Estuary Specific Outcomes</u>: The work performed here meets the needs of the following topics in the Colorado and Lavaca Rivers and Matagorda and Lavaca Bays Basin and Bay Area Stakeholder Committee (CL-BBASC 2012) Scope of Work:

Tier 1 Priorities:
- *Task 2, sub 3, Describe relationships between physical habitat and flow;*
- *Task 12, sub 1, Identify improvements made in methods for determining environmental flow regimes for estuaries;*
- *Task 12, sub 8, Evaluate achievement of the BBEST freshwater inflow recommendations in Matagorda Bay (based on the Matagorda Bay Health Evaluation recommendations) and ecological response to those freshwater inflow quantities and distribution;*

Tier 2 Priorities:
- *Task 11, Refine estimates of freshwater flow to the bays; and*
- *Task 15, Implement a program to review effectiveness of strategies that could be used in areas where there may be inadequate amounts of water to support an ecologically sound stream or estuary.*

<u>Guadalupe Estuary Specific Outcomes</u>: The work performed here meets the needs of the following topics in the Guadalupe, San Antonio, Mission, & Aransas Rivers and Mission, Copano, Aransas, & San Antonio Bays Basin & Bay Area Stakeholders Committee (GSA-BBASC 2012) Scope of Work:

Tier 1 Priorities:
- *Priority 1, Life Cycle Habitat & Salinity Studies for Key Faunal Species;*
- *Priority 3,* Rangia *Clam Investigations;*

Tier 2 Priorities:
- *Habitat Suitability Models for Eastern Oysters, Blue Crabs & White Shrimp; and*

Tier 3 Priorities:
- *Nutrient Load & Concentration Monitoring.*

<u>Nueces Estuary Specific Outcomes</u>: The work performed here meets the needs of the following topics in the Nueces River and Corpus Christi and Baffin Bays Basin and Bay Area Stakeholders Committee (Nueces-BBASC 2012) Scope of Work:

Tier 1 Priorities:
- *Priority 4, Re-examination of the 2001 Agreed Order monthly targets* in the context of biological responses and
- *Priority 5, Describe and design studies to address relationships between abundance of fish and shellfish in the bay and bay salinities.*

Tier 2 Priorities:
- *Relationship between freshwater inflow and ecological health*;
- *Define ecological effects of zero flow event duration, intervals between periods of zero flow, and long-term frequency of zero flow occurrences*;

Ecologically sound environment strategy effectiveness program; and

Evaluate probable effects of climate change (a greenhouse warmed future) on water resources including supply, demand, and the ecological condition of rivers and streams and associated bays in the Nueces Basin.

5.2 Approach

The study focuses on three estuaries of the mid-Texas Coast: Lavaca-Colorado Estuary (Lavaca and Matagorda bays; LC), Guadalupe Estuary (San Antonio Bay; GE), and Nueces Estuary (Nueces and Corpus Christi Bays; NC) (Figure 3). Benthos abundance, biomass, and diversity were recorded to indicate secondary productivity in the estuaries. In addition, the relevant water quality variables (i.e., salinity, temperature, dissolved oxygen, nutrients, and chlorophyll), which already exist for each sampling period, were related to the benthos samples to assess inflow effects on the ecosystems. The study completes processing, identification, and analysis of benthic invertebrate samples collected from each estuary, and the data is used to evaluate the adequacy of the freshwater inflow standards adopted for the three basins.

The Domino Theory (Figure 2) guides identification of inflow effects on estuary resources. The relationship between biology and hydrology is complex and embedded in the food web and material flow dynamics of estuaries. For example, one cannot grow fish by simply adding water to a fish tank. Ultimately, biological resources in estuaries are affected by salinity more than inflow by itself, but salinity is affected by inflow. Because of the links between flow, salinity, and biology; determining the relationship between inflow and resources is a multi-step approach. First, the resource to be protected is identified. Second, the salinity range or requirements of that resource are identified in both space and time. Third, the flow regime needed to support the required distribution of salinity is identified, usually using hydrodynamic and salinity transport models. These experiences led to a generic framework that inflow hydrology drives estuarine condition and estuarine condition drives biological resources. The approach is to simply work backwards: identify bioindicators, identify conditions required to maintain the bioindicator, and identify the flow regimes necessary to maintain those conditions.

6 Methods

Water column and sediment samples were collected at stations in the Lavaca-Colorado Estuary (LC), Guadalupe Estuary (GE), Nueces Estuary (NC) during many other projects. Although most of the sample collections were supported by the TWDB, some of the collections were sponsored by the Texas Commission on Environmental Quality, Texas Sea Grant, Texas Advanced Research Program, Coastal Bend National Estuary Program (now the Coastal Bend Bays & Estuaries Program), Lower Colorado River Authority, National Oceanic and Atmospheric Administration, and National Science Foundation. The water column samples were always processed within 30 days after collection, but the archived benthic samples were primarily a product of past TWDB funding.

6.1 Study Area

Sampling was performed in three estuaries in the Texas mid-coastal zone: Lavaca-Colorado Estuaries, Guadalupe, and Nueces (Figure 3). The study area is ideal to answer questions related to altered hydrology and climate variability occurring at different temporal scales, e.g., seasonal, annual, multi-annual; and different spatial scales, e.g., within and among estuaries (Montagna and Kalke 1995, Kim and Montagna 2012, Van Diggelen and Montagna 2016). This is because there is great temporal variability in climate, and a climatic gradient (among estuaries) and an estuarine (within estuary) gradient (Montagna et al. 2013). The climatic gradient is caused by precipitation decreasing from northeast to southwest, this causing an inflow gradient. The within estuary gradient is caused by freshwater inflow from rivers at one end, to tidal mixing with Gulf of Mexico waters at the other end.

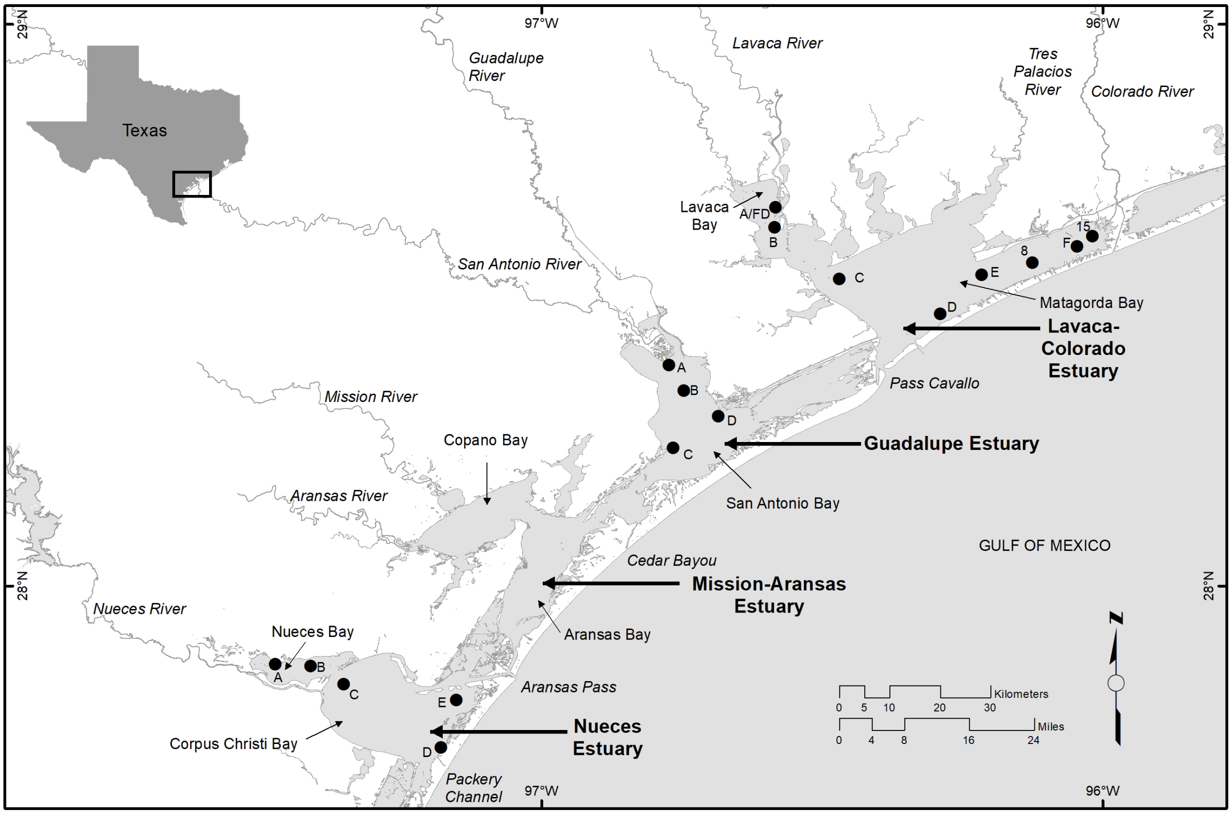


Figure 3. The three Texas Coastal Bend estuaries sampled. Station locations are along a climatic gradient (among estuaries) and estuarine gradient (within estuaries) as described in Table 1.

There was a common theme for station selection with stations A – D along the gradient from fresh to salt water within each estuary. Stations C and D were located in primary bays closer to the Gulf of Mexico exchange point, and stations A and B were located in secondary bays closer to the freshwater inflow sources (Table 1). To identify effects of the Colorado River, stations E and F were added in January 1993 to the eastern arm of Matagorda Bay. To increase resolution of Colorado River influence stations 8 and 15 were added in 2002. To examine possible effects of the Formosa Discharge, station FD was added in Lavaca Bay in 2007. In total, four stations were sampled in the Guadalupe Estuary, nine in the Lavaca-Colorado Estuary, and five in the Nueces Estuary.

Table 1. Locations of bays and stations within the Guadalupe (GE), Lavaca-Colorado (LC), and Nueces (NC) estuaries.

Estuary	Bay	Station	Latitude	Longitude
LC	Lavaca	A	28.67467	-96.58268
LC	Lavaca	B	28.63868	-96.58437
LC	Lavaca	FD	28.68096	-96.58218
LC	Matagorda	C	28.54672	-96.46894
LC	Matagorda	D	28.48502	-96.28972
LC	Matagorda	E	28.55450	-96.21550
LC	east Matagorda	F	28.60463	-96.04600
LC	Matagorda	8	28.57639	-96.11920
LC	east Matagorda	15	28.62232	-96.01878
GE	San Antonio	A	28.39352	-96.77240
GE	San Antonio	B	28.34777	-96.74573
GE	San Antonio	C	28.24618	-96.76488
GE	San Antonio	D	28.30210	-96.68435
NC	Nueces	A	27.86069	-97.47358
NC	Nueces	B	27.85708	-97.41025
NC	Corpus Christi	C	27.82533	-97.35213
NC	Corpus Christi	D	27.71280	-97.17872
NC	Corpus Christi	E	27.79722	-97.15083

A total of 975 archived samples were analyzed during the current study (Table 2). Of these, 264 were collected after Hurricane Harvey because they were collected in 2018 and 2019. Hurricane Harvey hit the Texas coast on August 25, 2017. An additional 711 archived benthic samples were analyzed that were from the period 2009 to 2015 (Table 2B).

Table 2. Archived samples analyzed during the current study.

Period / Estuary	Dates	Samples Analyzed
A. Hurricane Harvey		
Lavaca-Colorado	4/2018 - 7/2019	168
Guadalupe	1/2019 - 7/2019	36
Nueces	10/2018 - 7/2019	60
Subtotal		*264*
B. Archives		
Lavaca-Colorado	4/2009 - 10/2014	480
Guadalupe		0
Nueces	1/2011 - 7/2016	231
Subtotal		*711*
Total all Samples		*975*

6.2 Sediment Samples

6.2.1 Sample Collection

Sediment samples were collected using cores deployed from small boats (Montagna and Kalke 1992). The position of all stations is established with a Global Positioning System (GPS) with an accuracy of about 3 m. Macrofauna were sampled with a 6.7-cm diameter core tube (35.4 cm^2 area). The cores were sectioned at 0-3 cm and 3-10 cm depths to ease the samples sorting and identification process for macrofauna but summed for whole core analyses here. Three replicates were taken per station.

6.2.2 Laboratory Analyses

Organisms were extracted on a 0.5 mm sieve and enumerated to the lowest taxonomic level possible, usually the species level. Biomass was determined for higher taxonomic groupings by drying at 55 °C for 24 hours. Calcium carbonate shells were dissolved by acid fumigation and not included in the biomass measurements.

6.3 Water Samples

Physical water quality measurements in addition to chlorophyll and nutrients were sampled in duplicate just beneath the surface (i.e., within the top 10 cm) and at the bottom of the water column (i.e., within 10 cm of the bottom) at all stations on every sampling date.

6.3.1 Hydrographic Measurements

Hydrographic measurements were made at each station with a Hydrolab or YSI multi parameter instrument by lowering the sonde into the water. The following parameters were read from the digital display unit (with a range of accuracy relative to actual value and units): temperature (± 0.15 ˚C), pH (± 0.1 units), dissolved oxygen (± 0.2 mg l^{-1}), depth (± 0.1 m), and salinity (practical salinity units, psu). Salinity is automatically corrected to 25 ˚C.

6.3.2 Chlorophyll

Water (about 25 ml) for chlorophyll samples were filtered onto glass fiber filters and placed on ice (< 4.0 °C). Chlorophyll is extracted overnight and read fluorometrically on a Turner Model 10-AU using the non-acidification technique (Welschmeyer, 1994; EPA method 445.0).

6.3.3 Nutrients

Nutrient samples (about 25 ml) were filtered to remove biological activity (0.45 µm polycarbonate filters) and placed on ice (< 4.0 °C). Water samples were analyzed at the Harte Research Institute using a OAI Flow-4 autoanalyzer with computer-controlled sample selection and peak processing (Montagna et al. 2018; Paudel et al. 2019). Chemistries are as specified by the manufacturer and have ranges as follows: nitrate+nitrate (0.03 - 5.0 µM; Quikchem method 31-107-04-1-A), silicate (0.03 - 5.0 µM; Quikchem method 31-114-27-1-B), ammonium (0.1 - 10 µM; Quikchem method 31-107-06-5-A) and phosphate (0.03 - 2.0 µM; Quikchem method 31-115-01-3-A.

6.4 Hydrology

Inflow data was downloaded from the TWDB maintained website, https://WaterDataForTexas.org/coastal/hydrology. Data available represents estimated freshwater inflows and inflow balances for Texas estuaries. Data is available on a daily, monthly and annual basis. Monthly data was downloaded for the current study. Data was downloaded May 30, 2018, but it is available only through December 31, 2015.

6.5 Analytics

The analytical methods are grouped into categories for main steps in the analyses: estuary condition identification, bioindicator identification, and using bioindicators of the flow regime effects that are necessary to maintain water and sediment quality conditions.

6.5.1 Water Column Conditions

Freshwater inflow drives changes in estuary condition, which includes salinity, nutrient concentrations, chlorophyll, and turbidity (Fig. 1). Thus, an indicator of water column condition as it relates to inflow can be calculated using multivariate analysis. Principal Components Analysis (PCA) is a variable reduction technique that the Montagna group has used to create a “freshwater inflow condition index” in many previous studies (Arismendez et al. 2009; Pollack et al. 2009, 2011; Palmer et al. 2011, 2016; Paudel and Montagna 2014).

6.5.2 Diversity Indicators

Diversity indices are univariate metrics that summarize multivariate community characteristics in a single number. Diversity is calculated using Hill's diversity number one (N1) (Hill, 1973). It is a measure of the effective number of species in a sample and indicates the number of abundant species. It is calculated as the exponentiated form of the Shannon diversity index:

$$N1 = eH' \tag{1}$$

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

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

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

Richness is an index of the number of species present. The obvious richness index is simply the total number of all species found in a sample regardless of their abundances.

Evenness is an index that expresses that all species in a sample are equally abundant. Evenness is a component of diversity. The most common form is J' of Pielou (1975). It expresses H' relative to the maximum value of H':

$$J' = \ln(N1) / \ln(R) \tag{3}$$

6.5.3 Estuary and Bay Differences

Analysis of variance (ANOVA) was used to determine if there were differences among estuaries, bays, and sampling dates. A partially hierarchical analysis design was used because bays are unique to estuaries, i.e., bays are nested within estuaries. Also, each station is unique to each bay within an estuary. Sampling dates are a fixed effect variable. Thus, the ANOVA model is a two-way, partially hierarchical design that can be described by the following formula: $Y_{ijkl} = \mu + \alpha_j + \beta_k + \beta\gamma_{k(l)} + \beta\gamma\delta_{k(lm)} + \alpha\beta\gamma\delta_{jk(l)} + e_{(i)jklm}$ where Y_{ijklm} is the dependent response variable; μ is the overall sample mean; α_j is the main fixed effect for sampling dates where *j*=1, 2, 3, …, 133 for each quarter; β_k is the main fixed effect for estuary where *k*=1, 2, or 3 for Lavaca-Colorado Estuary, Guadalupe Estuary, or Nueces Estuary; $\beta\gamma_{k(l)}$ is the main effect for bays that are nested (or unique) within each estuary and are thus a random effect as denoted by the parentheses around the subscript *l* that represents the 7 bays (Lavaca Bay, Matagorda Bay, East Matagorda Bay, Upper San Antonio Bay, Lower San Antonio Bay, Nueces Bay, and Corpus Christi Bay); $\beta\gamma\delta_{k(lm)}$ is the main effect for stations that are nested with bays; and $\alpha\beta\gamma\delta_{jk(lm)}$ is the interaction term for date, estuary, bay, and station; and $e_{(i)jkl}$ is the random error term for each of the *i* replicate measurements. Complex, quasi F-tests were calculated for each source of variation that was a random effect, such as bays, stations, and the interaction term. For water quality, there were no replicates per stations, so the interaction term is deleted, so that the model is not over-specified.

6.5.4 Community Structure

Community structure of macrofauna species was analyzed by non-metric multidmensional scaling (nMDS) and cluster analysis using a Bray-Curtis similarity matrix (Clarke 1993, Clarke and Warwick 2001). Prior to analysis, the data was square root transformed. Transformations improve the performance of the analysis by decreasing the weight of the dominant species. The nMDS was used to compare numbers of individuals of each species for each station-date combination. The distance between station-date combinations can be related to community similarities or differences between different stations. Cluster analysis determines how much each station-date combination resembles each other based on species abundances. The percent resemblance can then be displayed on the nMDS plot to elucidate grouping of station-date combinations. The group average cluster mode was used for the cluster analysis to identify different groups.

Multivariate analyses were used to analyze how the physical-chemical environment changes over time. The physical-chemical water column characteristics were analyzed using Principal Component Analysis (PCA). PCA reduces multiple environmental variables into a smaller set of uncorrelated variables that explain much of the variation in the original data. The new variables are component loads, which describe the variance of the underlying structure in a data set (Clarke and Warwick 2001). Components are extracted in order of importance based on the eigenvalue, or weight, of each factor on the overall model, and factors with eigenvalues greater than 1 are usually considered. Data was normalized to a mean of zero and standard deviation of one prior to PCA. A nMDS was also performed on water quality variables, using a normalization transformation and Euclidean distances to create the resemblance matrix.

6.5.5 Time Series Analysis

Time series, autocorrelation, and confounding factors identification: The fundamental assumption when using long-term data is that changes over time in the drivers (which is freshwater inflow rates here) are affecting the response variables (which are the biological indicators here). However, there are several aspects of time series data that must be addressed because change of the response variables from one time step to the next is dependent on the preceding environmental conditions and community state. Thus, autocorrelation is a key factor in time series data. Additionally, biological responses are not necessarily instantaneous, and there are usually lags in response to change because of the life cycles and growth rates of the organisms effected.

An exponential smoothing model (ESM) was used to create a forecast of benthic data after Hurricane Harvey. ESM is especially useful for fitting non-stationary time series. The ESM model is based on the premise that weighted averages of past values can produce good forecasts of the future, the weights should emphasize the most recent data, and the forecast should require only a few parameters. The software package PROC ESM was used in SAS (2017) software.

For this study, benthic abundance, biomass, and species richness was averaged for all replicates in upper San Antonio Bay (i.e., stations A and B) and lower San Antonio Bay (i.e., stations C and D) for each quarter, to create two values for the whole bay for each quarter. Two values were necessary because the upper bay has more river influence than the lower bay. The data set was with optimized smoothing weights for seasonal adjustments, i.e., seasonal exponential smoothing. Parameters associated with the forecasting model are optimized by PROC ESM based on the data. There is a data gap from 2000 to 2004 for the Guadalupe Estuary, therefore, all the continuous data from January 2004 to July 2017 was used to create the model, and then responses for October 2017 through July 2019 were extrapolated as forecasts. The actual data were plotted against the forecast values to compare the observed versus predicted response.

6.5.6 Linking Inflow Events and Communities

Community structure is linked with environmental variables using the non-metric multivariate BIO-ENV and RELATE procedures calculated with PRIMER software (Clarke and Gorley 2015). The BIO-ENV procedure calculates weighted Spearman rank correlations (ρw) between sample ordinations from all of the environmental variables and an ordination of biotic variables. Correlations are then compared to determine the best match. The null hypothesis of no agreement in the multivariate patterns was tested using the rho (ρ) statistic.

Linkage between biotic response and water column conditions was also examined with correlation analysis using the Spearman rank correlation method.

7 Results

Inflow drives water column conditions and benthos respond to those conditions, so data is presented in that order.

7.1 Freshwater Inflow

Inflow into the Lavaca-Colorado Estuary ranged from 4,903 to 3,907,579 ac-ft/mo, while the Guadalupe Estuary ranged from 17,853 to 2,534,016 ac-ft/mo, and Nueces Estuary ranged from 6,403 to 972,805 ac-ft/ mo (Figure 4). Mean inflow rates were 350,832 ac-ft/mo for Lavaca-Colorado Estuary, 222,792 ac-ft/mo for Guadalupe Estuary, and 98,425 ac-ft/mo for Nueces Estuary.

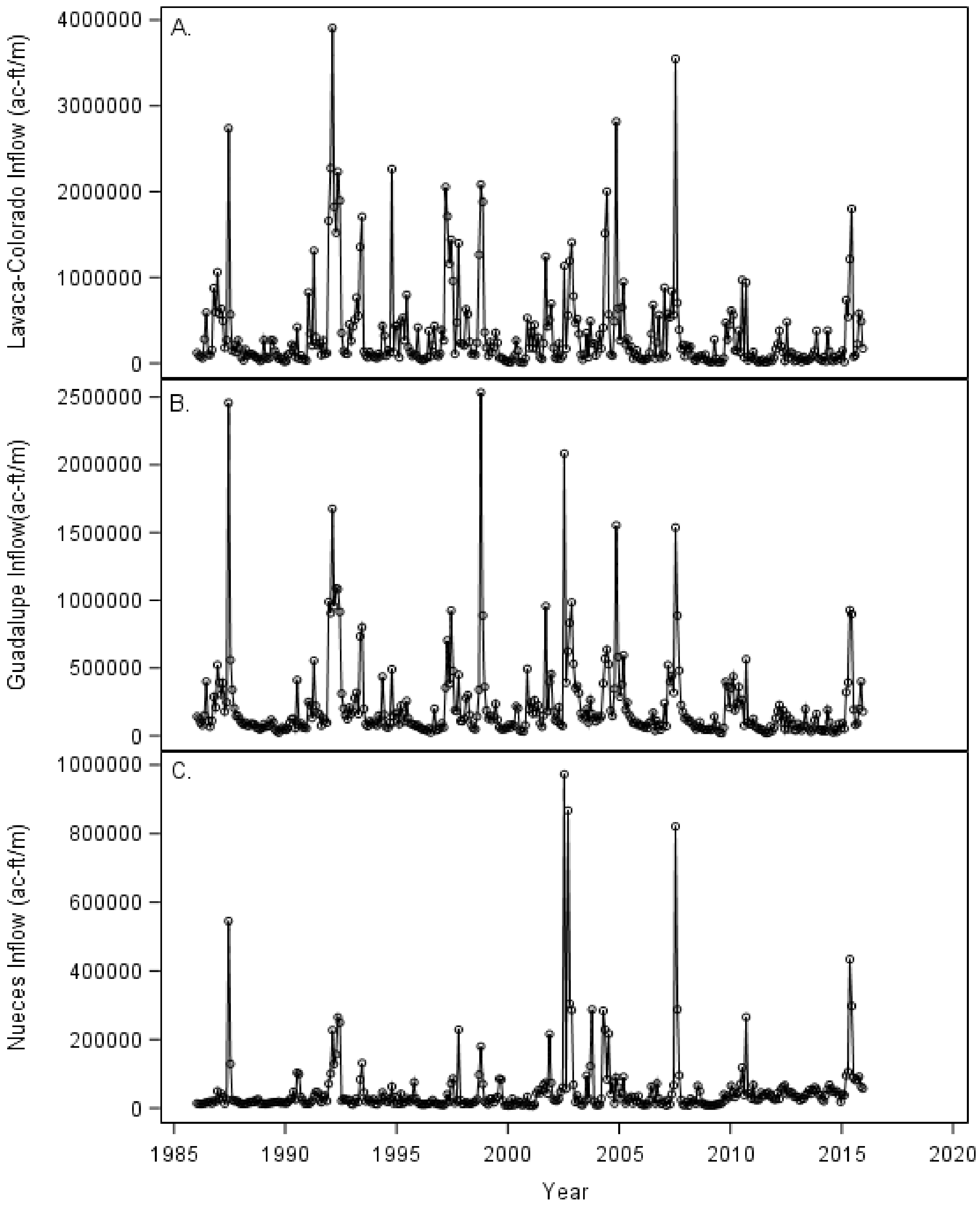


Figure 4. Average monthly gauged inflow within estuaries. Each point represents a monthly average inflow estuary-wide.

The two more northern estuaries, Lavaca-Colorado and Guadalupe have highest average inflows in June, compare to the Nueces Estuary, which has the highest average inflow in July (Figure 5). All of the estuaries have the lowest average monthly inflow in August.

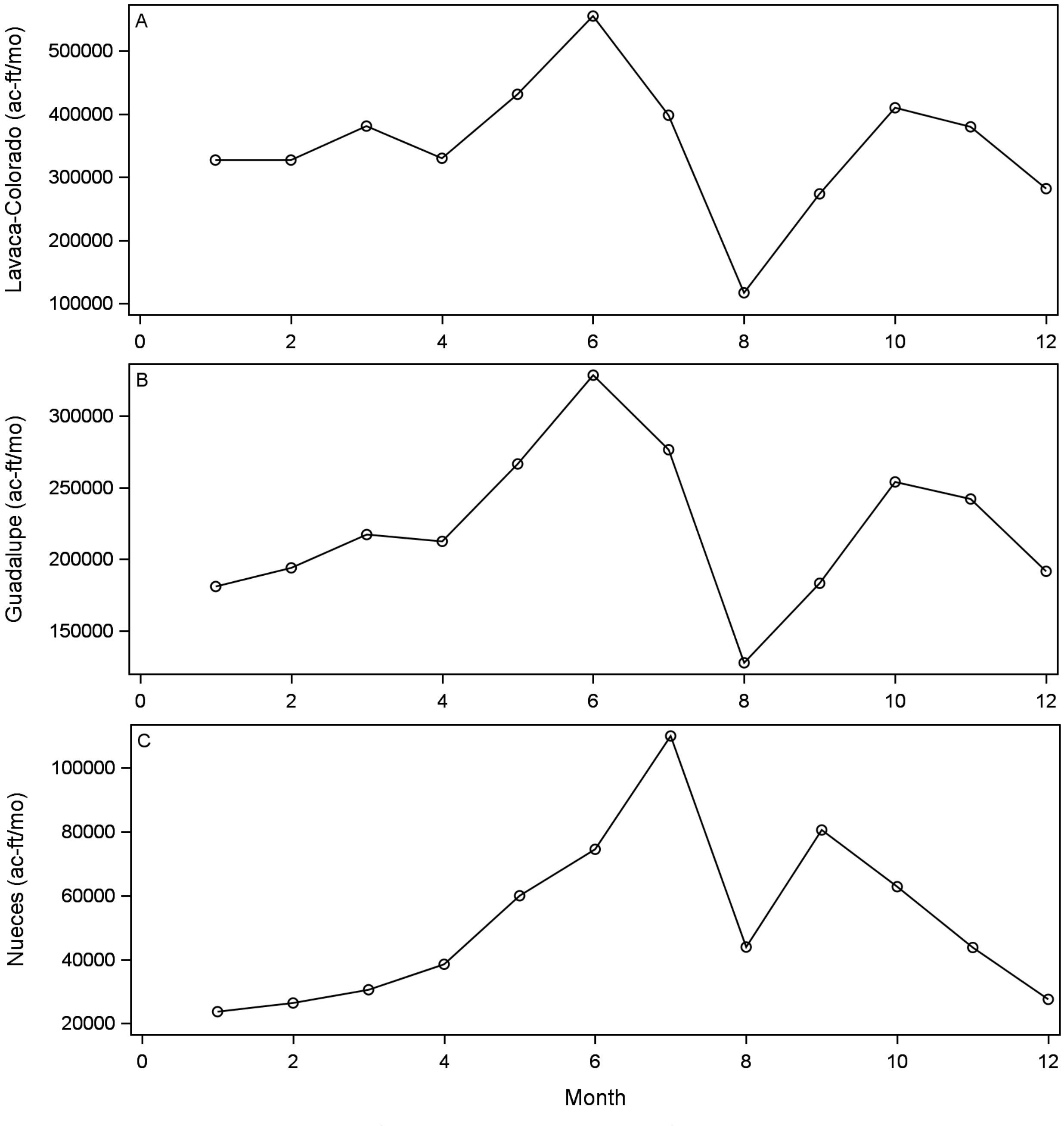


Figure 5. Average monthly inflow in three estuaries from January 1986 to December 2015. A) Lavaca-Colorado. B) Guadalupe. C) Nueces.

7.2 Water Quality Conditions

An ANOVA of hydrographic metrics of dissolved oxygen, salinity, temperature, pH, NH4, PO4, SiO4, and NOx were different by date (P-Value = <0.0001), and bay (Table 3). There was no difference across estuaries.

Table 3. ANOVA results for water column metrics. A) Dissolved oxygen (DO), salinity (Sal), temperature (Temp), pH. B) ammonioum (NH4), nitrite + nitrate (NOx), phosphate (PO4), silicate (SiO4). Abbreviations: N = row number, DF = degrees of freedom.

A)

				P-Value			
N	**F-Test**	**Source**	**DF**	**DO**	**Sal**	**Temp**	**pH**
1	1/5	Date	123	<0.0001	<0.0001	<0.0001	<0.0001
2	2/(3+4)	Est	2	0.1222	0.0561	0.7411	0.1390
3	3/4	Bay(Est)	4	0.0005	0.0003	0.0617	0.0064
4	4/5	Sta(Est*Bay)	11	<0.0001	<0.0001	0.0097	0.0313
5	5/5	Error	1633				

B)

N	**F-Test**	**Source**	**DF**	**NH4**	**NOx**	**PO4**	**SiO4**
1	1/5	Date	123	<0.0001	<0.0001	<0.0001	<0.0001
2	2/(3+4)	Est	2	0.4078	0.3678	0.4005	0.3828
3	3/4	Bay(Est)	4	0.0009	0.0238	0.0022	0.0002
4	4/5	Sta(Est*Bay)	11	0.2144	<0.0001	0.0032	<0.0001
5	5/5	Error	1565				

As mentioned above, dissolved oxygen concentration is lowest at station D in the Nueces estuary (Table 4). Salinity increases from the rivers (A and B) to the Gulf of Mexico (C and D) in all estuaries. In Matagorda Bay, station F is closest to the Colorado River, and E is in between D and F. All nutrient concentrations decrease from near rivers to the sea. San Antonio Bay is different from the other two estuaries in that it has nitrate plus nitrite (NOx) concentrations that are six times higher than Lavaca and 20 times higher than Nueces.

Table 4. Water column constituent concentration (μmol l^{-1}) average and standard error by stations within estuaries. A) Physical attributes. B) Nutrients.

A)				Temperature		DO		Salinity		pH	
Est	**Bay**	**Sta**	**N**	**Mean**	**StdErr**	**Mean**	**StdErr**	**Mean**	**StdErr**	**Mean**	**StdErr**
LC	LB	A	116	22.12	0.63	8.07	0.14	15.90	0.92	8.12	0.06
LC	LB	FD	34	23.98	0.99	8.12	0.22	16.16	2.03	8.06	0.05
LC	LB	B	116	22.01	0.64	7.89	0.14	18.79	0.84	8.12	0.04
LC	MB	C	116	21.94	0.63	7.51	0.13	24.35	0.63	8.08	0.04
LC	MB	D	117	21.99	0.59	7.31	0.13	27.96	0.42	8.12	0.03
LC	MB	E	85	22.40	0.71	7.39	0.17	25.53	0.62	8.15	0.04
LC	MB	8	38	22.38	1.09	7.68	0.24	26.31	1.03	8.22	0.02
LC	EM	F	85	22.71	0.69	8.13	0.22	20.92	0.92	8.24	0.04
LC	EM	15	37	22.84	1.06	8.67	0.33	21.89	1.57	8.24	0.03
GE	US	A	116	22.79	0.60	8.86	0.23	9.34	0.75	8.33	0.04
GE	US	B	116	22.53	0.60	8.55	0.23	13.76	0.80	8.31	0.04
GE	LS	C	116	22.45	0.61	8.18	0.17	18.42	0.87	8.24	0.03
GE	LS	D	116	22.45	0.60	8.05	0.16	19.11	0.87	8.16	0.03
NC	NB	A	123	22.72	0.58	7.56	0.13	25.66	0.94	8.13	0.03
NC	NB	B	123	22.87	0.59	7.49	0.13	29.40	0.69	8.13	0.03
NC	CC	C	124	22.57	0.58	7.14	0.12	31.42	0.43	8.13	0.02
NC	CC	D	123	22.29	0.58	6.65	0.17	32.81	0.46	8.15	0.02
NC	CC	E	115	22.57	0.61	7.06	0.13	31.77	0.43	8.10	0.01

B)				NH4		NOx		PO4		SiO4	
Est	**Bay**	**Sta**	**N**	**Mean**	**StdErr**	**Mean**	**StdErr**	**Mean**	**StdErr**	**Mean**	**StdErr**
LC	LB	A	115	2.223	0.257	5.08	0.997	1.596	0.132	101.956	6.309
LC	LB	FD	51	2.502	0.537	8.614	1.97	2.735	0.387	98.905	7.68
LC	LB	B	115	3.022	0.86	4.456	0.984	2.231	0.944	86.208	5.879
LC	MB	C	115	1.497	0.15	1.624	0.393	0.78	0.066	54.677	4.081
LC	MB	D	115	1.536	0.176	1.037	0.175	0.714	0.058	38.148	2.862
LC	MB	E	93	1.665	0.225	1.431	0.281	0.992	0.091	45.576	4.042
LC	MB	8	46	1.263	0.319	2.172	0.63	0.925	0.129	38.918	5.204
LC	EM	F	93	3.231	0.516	7.714	1.523	1.761	0.182	61.497	4.792
LC	EM	15	46	3.149	0.722	13.051	3.203	2.158	0.224	54.369	5.485
GE	US	A	111	3.049	0.349	31.757	3.985	3.502	0.303	151.113	12.606
GE	US	B	111	2	0.23	10.818	1.447	2.387	0.238	127.713	10.564
GE	LS	C	110	1.663	0.225	4.817	1.108	1.814	0.179	102.644	7.597
GE	LS	D	110	1.624	0.207	3.908	0.762	1.641	0.169	94.262	6.094
NC	NB	A	122	2.407	0.303	2.335	0.326	2.08	0.12	123.98	6.884
NC	NB	B	122	1.728	0.231	1.748	0.279	1.309	0.092	84.301	5.522
NC	CC	C	122	1.332	0.227	0.785	0.112	0.63	0.06	49.587	3.573
NC	CC	D	122	1.539	0.212	0.869	0.17	0.545	0.066	46.214	3.336
NC	CC	E	116	1.035	0.105	0.512	0.076	0.48	0.056	43.441	3.446

Estuary condition is defined by the relationship between freshwater inflow and water quality variables. Condition is commonly identified by multivariate analysis to classify stations. Principal Components (PC) analysis was performed on the water quality data obtained during sampling. The first axis (PC1) explained 30% of the variance in the data set and was represented by high nutrient and chlorophyll concentrations correlated to low salinities (Figure 6A). Thus, PC1 is the new variable representing freshwater inflow and estuary condition effects. The second axis (PC2) explained 22% of the variability and is represented by high values of dissolved oxygen (DO) correlated to low temperatures (Figure 6B). Thus, PC2 is the new variable that is related to seasonal effects. The third axis (PC3) explained 13% of the variability and is represented by high chlorophyll and pH values vs. low NH4 values. Thus, PC3 represents a metabolism variable because when high amounts of chlorophyll are present, photosynthesis is high and production of oxygen is high. In contrast, ammonium is present under reducing, or anaerobic, conditions.

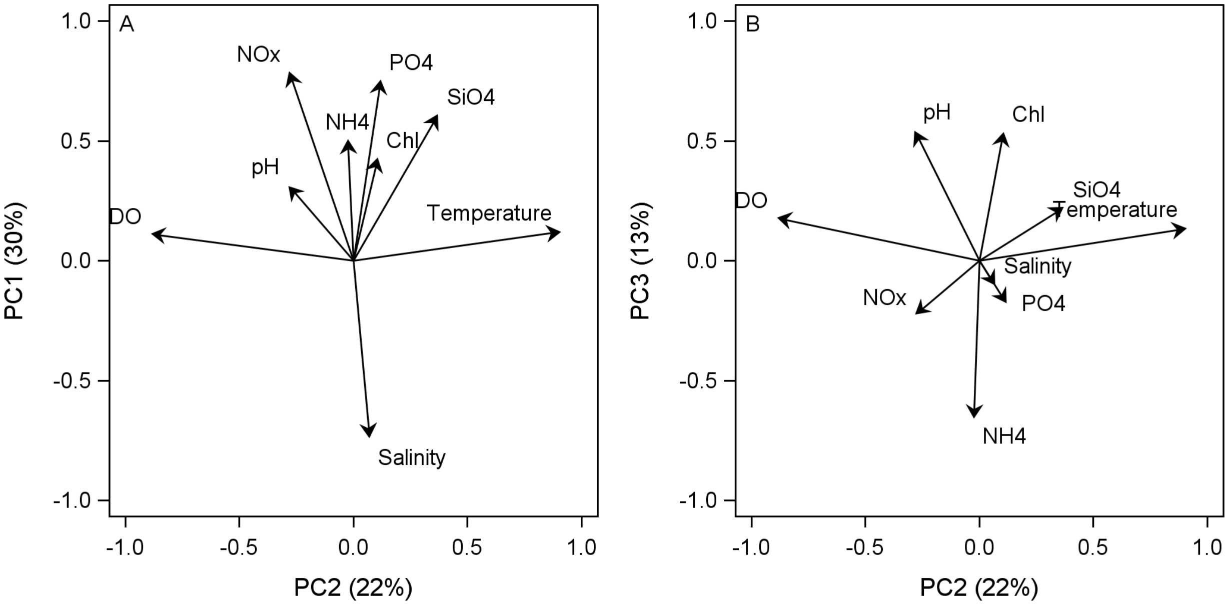


Figure 6. Principal Components (PC) Analysis of estuary condition indicators. A) PC1 versus PV2. B) PC2 versus PC3.

The new PC axes for freshwater inflow (i.e., PC1) and seasons (i.e., PC2) allow samples to be classified (Figure 7). When samples are plotted according to the season collected, there is scatter along the entire freshwater inflow axis (PC1), meaning different inflow scenarios can happen at any time during the year. However, winter samples cluster on the left of the seasonal axis (PC2) and summer and fall samples cluster on the right of the axis because negative PC2 values represent cold temperatures and positive PC2 values represent warm temperatures. When estuaries are used as symbols for samples, the samples from the Guadalupe Estuary (GE) cluster on the top of PC1, and Nueces Estuary (NC) cluster on the bottom of the axis because inflow has greater effects (i.e., larger volumes of freshwater) in GE than in NC.

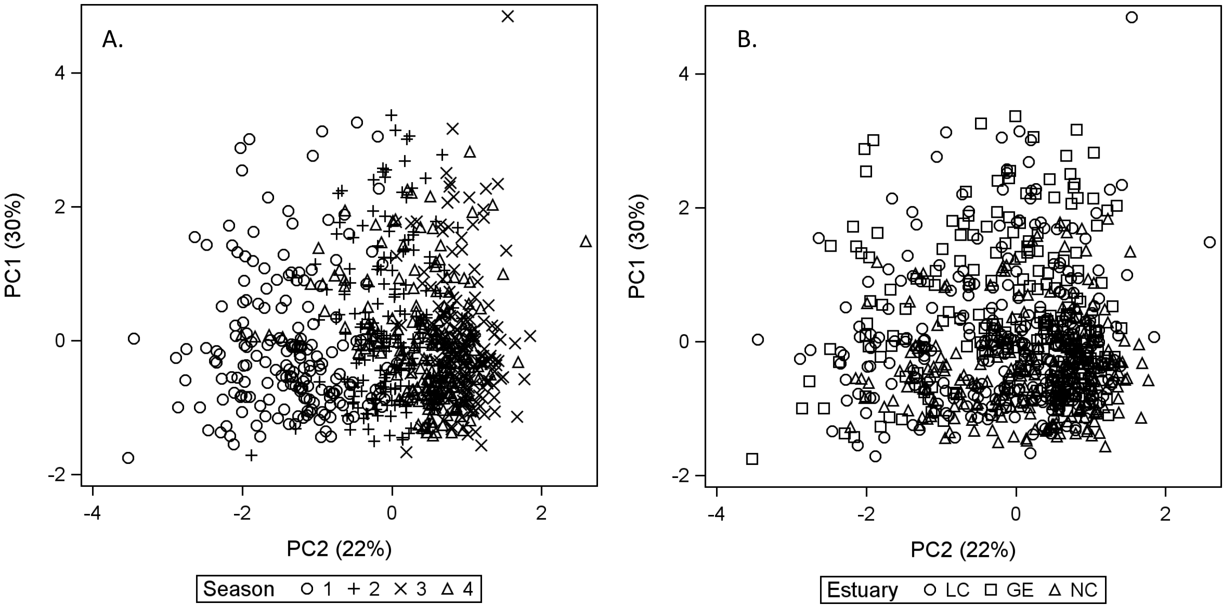


Figure 7. Principal component sample scores for estuary conditions. A) Seasons (1 = winter, 2 = spring, 3 = summer, and 4 = fall) as markers. B) Estuaries as markers.

7.3 Macrofauna Response

When averages across bays were compared, the highest abundances and biomass were found in Upper San Antonio and the lowest values were found in Lavaca Bay (Table 5). The highest diversity was found in Corpus Christi Bay with the lowest values in Lavaca Bay (Table 5). The highest evenness was found in Corpus Christi Bay and the lowest value was found in Upper San Antonio Bay (Table 5). Therefore, Lavaca Bay contained the lowest values for all macrofauna community metrics. With regard to hydrographic variables the highest values for dissolved oxygen and pH were found in Upper San Antonio Bay and the lowest salinity value. (Table 5). Lavaca Bay had the lowest pH and highest NH4. Nueces Bay had the lowest Chlorophyll, NH4, NOx, PO4, and SiO4. East Matagorda Bay had the highest Chlorophyll, NOx, PO4, and SiO4.

Table 5. Averages for all macroinfauna and hydrographic variables sampled quarterly in each estuary from 1987-2019. Matagorda Bay, Lower San Antonio Bay, and Corpus Christi Bay are the primary bays. Lavaca Bay, East Matagorda Bay, Upper San Antonio, and Nueces Bay are the secondary Bays.

	Estuary and Bay						
	Lavaca			**Guadalupe**		**Nueces**	
Variable	**Lavaca**	**Mata-gorda**	**East Mata-gorda**	**Upper San Antonio**	**Lower San Antonio**	**Nueces**	**Corpus Christi**
Abundance (n m^{-2})	5,495	9,865	9,633	19,119	9,585	11,435	15,914
Biomass (g m^{-2})	1.47	4.61	3.76	11.92	5.96	8.37	9.61
Richness (S 35 cm $^{-2}$)	4.46	8.90	7.34	5.66	6.60	9.72	15.05
Diversity (H´ 35 cm $^{-2}$)	0.95	1.56	1.37	1.02	1.15	1.59	2.03
Diversity (N1 35 cm $^{-2}$)	2.94	5.40	4.43	2.99	3.76	6.07	9.12
Evenness (J´ 35 cm $^{-2}$)	0.66	0.77	0.74	0.63	0.66	0.76	0.78
Temperature (°C)	22.70	22.11	22.64	22.66	22.45	22.80	22.48
Salinity	16.95	25.95	23.04	11.55	18.76	27.53	32.00
DO (mg l^{-1})	8.02	7.40	8.16	8.70	8.12	7.52	6.95
pH	8.10	8.11	8.23	8.32	8.20	8.13	8.12
Chlorophyll a (ug $^{-1}$)	7.90	8.70	16.58	9.92	7.55	5.44	7.90
NH4 (μmol l $^{-1}$)	2.58	2.06	2.52	1.64	2.07	1.30	2.58
NOx (μmol l $^{-1}$)	6.05	4.51	21.29	4.36	2.04	0.72	6.05
PO4 (μmol l $^{-1}$)	2.19	1.22	2.95	1.73	1.69	0.55	2.19
SiO4 (μmol l $^{-1}$)	95.69	48.86	139.41	98.45	104.14	46.41	95.69
N:P ratio	3.9	5.4	8.1	3.5	2.4	3.7	3.9

Although 462 species were found, only the 14 most abundant species all had at least 1% of the total abundance (Table 6). The most abundant species was *Mediomastus ambiseta*, which accounted for 37.0% of total species abundance. *Mediomastus ambiseta* was most abundant in Upper San Antonio Bay and least abundant in Lavaca Bay. *Streblospio benedicti* was the second most abundant species which accounted for 11.1% of total species abundance. *Streblospio benedicti* was most abundant in Upper San Antonio Bay and least abundant in Matagorda Bay. Both species are polychaete worms, but the third most abundant species at 6.4% was *Mulinia lateralis*, a bivalve mollusk.

Table 6. Average infauna species abundance (n m^{-2}) measured in each bay over all samples collected from 1987-2019. Abbreviation: Cum%= cumulative percent.

Rank	**Taxa Name**	**Lavaca Bay**	**Matagorda Bay**	**East Matagorda Bay**	**Upper San Antonio Bay**	**Lower San Antonio Bay**	**Nueces Bay**	**Corpus Christi Bay**	**Mean**	**%**	**Cum%**
1	*Mediomastus ambiseta*	2,796	2,903	5,760	7,363	4,857	3,514	3,271	4,352	37.0%	37%
2	*Streblospio benedicti*	740	224	806	4,869	922	1,041	533	1,305	11.1%	48%
3	*Mulinia lateralis*	671	314	610	1,895	648	989	101	747	6.4%	54%
4	*Dipolydora caulleryi*	1	442	603	1	207	436	2,128	545	4.6%	59%
5	*Texadina sphinctostoma*	76	-	-	2,810	239	-	-	446	3.8%	63%
6	*Tharyx setigera*	4	66	228	-	16	476	1,692	355	3.0%	66%
7	Oligochaeta (unidentified)	37	422	118	234	11	10	639	210	1.8%	68%
8	*Phoronis architecta*	4	24	1,098	-	31	187	99	206	1.8%	69%
9	Nemertea (unidentified)	71	229	205	174	167	131	335	187	1.6%	71%
10	*Cossura delta*	141	482	206	53	68	70	194	173	1.5%	73%
11	*Spiochaetopterus costarum*	5	208	530	14	272	25	77	161	1.4%	74%
12	*Clymenella torquate*	7	25	28	0	73	496	380	144	1.2%	75%
13	*Ampelisca abdita*	163	22	184	251	29	264	36	135	1.2%	76%
14	*Gyptis brevipalpa*	12	148	95	13	52	239	333	128	1.1%	77%
14	Subtotal dominant species	4,728	5,509	10,471	17,677	7,593	7,877	9,817	9,096		77%
448	Subtotal other Species	766	3,020	1,712	1,441	1,990	3,559	6,126	2,659		23%
462	Total	5,495	8,529	12,183	19,118	9,583	11,436	15,943	11,755		100%

The non-metric multidimensional scaling (nMDS) analysis of macrofauna community structure found three different statistical groupings of bays (Figure 8). The first group contains Lower San Antonio (LS), East Matagorda (EM), and Lavaca Bays (LB). This group also clustered with Upper San Antonio Bay (US) at the 50% similarity level. The second group contains Nueces (NB) and Corpus Christi Bays (CC). This group also clustered with Matagorda Bay (MB) at the 50% similarity level. The bay groupings were correlated with salinity. From left to right bay salinities (psu) are: CC = 32, NB = 28, and MB =26; and in contrast, EM = 23, LS = 19, LB = 17, and US =12 (Table 5). Bays with similar salinity group most closely together indicating salinity is driving community structure.

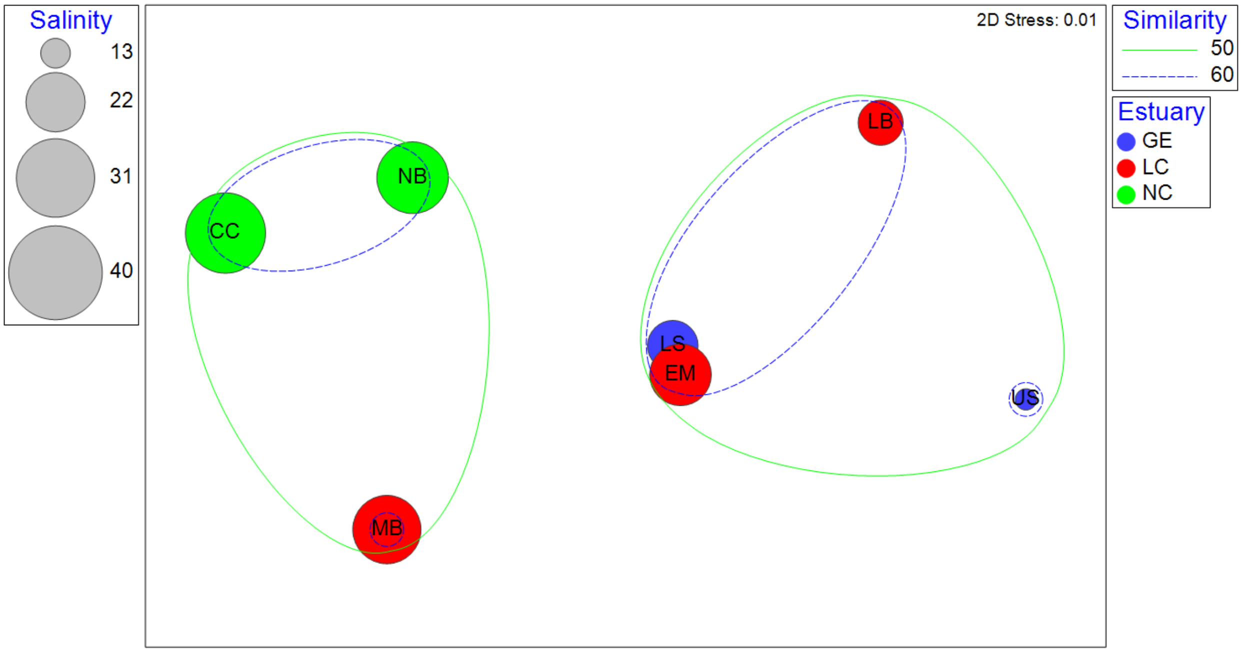


Figure 8. nMDS Plot of community structure by estuary and bay. The size of each symbol is representative of salinity (psu) of a bay, and color represents an estuary. Bay symbol abbreviations: CC = Corpus Christ, EM = East Matagorda, LB = Lavaca Bay, LS = lower San Antonio, MB = Matagorda Bay, NB = Nueces Ba y, US = Upper San Antonio.

An ANOVA of macrofauna metrics of abundance, biomass, diversity, and evenness were statistically different by date (P-Value = < 0.0001), station (P-Value = < 0.0001), and the station*date*bay interaction (P-Value = < 0.0001) (Table 7). There were no differences across estuaries or bays. The differences by date are expected and dealt with in the time-series analysis section below.

Table 7. ANOVA results for macrofauna total abundance (n/m^2), biomass (g/m^2), diversity (Hill N1), and evenness (Pielou J´). n = row number, F-test = row number as numerator and denominator, DF = degrees of freedom.

				P-Value			
n	**F-Test**	**Source**	**DF**	**Abundance**	**Biomass**	**N1**	**J´**
1	1/5	Date	135	<.0001	<0.0001	<.0001	<0.0001
2	2/(3+4-5)	Estuary	2	0.3475	0.1499	0.0590	0.1816
3	3/(4+5)	Bay(Est)	4	0.1032	0.2946	0.3818	0.1123
4	4/5	Sta(Est*Bay)	11	<.0001	<.0001	<.0001	<.0001
5	5/6	Date*Sta(Est Bay)	1663	<.0001	<.0001	<.0001	<.0001
6		Error	5446				

Patterns of benthic metrics among stations are different in different estuaries (Table 8). In the Lavaca-Colorado estuary, abundance biomass and diversity increase from the rivers (stations A, B, E, and F) to the Gulf of Mexico (stations C and D). In the Guadalupe Estuary, abundance and biomass decrease from near the river (A and B) toward the Gulf of Mexico (stations C and D). In the Nueces Estuary, abundance biomass and diversity increase from the rivers (stations A, B) to the Gulf of Mexico (stations C and E). In Nueces, station D, metrics are lower because of hypoxia, which occurs every summer.

Table 8. Benthic metrics (average and standard error) by stations. Abbreviations: Est = estuary, Sta = station, Freq = frequency.

Est	Bay	Sta	Freq	Abundance ($n\ m^{-2}$)		Biomass ($g\ m^{-2}$)		Diversity (N1/sample)	
				Mean	**StdErr**	**Mean**	**StdErr**	**Mean**	**StdErr**
LC	LB	A	348	6,281	294	1.43	0.11	3.03	0.09
LC	LB	FD	102	5,247	603	1.78	0.30	2.72	0.19
LC	LB	B	348	4,956	203	1.21	0.08	3.05	0.08
LC	MB	C	348	8,785	382	4.70	0.32	5.91	0.16
LC	MB	D	351	13,315	855	5.79	0.42	5.72	0.16
LC	MB	E	255	7,495	500	3.33	0.48	4.58	0.13
LC	MB	8	114	4,533	439	1.76	0.14	4.87	0.17
LC	EM	F	255	8,669	476	2.79	0.21	4.37	0.15
LC	EM	15	111	15,697	907	6.73	0.70	4.05	0.19
GE	US	A	348	21,873	1,002	20.52	1.48	3.29	0.06
GE	US	B	348	16,364	1,162	3.33	0.22	2.68	0.05
GE	LS	C	348	8,573	520	2.49	0.20	2.87	0.07
GE	LS	D	348	10,596	522	9.43	1.57	4.65	0.17
NC	NB	A	369	8,843	343	4.39	0.33	3.87	0.12
NC	NB	B	369	14,027	618	12.36	0.61	8.28	0.21
NC	CC	C	375	11,924	357	10.17	0.40	9.71	0.2
NC	CC	D	369	12,705	897	3.55	0.25	4.96	0.16
NC	CC	E	341	23,142	624	15.23	0.51	12.72	0.19

7.4 Time Series Analysis

7.4.1 Physical Setting

Water temperature increased over the course of the study in each estuary and had a seasonal signal. Warmer temperatures occurred in summer months and cooler temperatures occurred in winter months (Figure 9). Average temperature of each bay over the course of the study, was similar ranging from 22 °C in Lavaca Bay to 23 ˚C in Nueces Bay.

Warming occurred over the study period. The increase in temperature was at a rate of 0.065 °C per year in the Lavaca-Colorado Estuary ($p = 0.0229$). The increase in temperature was at a rate of 0.073 °C per year in the Guadalupe Estuary ($p = 0.0121$). Although not significant ($p = 0.1441$), the increase temperature was at a rate of 0.043 °C per year in the Nueces Estuary. The statistics reported here are based on quarterly samples with missing quarters. The Texas Parks and Wildlife Department (TWPD) data are monthly, without missing months, and over a longer period (1977 - 2018). The increases in the TPWD data set are: 0.039 °C per year in the Lavaca-Colorado Estuary ($p = 0.0772$), 0.031 °C per year in the Guadalupe Estuary ($p = 0.1538$), and 0.047 °C per year in the Nueces Estuary ($p = 0.0266$) (Hardegree 2018).

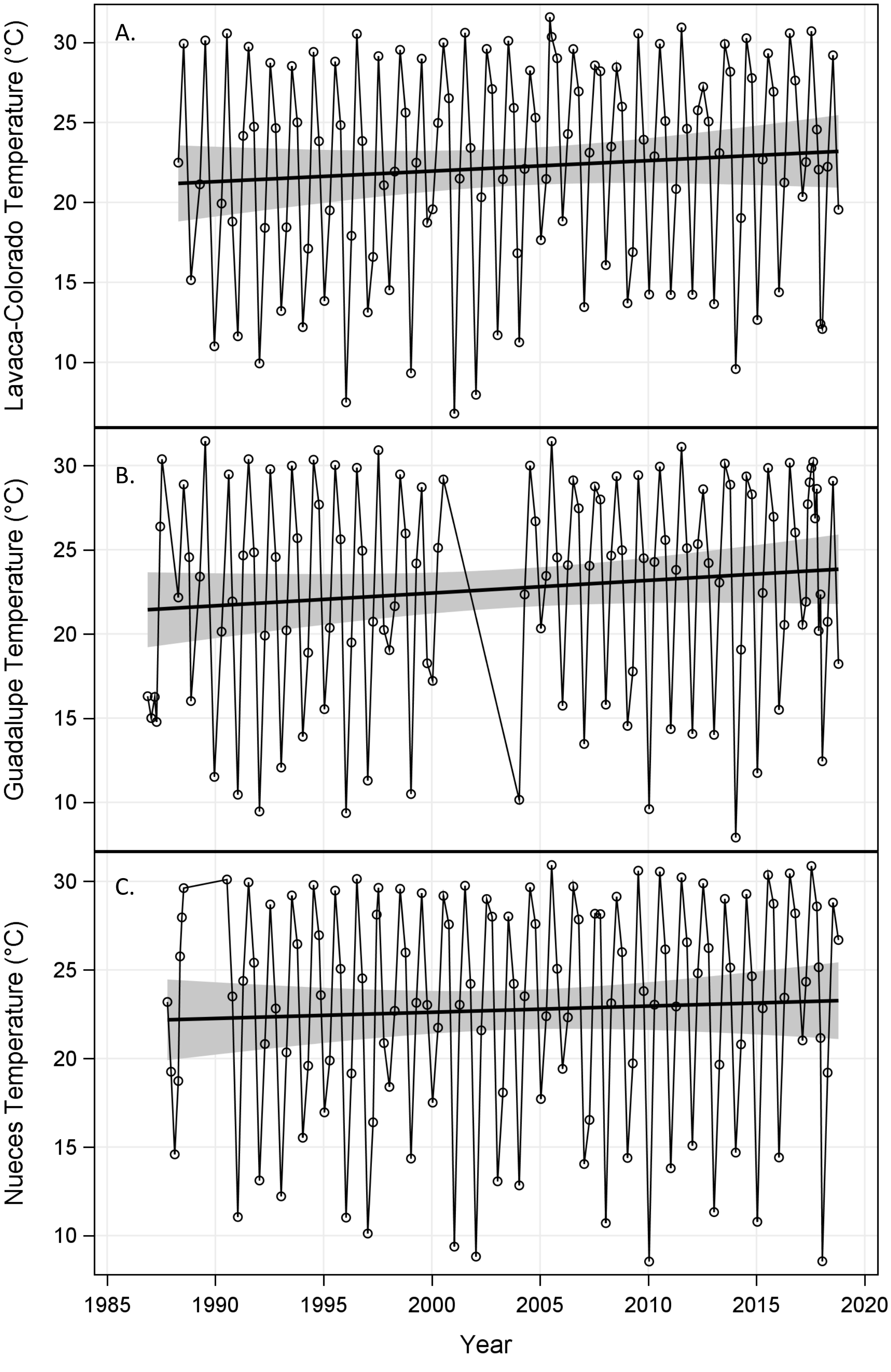


Figure 9. Average monthly temperature estuary-wide, with a linear regression over time and 95% confidence limits. A) Lavaca-Colorado Estuary. B) Guadalupe Estuary. C) Nueces Estuary.

In each estuary, dissolved oxygen decreased over time (Lavaca Colorado r = -0.21 p = 0.0004, Guadalupe Estuary r = -0.18 p = 0.0018, Nueces Estuary r = -0.23 p < 0.0001). Dissolved oxygen showed a strong seasonal signal with a maximum concentration in the winter and a minimum concentration in the summer for each estuary (Figure 10). Average dissolved oxygen concentration over the study period was similar for each bay. Corpus Christi Bay had the lowest average dissolved oxygen concentration 6.85 mg l^{-1} and Upper San Antonio Bay had the highest average dissolved oxygen concentration 8.48 mg l^{-1}. Overall dissolved oxygen concentrations were higher in the secondary bay than the primary bay.

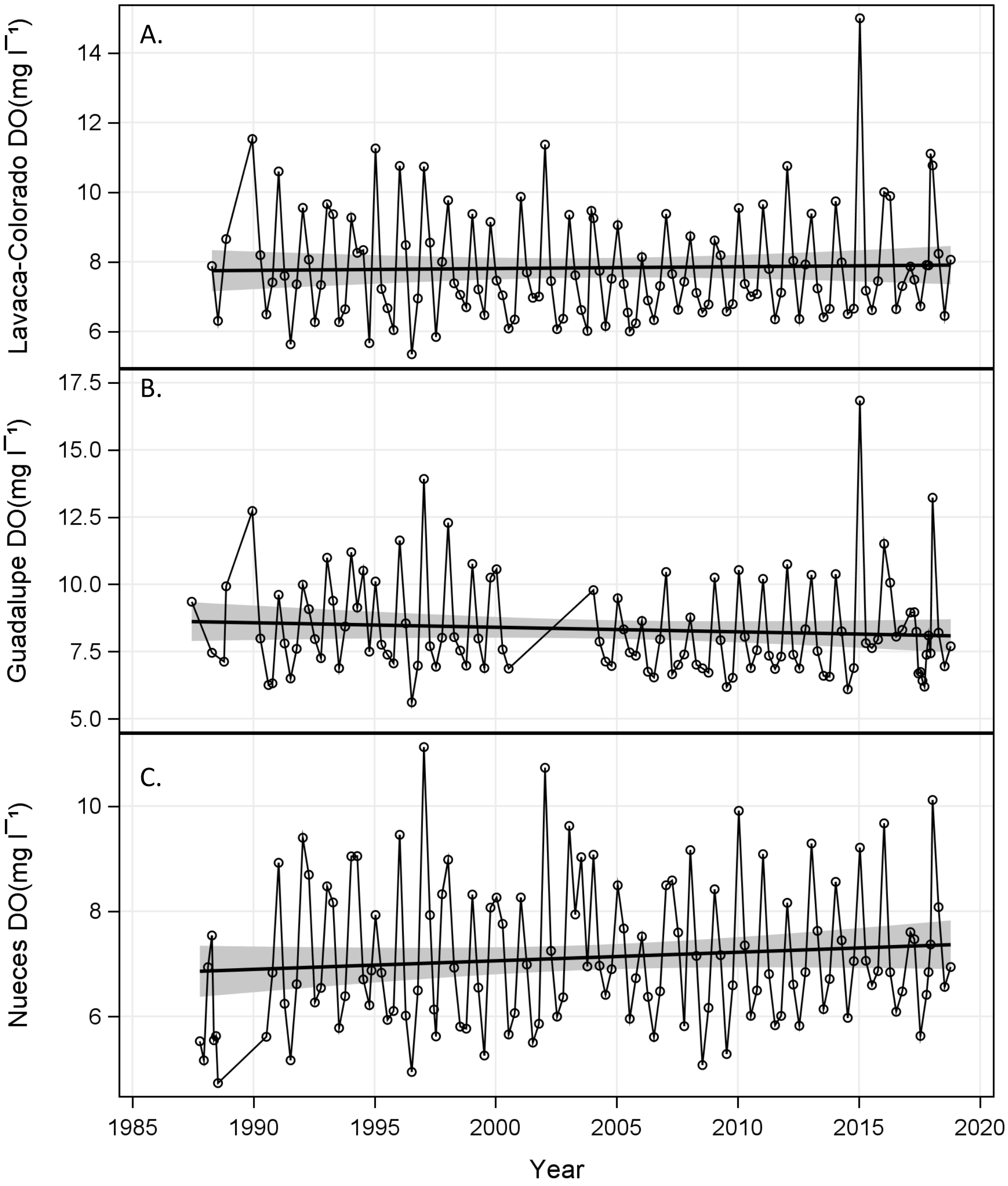


Figure 10. Average monthly dissolved oxygen (DO) concentrations estuary-wide with a linear regression over time and with 95% confidence limits. A) Lavaca-Colorado Estuary. B) Guadalupe Estuary. C) Nueces Estuary.

Salinity slightly increased over the course of the study within each estuary (Figure 11). The increase (in psu/year) was 0.13 (p = 0.0137) for Lavaca-Colorado, 0.20 (p = 0.0018) for Guadalupe, and 0.18 (p = 0.0013) for Nueces. Average salinity of each bay over the course of the study, was different ranging from 15.5 psu in Guadalupe Estuary to 21.3 psu in Lavaca-Colorado to 29.9 psu in Nueces.

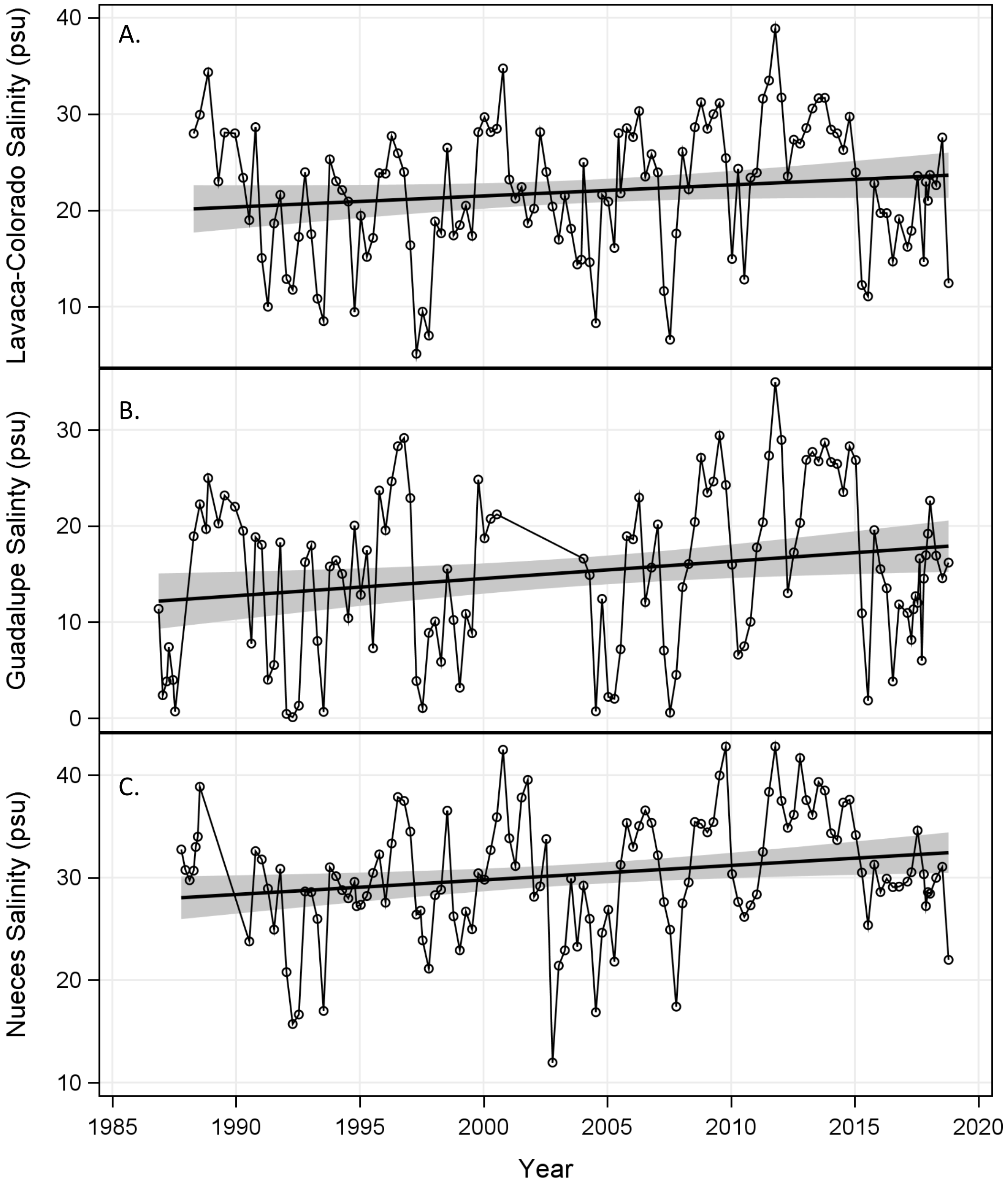


Figure 11. Average monthly salinity (psu) estuary-wide with a linear regression over time and 95% confidence limits. A) Lavaca-Colorado Estuary. B) Guadalupe Estuary. C) Nueces Estuary.

7.4.2 Macrofauna

In general, there were declining trends in benthic abundance across all three estuaries over the 31-year study period. In the Lavaca-Colorado Estuary and the Nueces Estuary, benthic abundance was higher in the primary bay than the secondary bay. In the Guadalupe Estuary, benthic abundance was higher in the secondary bay (Figure 12).

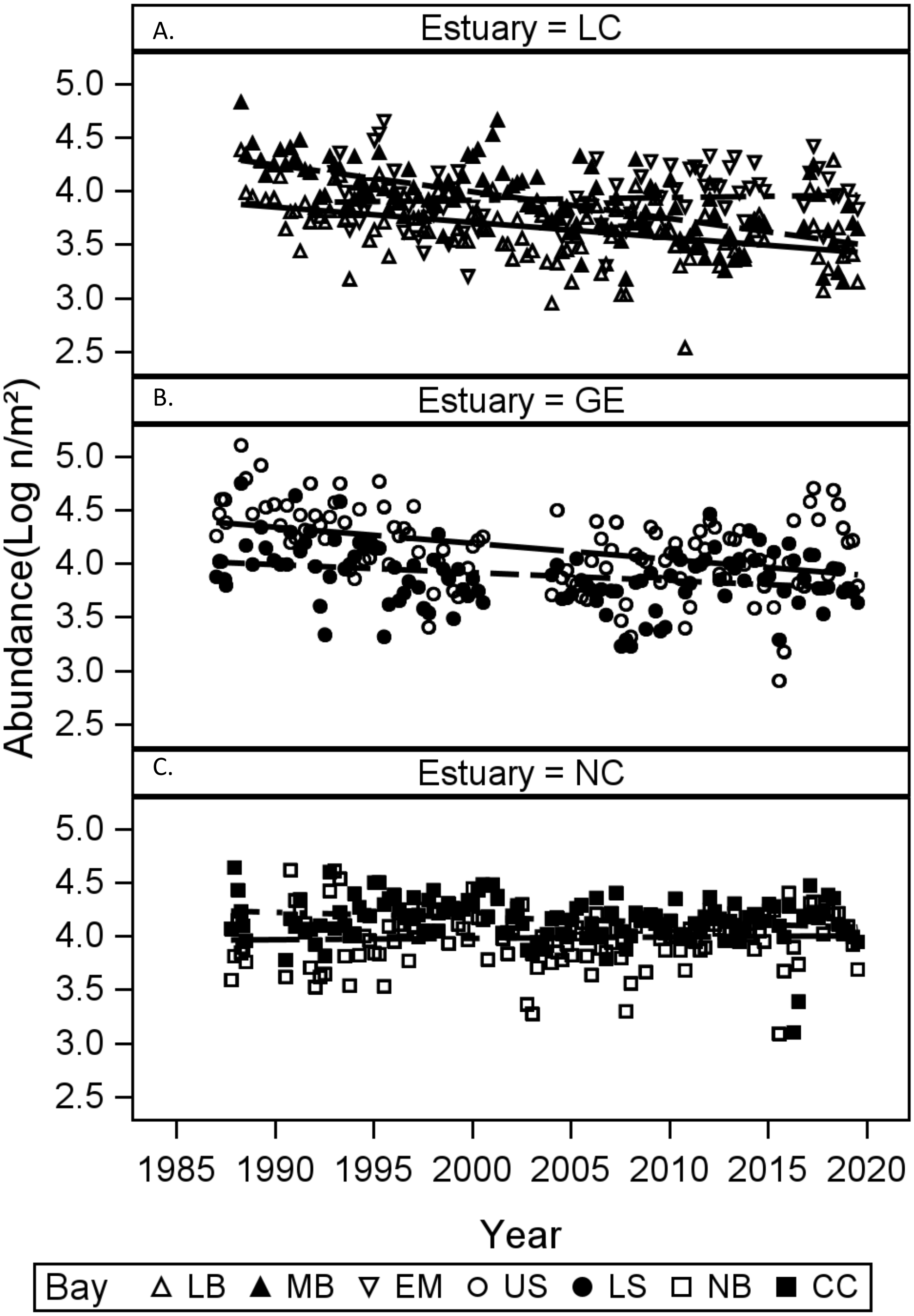


Figure 12. Average quarterly (January, April, July, and October) log10 transformed benthic infauna abundance by bay within estuary. A) Lavaca-Colorado Estuary (LC) includes Lavaca Bay (LB, open triangles), Matagorda Bay (MB, closed triangles), and East Matagorda Bay (EM, open upside-down triangles). B) Guadalupe Estuary (GE) includes Upper San Antonio Bay (US, open circles) and Lower San Antonio Bay (LS filled circles). C) Nueces Estuary (NC) includes Nueces Bay (NB, open squares) and Corpus Christi Bay (CC, filled squares).

The declining trends for abundance were significant for the primary and secondary bays in the Lavaca-Colorado Estuary and Guadalupe Estuary, but not the Nueces Estuary (Table 9).

Table 9. Linear regression for abundance ($\log_{10}$ n + 1), biomass ($\log_{10}$ g +1), diversity (N1) over time by bay.

Metric	**Bay**	**Model**	**R^2**	**P**
Abundance	LB	Y = 4.276 - 0.000039036 * Year	17%	<0.0001
	MB	Y = 4.989 - 0.000068327 * Year	43%	<0.0001
	EM	Y = 3.813 + 0.000006759 * Year	1%	0.5212
	US	Y = 4.788 - 0.000041179 * Year	16%	<0.0001
	LS	Y = 4.211 - 0.000020407 * Year	7%	0.0047
	NB	Y = 3.927 + 0.000003385 * Year	0%	0.6456
	CC	Y = 4.359 - 0.000012710 * Year	4%	0.0238
Biomass	LB	Y = 0.469 - 0.000010011 * Year	2%	0.1036
	MB	Y = 1.585 - 0.000057847 * Year	36%	<0.0001
	EM	Y = 0.597 - 0.000002632 * Year	0%	0.8238
	US	Y = 0.898 + 0.000000007 * Year	0%	0.9995
	LS	Y = 0.485 + 0.000005459 * Year	0%	0.5919
	NB	Y = 0.392 + 0.000028885 * Year	8%	0.0012
	CC	Y = 0.811 + 0.000009909 * Year	3%	0.0783
Diversity	LB	Y = 0.467 - 0.000001361 * Year	0%	0.7799
	MB	Y = 1.157 - 0.000026896 * Year	39%	<0.0001
	EM	Y = 0.527 + 0.000002603 * Year	0%	0.7271
	US	Y = 0.545 - 0.000005238 * Year	3%	0.0662
	LS	Y = 0.529 + 0.000000135 * Year	0%	0.9787
	NB	Y = 0.376 + 0.000022752 * Year	14%	<0.0001
	CC	Y = 0.686 + 0.000015555 * Year	18%	<0.0001

*Abbreviations: LB = Lavaca Bay, MB = Matagorda Bay, US = Upper San Antonio Bay, LS = Lower San Antonio Bay, NB = Nueces Bay, and CC = Corpus Christi Bay. P = probability that the slope equals zero.

Benthic infauna biomass declined in both bays of the Lavaca-Colorado Estuary (Figure 13, Table 9). Biomass was higher in the primary bay. In the Guadalupe Estuary, biomass increased in the primary bay and decreased in the secondary bay. There was no significant trend over time for biomass in either Nueces or Corpus Christi Bays.

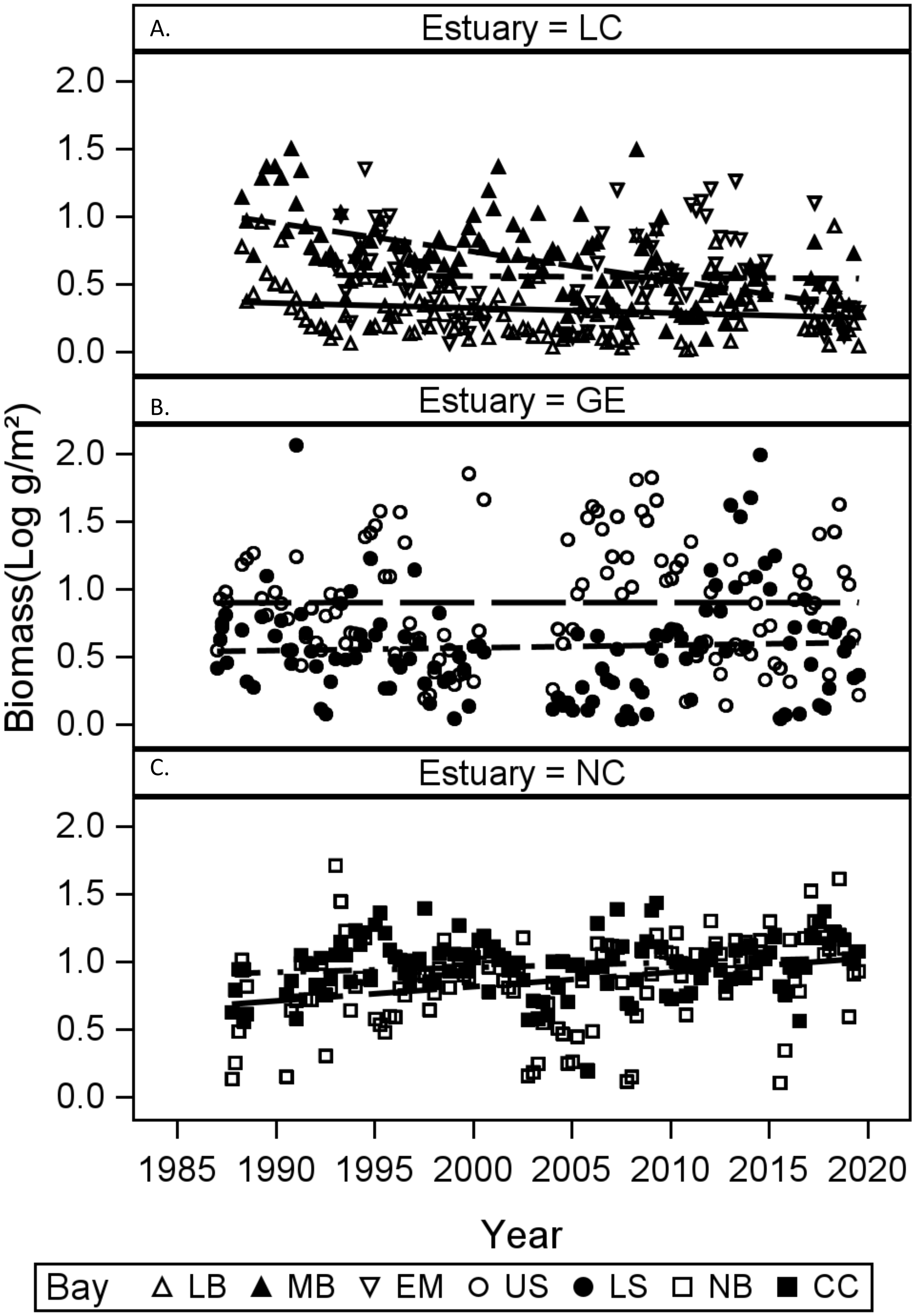


Figure 13.Average quarterly (January, April, July, and October) log10 transformed benthic infauna biomass by bay from 1987-2018. Abbreviations and symbols defined in Figure 12. A) Lavaca-Colorado Estuary. B) Guadalupe Estuary. C) Nueces Estuary.

Infauna diversity in the Lavaca-Colorado Estuary and Guadalupe Estuary declined over the 22-year study period and increased in the Nueces Estuary (Table 9, Figure 14). Primary bays had higher diversity than secondary bays for all estuaries.

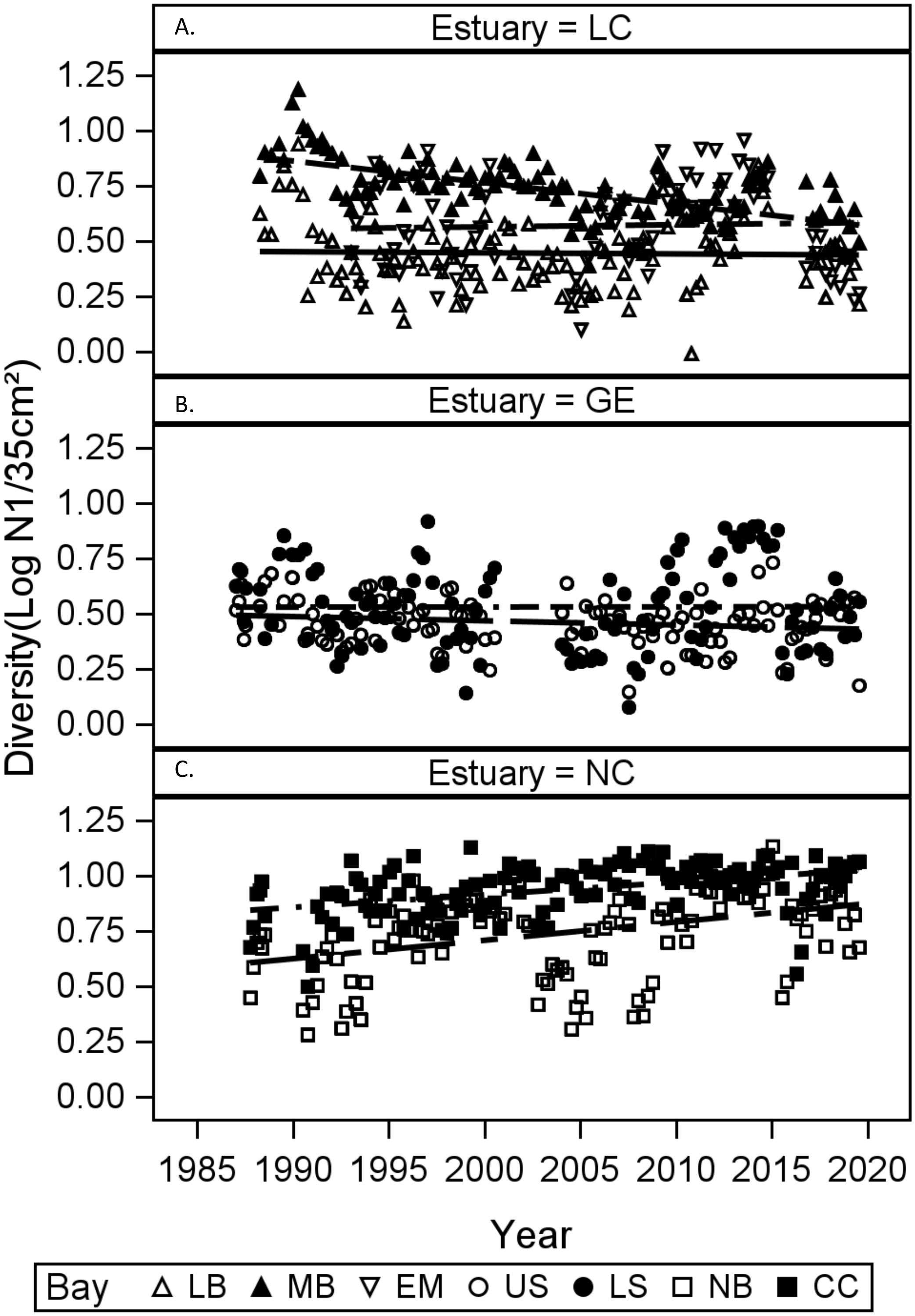


Figure 14. Average quarterly (January, April, July, and October) log10 transformed benthic infauna Hill's N1 diversity by bay from 1987-2018. Abbreviations and symbols defined in Figure 12. A) Lavaca-Colorado Estuary. B) Guadalupe Estuary. C) Nueces Estuary.

7.5 Linking Inflow Events and Communities

The BIO-ENV analysis between the macrofauna community and hydrographic measurements is used to find a combination of variables that maximizes the matching coefficient between the two. The highest correlation was with salinity, temperature, dissolved oxygen, NH4, and PO4 between bays (R = 0.905, P-Value = 0.001). The highest correlation to a single variable was to PO4 (R = 0.710, P-value = 0.001).

A nMDS and a PCA of the water quality variables including temperature, salinity, dissolved oxygen, chl-a, and the N:P ratio was performed (Figure 15). Three bays (Matagorda, Corpus Christi and Nueces Bays) had the highest salinities and three bays (Lavaca, and upper and lower San Antonio Bays) had the lowest salinities. East Matagorda had the highest nitrogen to phosphorous (N:P) ratios and chlorophyll-*a* measurements. The spatial patterns of the bays for the macrofauna nMDS (Figure 8) and water quality nMDS (Figure 15) were not significantly different (ρ = 0.322, p = 0.089). The largest difference in the spatial patterns was the location of eastern Matagorda Bay, which separates from San Antonio Bay based on very high chlorophyll-a values (Table 5).

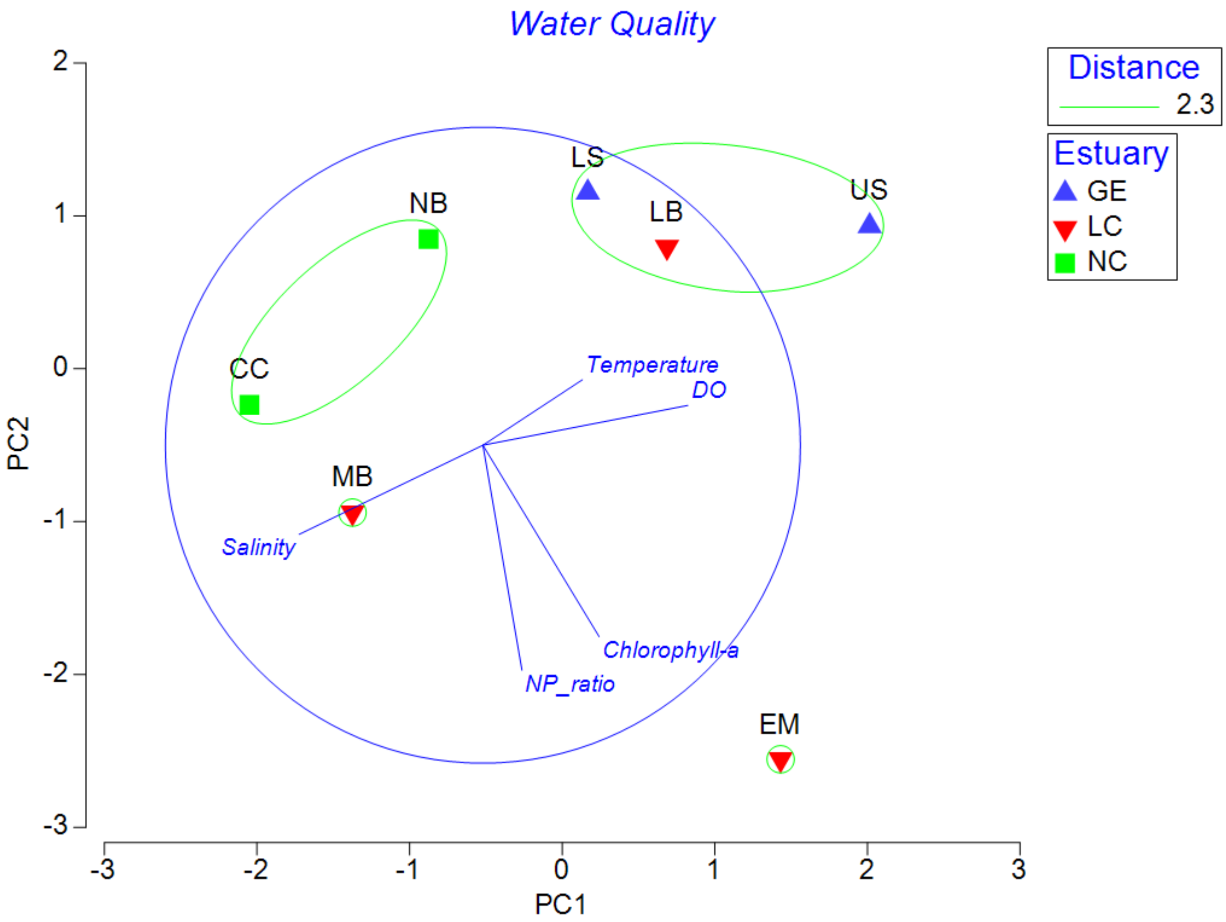


Figure 15. PCA and nMDS Plot on water quality variables by estuary and bay with cluster analysis by Euclidean distance overlaid. Each symbol on the nMDS is representative of an estuary, and bay abbreviations as in Figure 8.

Macrofauna abundance and diversity were negatively correlated to temperature in Lavaca-Colorado estuary (Table 10). In Guadalupe estuary macrofauna biomass and diversity were positively correlated to salinity and diversity was negatively correlated to temperature. In Nueces estuary macrofauna abundance was positively correlated to dissolved oxygen but negatively correlated to temperature.

Table 10. Spearman correlations (r) and probability that the correlation equals zero (P) for the relationship between macrofauna metrics and water column metrics by estuary from 1987-2019. Abbreviations: Stat = statistic, n = number, Sal = salinity (psu), DO = dissolved oxygen (mg/L), Temp = temperature (°C).

Metric (unit)		Lavaca-Colorado			Guadalupe			Nueces		
	Stat	Sal	DO	Temp	Sal	DO	Temp	Sal	DO	Temp
Abundance (n/m^2)	r	0.10	0.15	-0.21	-0.05	0.13	-0.14	0.12	0.11	-0.20
	P	0.0059	<0.0001	<0.0001	0.2956	0.0075	0.0027	0.0032	0.0054	<0.0001
	n	721	710	721	464	434	464	600	600	600
Abundance (Log n+1/m^2)	r	0.10	0.15	-0.21	-0.05	0.14	-0.15	0.11	0.12	-0.20
	P	0.0056	<0.0001	<0.0001	0.3275	0.0048	0.0016	0.0057	0.0032	<0.0001
	n	721	710	721	464	434	464	600	600	600
Biomass (g/m^2)	r	0.23	0.05	-0.11	-0.03	0.08	-0.08	0.16	0.06	-0.05
	P	<0.0001	0.2102	0.0044	0.4713	0.0786	0.1009	<0.0001	0.1669	0.2052
	n	721	710	721	464	434	464	600	600	600
Biomass (g+0.001/m^2)	r	0.22	0.07	-0.13	-0.03	0.10	-0.08	0.15	0.06	-0.05
	P	<0.0001	0.0576	0.0006	0.4523	0.0459	0.0679	0.0002	0.1596	0.2455
	n	721	710	721	464	434	464	600	600	600
Richness (S/sample)	r	0.36	0.08	-0.18	0.26	0.17	-0.25	0.21	0.06	-0.13
	P	<0.0001	0.0263	<0.0001	<0.0001	0.0005	<0.0001	<0.0001	0.1182	0.0011
	n	721	710	721	464	434	464	600	600	600
Diversity (N1/sample)	r	0.43	0.02	-0.12	0.20	0.10	-0.21	0.23	0.01	-0.06
	P	<0.0001	0.5587	0.0012	<0.0001	0.0352	<0.0001	<0.0001	0.8057	0.1371
	n	721	710	721	464	434	464	600	600	600

7.5.1 Hurricane Harvey

Hurricane Harvey made landfall Friday August 25, 2017 at 22:00 Central Time about 30 miles northeast of Corpus Christi, Texas as a Category 4 hurricane with winds up to 130 mph (Figure 16). This is the strongest hurricane to hit the middle Texas coast since Carla in 1961. After the windstorm and storm surge, coastal flooding occurred due to the storm lingering over Texas for four more days, dumping as much as 50" of rain near Houston. This produced one of the largest floods ever to hit the Texas coast, and it is estimated that the flood was a 1:1000-year event. Increased inflows to the estuaries caused increased loads of inorganic and organic matter, which in turn drove primary production of coastal "blue carbon." The biological responses were immediate because the enhanced nutrient and carbon loads can significantly enhance respiration. The storm also represents a large change in salinity and dissolved oxygen deficits, which could kill or stress many estuarine and marine organisms. Hurricane Harvey went through the study area twice (on landfall and as it moved back into the Gulf of Mexico), and it provided a huge freshwater inflow event. Harvey provides an opportunity to study the effects of a very large inflow event.

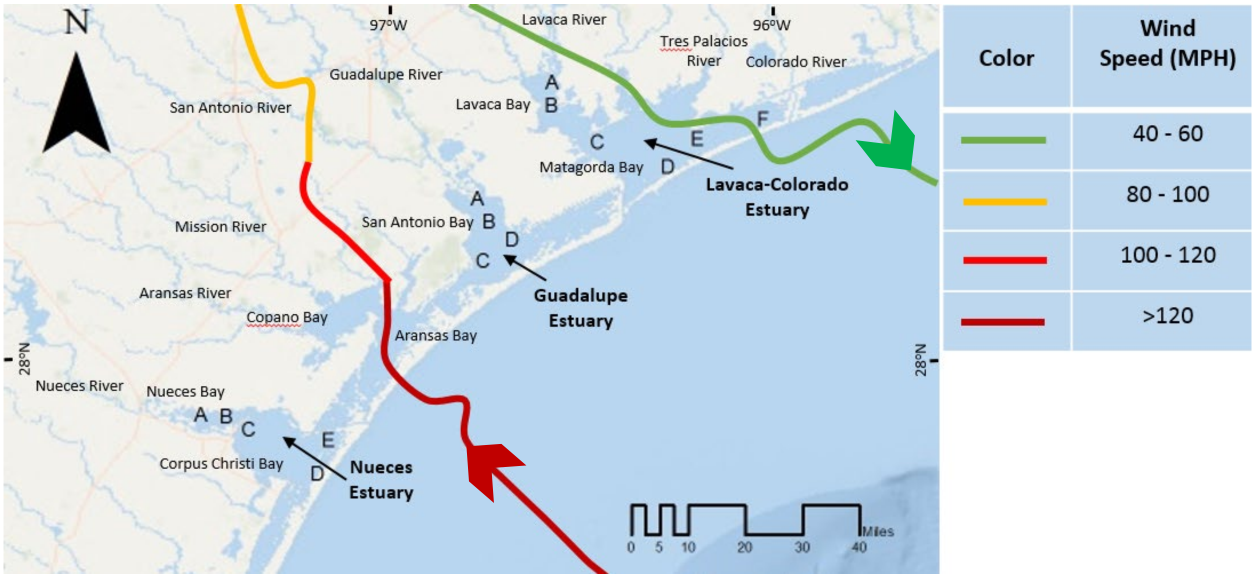


Figure 16. Long-term benthic sampling stations overlaid with the track of Hurricane Harvey (August 25 -27 2017).

The climatic conditions in the Guadalupe Estuary (i.e., San Antonio Bay) prior to the storm were relatively average with salinity around 10 psu prior to the storm (Figure 17). As the storm approached, storm surge pushed salinities over 30 psu with in-rushing sea water. Salinities dropped as the storm passed and the rain swollen rivers began to flow. Salinity dropped to zero within 7 days of the storm. Salinity recovered to 6 psu by October 6, 2017, and to 10 psu by October 9, 2017.

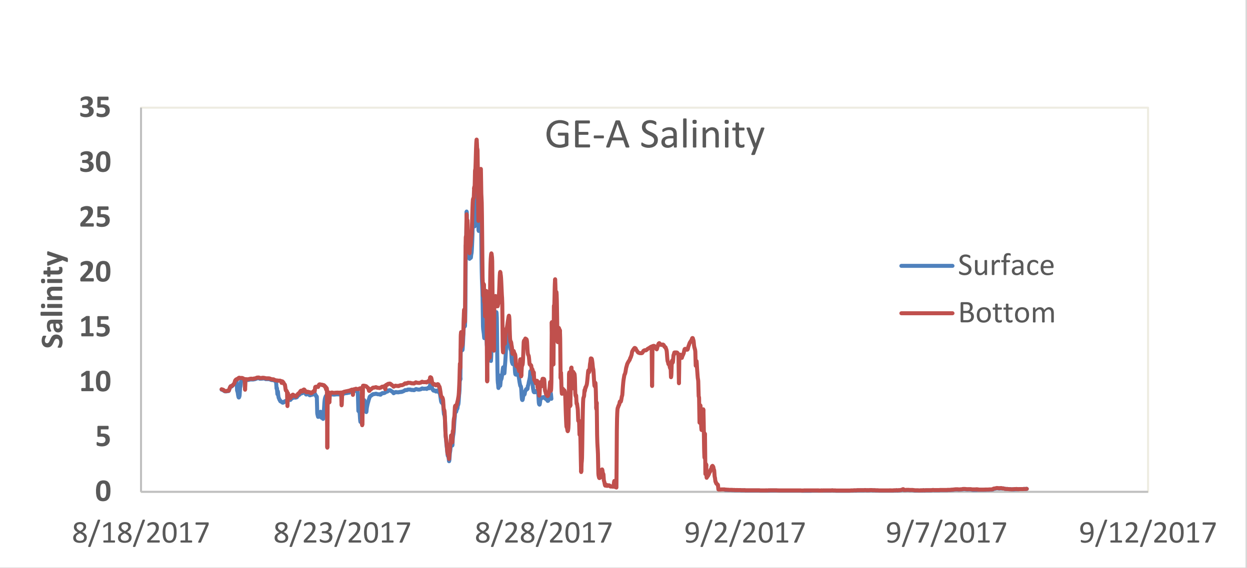


Figure 17. Continuous salinity measurements at station GE-A in the Guadalupe Estuary (From: Walker et al. 2021).

Once the rivers started to flow, nutrients and organic matter loading enhanced respiration of organic matter (i.e., coastal blue carbon), and dissolved oxygen (DO) started to decline, reaching zero about 9 days after the storm (Figure 18). The DO did not recover until 15 days after the storm.

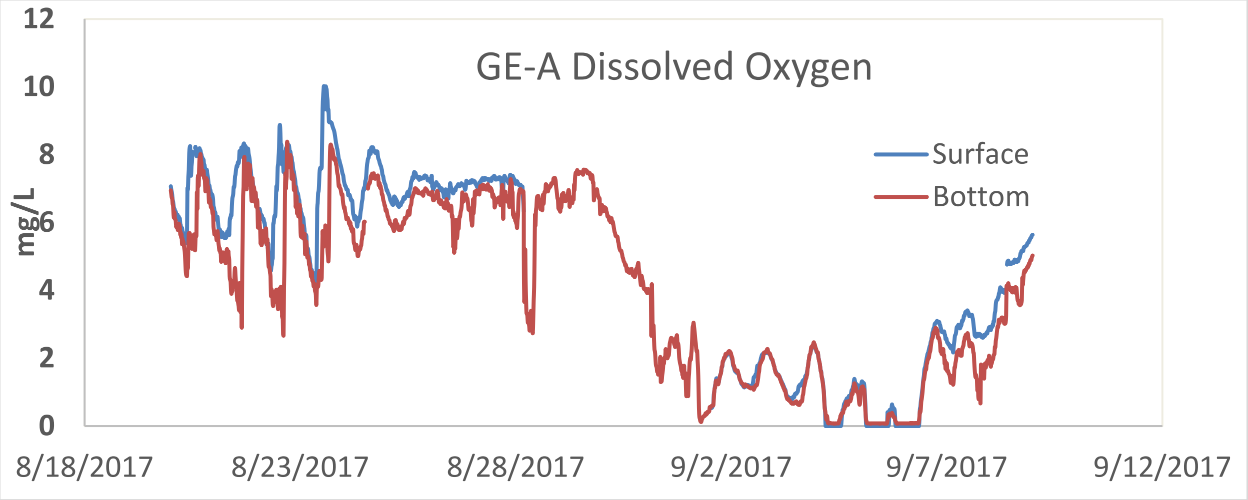


Figure 18. Continuous dissolved oxygen measurements at station GE-A in the Guadalupe Estuary (From: Walker et al. 2021).

Comparing three months prior to the storm in the Guadalupe Estuary, a combination of the freshening and low DO conditions caused a large decline in benthos abundance, biomass, diversity at all stations, but especially upper San Antonio Bay (Figure 19).

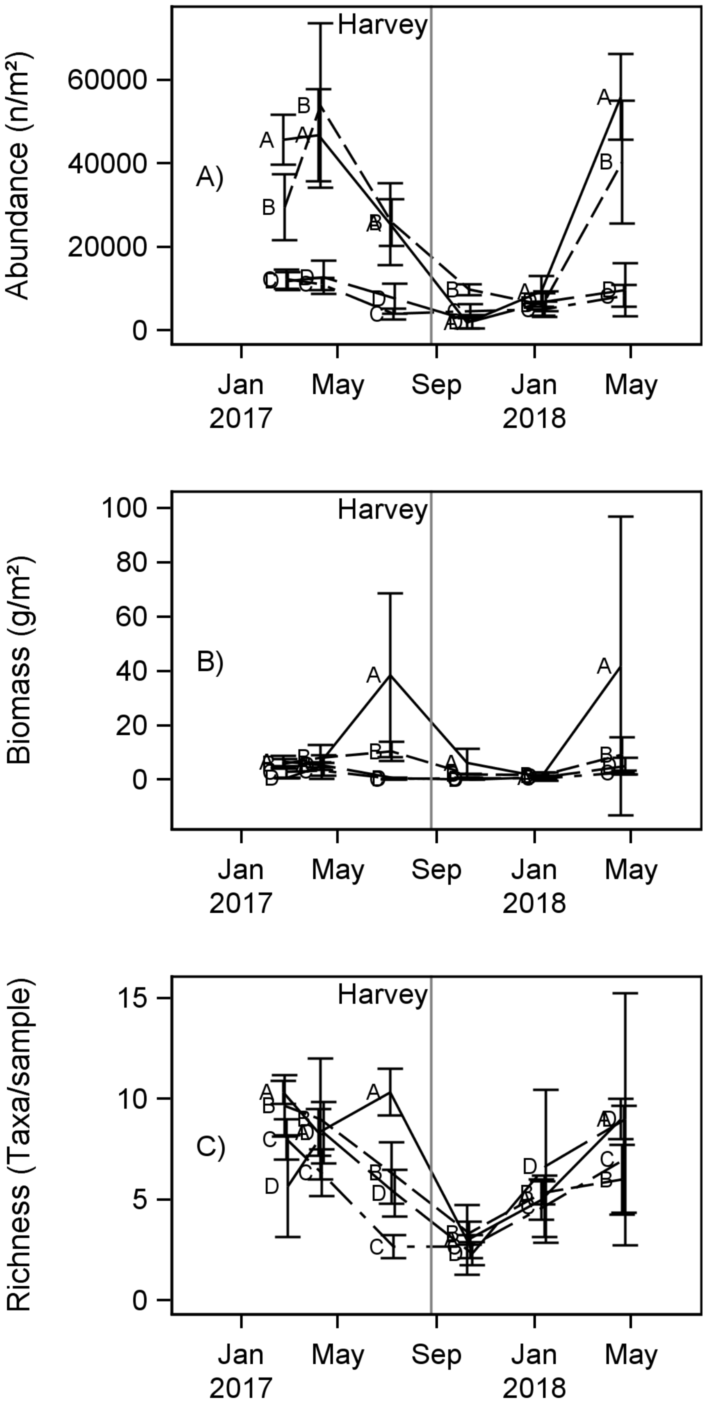


Figure 19. Benthic metrics three quarters before and three quarters after Hurricane Harvey. A) Abundance. B) Biomass. C) Richness, i.e., number of species.

Prior to the storm all stations were similar, i.e., clustered together in the center of the nMDS plot, but after the storm the distribution of the samples is much more scattered, especially the stations in lower San Antonio Bay (stations C and D) (Figure 20). The two dominant polychaete species (*Mediomastus ambiseta* and *Streblospio benedicti*) declined 58% and 91% respectively after the storm. The dominant bivalve (*Mulinia lateralis*) increased 63% after the storm.

The bivalves (*Macoma mitchelli*, *Mulinia lateralis*, and *Rangia cuneata*) had an average abundance (5.4/sample) and average size distribution (6.8 mm) prior to the storm. There was nearly nothing (i.e., only one mollusk found in all the samples) in the sediment for the first five months after the storm. There was a recruitment event (average 33.4/sample) of small (average 3.8 mm) *Mulinia lateralis* by April 2018. These newly recruited mollusks grew to an average of 5.7 mm by July 2018, and to an average of 6.2 mm by October 2018. This short-term view makes it appear as if there was a large loss, but a recovery within nine months after the storm, which implies that benthos are vulnerable but resilient.

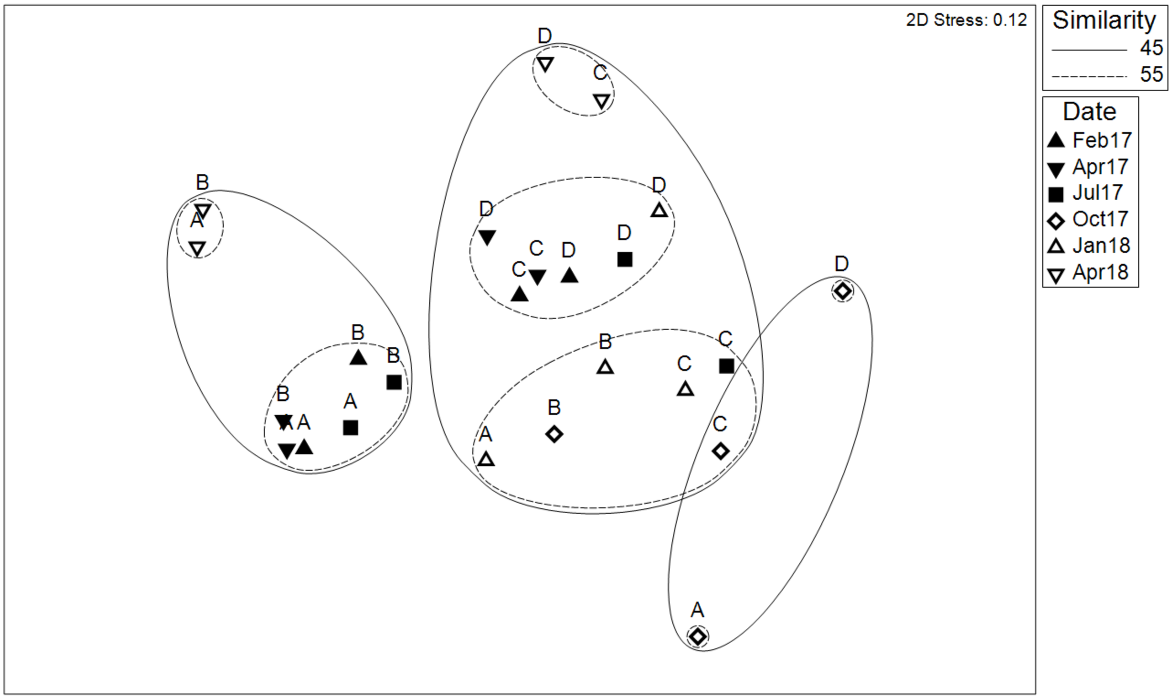


Figure 20. Benthic community structure change in San Antonio Bay stations due to Hurricane Harvey from February 2017 to April 2018. Data labels are stations. Filled symbols are before, and open symbols are after the hurricane. Lines indicate percent similarity.

The short-term view makes it appear as if the Hurricane had a large devastating effect on benthos in San Antonio Bay. However, how does that response compare to the long-term dynamics? Thirteen years of quarterly benthic data from January 2004 to July 2017 was used to forecast benthic response for the five quarters after the storm, i.e., October 2018 to July 2019 and then compared to actual values for stations A and B in upper San Antonio Bay and stations C and D in lower San Antonio Bay. If the hurricane is having an unusual effect, then the actual values should fall outside the confidence bands.

The exponential smoothing forecast model predicts actual benthic abundance, biomass, and diversity very well because the actual values are very close to predicted values (Figures 21 to 23). However, the long-term view makes it appear as the benthic response is within the range of responses expected if the storm did not occur. The forecast model predicts that benthic abundance would have gone down anyway as it does every fall and recover as it does every spring (Figure 21). The abundance recovery after the storm was greater than expected but within bounds of error.

There were only three periods when the abundance forecast was outside the 95% confidence interval, and this was in July 2007 in lower San Antonio Bay (i.e., stations C and D), and July 2009, and July 2015 in upper San Antonio Bay (i.e., stations A and B) (Figure 21). The period in 2015 was also a flood period with very low salinities near zero. However, the middle period in July 2009 was a drought when salinities were very high, around 35. So, it does appear the extreme events (both floods and droughts) can disturb benthic communities.

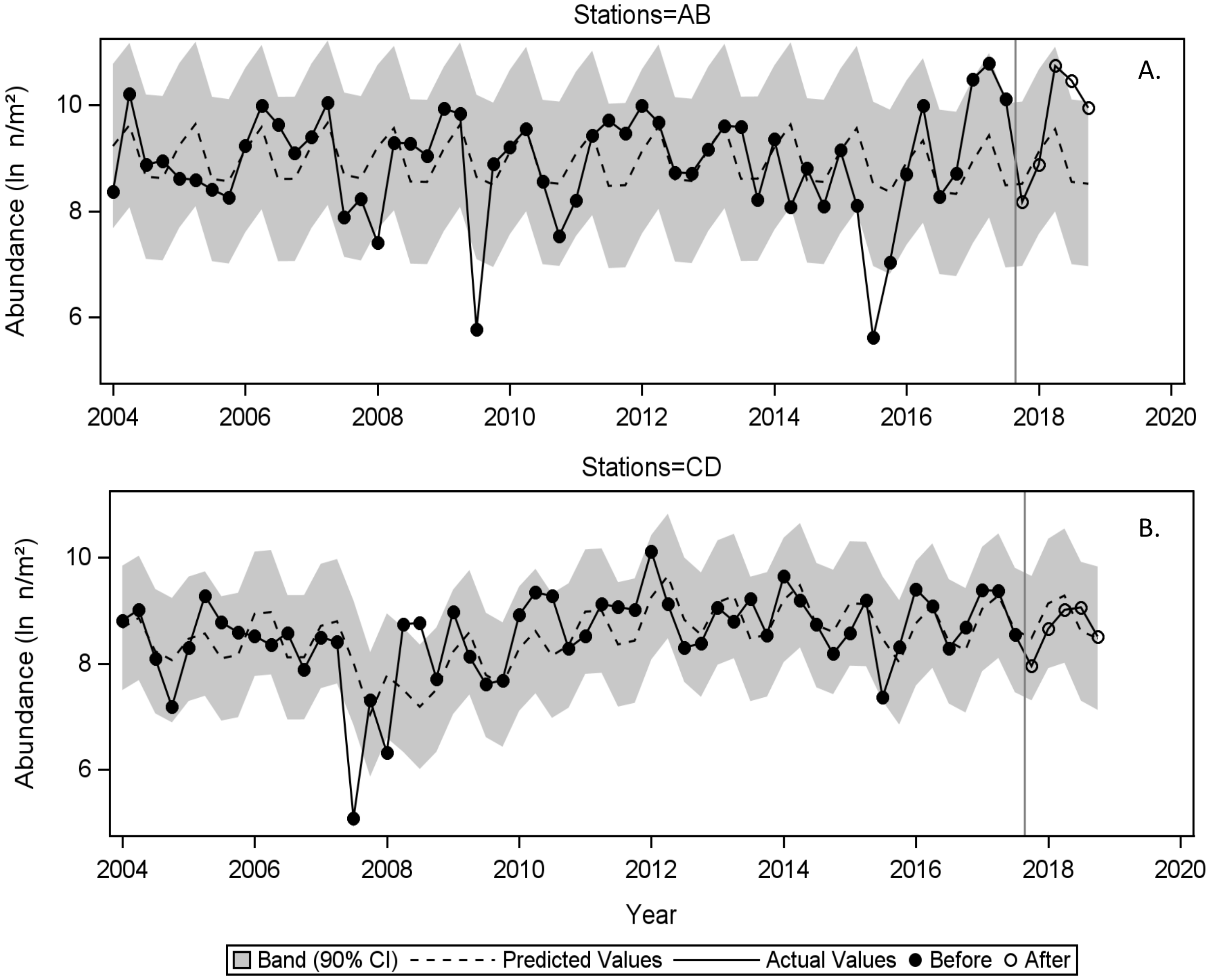


Figure 21. Long-term benthic dynamics used to predict benthic abundance from January 2004 to July 2019. Black circle symbols are values used to forecast the post-storm effects. Open circle symbols are the actual measured values. Black lines are actual measured values. Dashed lines are predicted values. Shaded areas are the 95% confidence bands. A) Upper San Antonio Bay, stations A and B. B) Lower San Antonio Bay, stations C and D.

The forecast model predicts that benthic biomass would have gone down as well, and the decline was lower than expected for upper San Antonio Bay, but not for lower San Antonio Bay (Figure 22). The biomass of the spring 2019 recruitment event in the upper and lower parts of San Antonio Bay was also higher than expected and almost reached beyond the expected bounds.

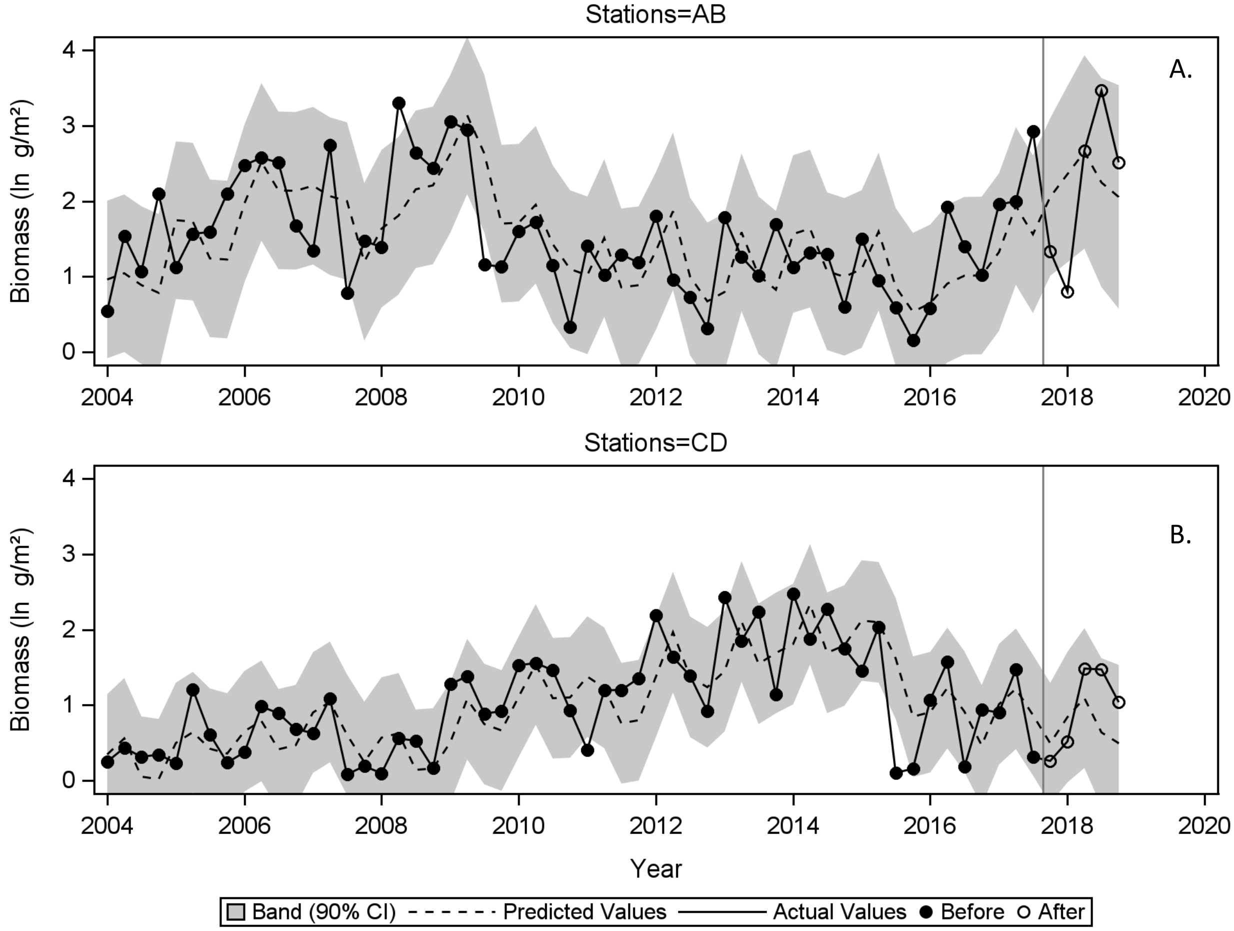


Figure 22. Long-term benthic dynamics used to predict benthic biomass from January 2004 to July 2019. Symbols and lines as in Figure 21. A) Upper San Antonio Bay, stations A and B. B) Lower San Antonio Bay, stations C and D.

The forecast model predicts that benthic diversity went down more than expected, and to a degree that was out of the bounds of the 95% confidence interval (Figure 23). In contrast, the recovery was as expected in lower San Antonio Bay, with values that were nearly exactly as predicted. However, the decline in diversity in upper San Antonio Bay was much higher than expected. Even though the number of species was generally as predicted, the community structure was very different.

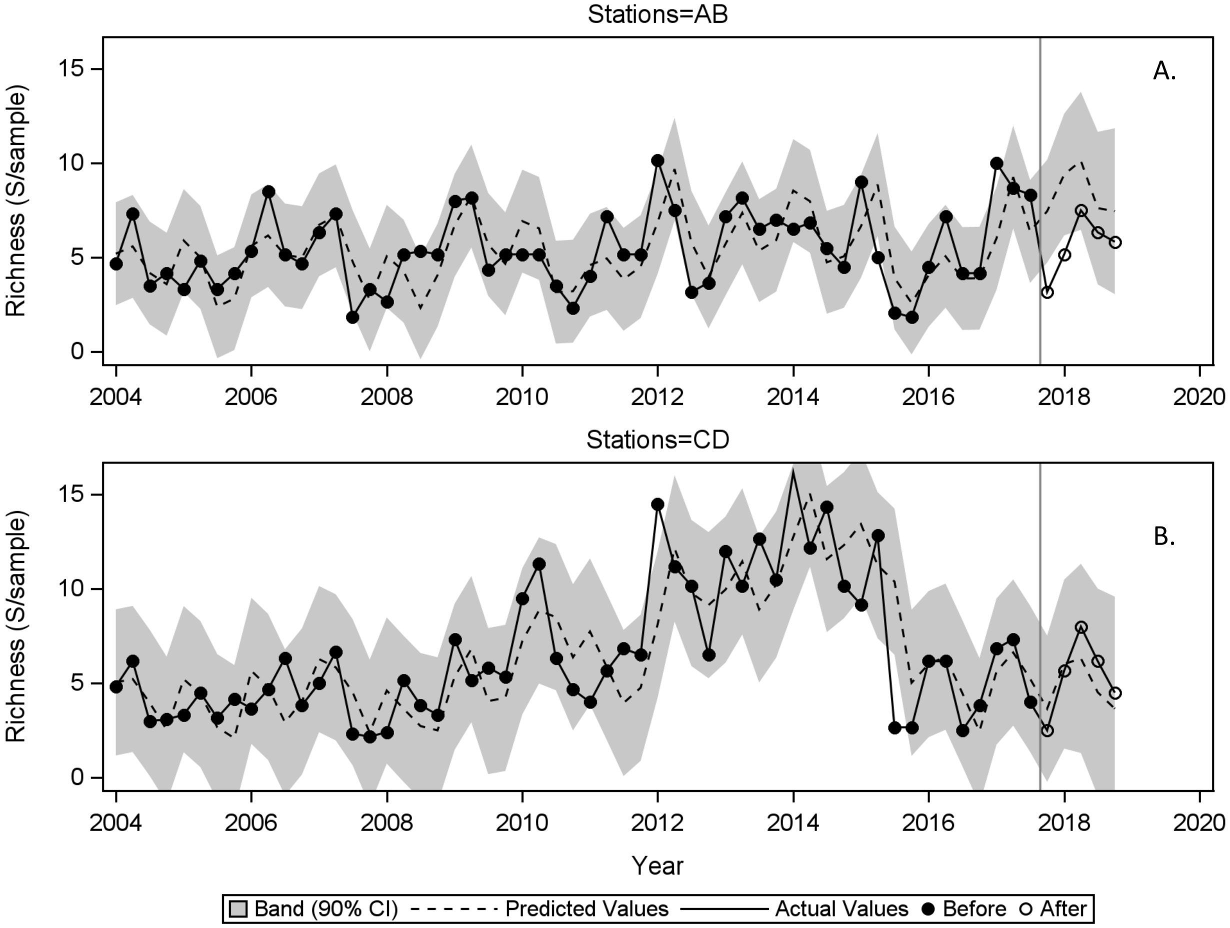


Figure 23. Long-term benthic dynamics used to predict benthic species richness from January 2004 to July 2019. Symbols and lines as in Figure 21. A) Upper San Antonio Bay, stations A and B. B) Lower San Antonio Bay, stations C and D.

8 Discussion

The objective of the current study is to analyze archived benthic samples and use the data to evaluate the adequacy of the freshwater inflow standards adopted for three (Lavaca-Colorado, Guadalupe, and Nueces) basins as part of the Senate Bill 3 adaptive management process. Environmental flow standards for the three basins were adopted on August 30, 2012 for Matagorda and Lavaca Bays (TCEQ §298.330) and for San Antonio Bay (TCEQ §298.380), and on March 6, 2014 for Nueces Bay and Delta (TCEQ §298.430). The rules are quite complex and describe different attainment frequencies over 4-year to 6-year periods of time, in different seasons, and under different conditions. There is little in common in the structure of the standards among or within the basins. For example, in Matagorda Bay the standards are based on “monthly” thresholds annually and four “seasonal” thresholds at different “levels” where levels are defines as different inflow regimes. For Lavaca Bay, there are annual attainment frequencies for fall and spring only, and for defined “regimes” (subsistence, base dry, base average, and base wet). In San Antonio Bay there are separate tables for spring and summer attainment frequencies based on six consecutive years. For Nueces Bay and Delta, there are attainment frequencies for three time periods (November to February, March to June, and July to October) at three different “levels” where levels are defines as three different inflow regimes (wet, average, dry). It is impossible to link specific benthic responses in any one year to a specific standard, instead the response must be linked to the attainment frequency of the standards.

8.1 Spatial Considerations

While the information about long-term benthic dynamics as it relates to salinity is useful for evaluating environmental inflow standard in each basin, it is also important to compare effects among bays and estuaries to identify the general ecological principles that drive organismal response to inflow in estuaries. This is because the domino theory suggests community structure and function is controlled by long-term water quality dynamics (Alber 2002, Montagna et al. 2013). Because the Texas coast lies in a climatic gradient, different bay systems have different long-term water quality dynamics (Montagna et al. 2018). So, it is not surprising that the different bay systems have different mollusk communities (Montagna and Kalke 1995), different diversity patterns (Van Diggelen and Montagna 2015), and different secondary productivity patterns (Montagna and Li 2010, Kim and Montagna 2012). All of these previous findings are confirmed here, see Figure 6 and Figure 7 for water quality differences, and Figure 8 for benthic community differences.

8.2 Temporal Considerations

The long-term data set is important because ecological relationships can be obscured in short term studies by common features such as time lags, natural variability, nonlinear relationships, interactive drivers, or relatively slow processes (Hampton et al. 2019). Thus, long-term research provides a unique perspective on environmental processes, dynamics of populations and communities of organisms, and has led to major scientific discoveries.

Over time there are seasonal, year-to-year, and random storm events. The Texas coast does not have very cold temperatures during winter, yet the biological responses are still what one would expect of a temperate estuary, that is, fall and winter die-offs and spring and summer blooms. The cycle of floods and droughts moderate or exacerbate the natural cycles.

We jump to the wrong conclusions by looking at the noise (over short-term periods) rather than the signal (over long-term periods). This is especially evident when we look at the benthic response after hurricanes. The short-term view leads to the conclusion that benthos are vulnerable but resilient, meaning they die off but recover after a period of time. On the other hand, the long-term view is very different, and leads to the conclusion that the benthos responses to the storm are a bit larger than expected, but still within the range of error. Thus, the long-term view is that benthos are actually both resistant (meaning they bend without breaking) because of seasonal dynamics and resilient (meaning they can recover when knocked down) because of responses many months after a storm.

8.3 Bioindicators of Salinity Zone Habitats

The complex structure of estuarine habitats in Texas has long been recognized. In early descriptions, habitats were referred to as biotopes, i.e., a region with uniform environmental conditions and populations of animals and plants for which it is the habitat (Oppenheimer and Gordan 1972). Oppenheimer and Gordan (1972) listed 18 biotypes in Texas estuaries (Table 11). Even though these habitats fall in distinct zones with respect to distance from river sources, salinity was not considered the driver of these habitat associations. However, the importance of salinity in controlling organisms in Texas bays was well established in the 1950's and 1960's (Galtsoff 1964, Copeland 1966). More recent descriptions of Texas habitats have specifically focused on the role of freshwater inflow and salinity in organizing communities (Blackburn 2004). Inflow, and thus salinity gradients with secondary and primary bays are key drivers of the spatial distribution of habitats in the Texas Coastal Bend (Figure 1, Montagna et al. 1996).

Table 11. Biotopes of the Texas Coastal Zone (Oppenheimer and Gordan 1972).

Biotopes
Open Beach and Shelf
Dune and Barrier Flat
Spoil Bank
Jetty and Bulkhead
Oyster Reef
Thalassia (grass flat)
Spartina (saltwater marsh)
Juncus (freshwater marsh)
Mud Flat
Sand Flat
Blue-Green Algal Flat
Hypersaline
River Mouth
Bay Planktonic
Channel
Prairie Grassland
Upland Deciduous Forest
River Floodplain Forest

Infaunal benthic organisms (e.g., polychaetes, amphipod crustaceans, and mollusks) are good indicators of salinity effects because they are relatively immobile compared to epibenthos (e.g., large mobile crustacean like shrimp and crabs, and demersal fish), plankton, and nekton (e.g., fish). The immobility means that benthos must adapt or survive to changing conditions in their habitat because they cannot move. Variability of benthos communities is shaped by morphology of habitats, but the "hydrological seascape," i.e., the interaction between habitats and salinity, is the major driver that explains the role benthos play in estuaries (Tenore et al. 2006). The importance of benthic indicators was recognized by the BBESTs. Five of the seven BBESTs used oysters, *Rangia*, or benthos to guide derivation of inflow standards. Benthos are also at the base of food webs, and are thus important forage for higher trophic levels, i.e., crab, shrimp, and fish. There are three main types of feeding strategies among benthic organisms: predation/omnivory, deposit feeding, and filter/suspension/epistrate feeding (Montagna and Li 2010, Kim and Montagna 2010, 2012). The filter/suspension/epistrate feeders are selecting food from the water column or the surface sediments (Tenore et al. 2006), and are thus most directly affected by inflow dynamics, which can influence nutrient loading and primary productivity (Figure 6).

Benthic community structure in the mid-Texas bays is linked to salinity (Figure 8, Table 6). There is extreme dominance in Texas estuaries, and two polychaete species, *Mediomastus* *ambiseta* and *Streblospio benedicti* represent 48% of all individuals found. Both species are freshwater inflow indicators because they are more abundant in the secondary bays than primary bays, and their distribution follows salinity distributions. For example, where the long-term average salinities for bays are similar (Table 5), the abundance of these two species are similar (Table 8). The third dominant species at 6.4% of total is the bivalve *Mulinia lateralis* but it is particularly dominant in upper San Antonio Bay, but less dominant in the other low salinity bays. However, the response to Hurricane Harvey indicates *Mulinia* recruitment is very dependent on the large salinity changes brought by large floods. The fifth dominant species at 3.8% of total is the gastropod *Texadina sphinctostoma*. While *Texadina* occurs primarily in upper San Antonio Bay, it is not a generic inflow indicator because it does not occur in East Matagorda Bay nor Nueces Bay and it appears to be a species mostly found in San Antonio Bay. The only infaunal crustacean that is an inflow indicator is the amphipod *Ampelisca abdita*, which made up 1.2% of total organisms, and occurs primarily in the secondary bays.

There are also marine indicators. The polychaete *Dipolydora caulleryi* is the fourth dominant species at 4.6% of all species and is found primarily in the primary bays (Table 8). The predatory worm Nemertea at 1.6% is also found in primary bays. The tenth dominant species at 1.5% is the polychaete *Cossura delta* and is found primarily in primary bays.

8.4 Linking Inflow, Salinity, and Ecological Response

We have learned that salinity is an important driver of estuarine benthic community structure. This is especially true within estuaries along the salinity gradient, and among estuaries along the coastal climatic gradient. However, we have also learned that climate variability is an important driver of salinity in Texas estuaries (Kim et al. 2014, Pollack et al. 2011, Tolan 2007). Instead of starting with inflow, the conceptual model in Figure 2 should start with climate because climate drives the hydrologic cycle, and thus the amount of freshwater inflow delivered to the coast. Texas estuaries are a suitable location to study the effects of climate variation because they are physically similar, each estuary drains one or two watersheds, and they lie in a climatic gradient with decreasing precipitation from the northeast to southwest. The local climatic gradient and ENSO are influencing hydrological (Tolan 2007) and ecological (Kim et al. 2014) dynamics in Texas estuaries.

Estuarine organisms exhibit optimal salinity tolerances for growth, development, and reproduction (Patillo et al. 1997). Fresh water inflow, and corresponding salinity changes, are the main factors controlling distribution and diversity of macroinfaunal communities. This is because benthic organisms are especially sensitive to changes in salinity because they typically are fixed in place and can’t move if conditions are unfavorable. Changes in salinity alter macroinfauna diversity (Van Diggelen and Montagna 2016) and biomass (Palmer et al. 2011) in Texas. Similar results were found in the Gulf of Riga in the North Sea (Kotta et al. 2009), in estuaries in India (Mulik et al. 2020), in the Yangtze Estuary in China (Wu et al. 2019), and many other places.

In Texas, the primary bays are different from secondary bays. The similarities in macroinfauna communities within bays were likely driven by similarities in salinity within bays. In Tees Bay, United Kingdom, long-term changes in macrobenthos abundance, diversity, and community structure changed differently near the river mouth compared to far from it (Warwick et al. 2002). Functional infauna diversity will decrease with changes in freshwater inflow and benthic infauna communities will acclimate to the changes in salinity, and more (or less) salt tolerant species will dominate the communities depending on the long-term salinity averages (Kim and Montagna 2009, 2012, Montagna et al. 2002, Palmer et al. 2002).

8.5 Evaluating Inflow Standards

In the past, it was easy to evaluate freshwater inflow standards to determine if they were working, i.e., protecting the living resources. This was because there was essentially one number for whole bay systems, and you could calculate how that number, and its year-to-year variability, would affect salinity and thus biological responses. A good example is the application of the domino theory (Figure 2) to the Caloosahatchee River in Florida (Palmer et al. 2016). Biological resources in estuaries are affected by salinity more than inflow by itself, so the links between flow, salinity, and biology will determine the relationship between inflow and living resources. The first step is to identify the resource to be protected. The second step is to identify the salinity range or requirements of the resource in both space and time. The third step is to calculate the flow regime needed to support the required distribution of salinity.

The adopted Texas environmental flow standards can be found in Chapter 298 of TCEQ's rules (https://www.tceq.texas.gov/permitting/water_rights/wr_technical-resources/eflows/rulemaking, Tables 12 - 15). The standards are complex, consisting of multiple tables that describe flow regimes that vary in three dimensions: over components or climatic periods (such as wet and dry years), over seasons, and spatially within rivers, streams, and bay systems. Additionally, terminology in the rules vary. For example, the component climatic periods for inflow regimes are called "wet, average, dry, and subsistence" for Lavaca Bay (Table 12), "level" for Matagorda Bay (Table 13) and Nueces Bay (Table 15), and by season name (i.e., spring, summer, summer, and fall) for San Antonio Bay (Table 14). The environmental flow standards were based on statistical evaluations of historical occurrence frequencies of different flow level hydrological categories, which also vary (Opdyke et al. 2014, Anchor QE 2021).

The Lavaca Bay standards are the simplest (Table 12). There are standards for two seasons, spring and fall, under for different climatic regimes (subsistence, dry, average, and wet).

Table 12. Bay and estuary freshwater inflow standards for Lavaca Bay System [30 TAC §298.330(a)(2)].

Inflow Regime	Spring Inflow Quantity (af)	Fall Inflow Quantity (af)	Intervening Inflow Quantity (af)	Annual Strategy Frequency
Subsistence	13,500	9,600	6,900	96%
Base Dry	55,080	39,168	28,152	82%
Base Average	127,980	91,080	65,412	46%
Base Wet	223,650	158,976	114,264	28%

The standards for Matagorda Bay are more complex (Table 13) because the concept of "levels" is introduced. Level are differences amongst years, that are necessarily tied to a regime. In addition, the concept of a monthly minimum is introduced, as is the long-term average.

Table 13. Bay and estuary freshwater inflow standards for Matagorda Bay Inflows from the Colorado River Basin [30 TAC §298.330(a)(2)].

Inflow Regime	Monthly Minimum Quantity (af)	Spring Season Quantity (af)	Fall Season Quantity (af)	Intervening Season Quantity (af)	Long-Term Annual Strategy Quantity (af)	Annual Strategy Frequency
Monthly Threshold Inflow	15,000	N/A	N/A	N/A	N/A	100%
Level 1	N/A	114,000	81,000	105,000	N/A	90%
Level 2	N/A	168,700	119,900	155,400	N/A	75%
Level 3	N/A	246,200	175,000	226,800	N/A	60%
Level 4	N/A	433,200	307,800	399,000	N/A	35%
Annual Average	N/A	N/A	N/A	N/A	1,400,000	N/A

For San Antonio Bay the complexity increases yet again because there are six levels of spring, seven levels of summer, and combined levels (Table 14). The standards are also for two specific periods: February, and March through May. Zero flows are allowed under certain circumstances.

Table 14. Bay and Estuary Freshwater Inflow standards for the San Antonio Bay System. A) The spring season [TAC §298.380(a)(3)]. B) The summer season [TAC §298.380(a)(4)].

A) Spring Inflow Regime	Inflow Quantity (February) (af)	Inflow Quantity (March-May) (af)	Strategy Target Frequency
Spring 1	N/A	550,000 925,000	at least 12% of the years
Spring 2	N/A	375,000 550,000	at least 12% of the years
Spring 3	N/A	275,000 375,000	N/A
Spring 4	greater than 75,000	150,000 275,000	N/A
Spring 5	less than 75,000	150,000 275,000	N/A
Spring 6	N/A	0 150,000	no more than 9% of the years
Spring 2 and Spring 3 combined	N/A	N/A	at least 17% of the years
Spring 4 and Spring 5 combined	N/A	N/A	less than 67% of the total

B) Summer Inflow Regime	Inflow Quantity (June) (af)	Inflow Quantity (July-September) (af)	Strategy Target Frequency
Summer 1	N/A	450,000 800,000	at least 12% of the years
Summer 2	N/A	275,000 450,000	at least 17% of the years
Summer 3	N/A	170,000 275,000	N/A
Summer 4	greater than 40,000	75,000 170,000	N/A
Summer 5	less than 40,000	75,000 170,000	N/A
Summer 6	N/A	50,000 75,000	N/A
Summer 7	N/A	0 50,000	no more than 6% of the years
Summer 2 and Summer 3 combined	N/A	N/A	at least 30% of the years
Summer 4 and Summer 5 combined	N/A	N/A	Summer 5 no more than 17% of the Total
Summer 6 and Summer 7 combined	N/A	N/A	no more than 9% of the years

For the Nueces system, there are standards for Nueces Bay and Delta only (Table 15). Here the standards are simplified as they are in Lavaca Bay. There are three levels ranging from wettest to driest. There are three periods within years, and annual targets for volumes and frequencies.

Table 15. Bay and estuary freshwater inflow standards for Nueces Bay and Delta [TAC §298.430(a)(3)].

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

Evaluating biological or ecological effects of a standard in real-time is difficult because the classification of current inflow component during a sampling event will be known only in the future. This is because which flow regime the sample is classified under cannot be known until the attainment frequency is known. There has been only one study of hydrological attainment frequencies and it was for instream flows of the Brazos, Trinity, and Neches Rivers only (Anchor QEA 2021). To use the benthic data presented here, the flow regime must be modeled to salinity at a point in space and time. Because organisms are responding to water column conditions, not to inflow directly (Figure 2).

8.6 Using Benthic Data in the Adaptive Management Process

The data set presented here fulfills aspects of the workplans for each basin. As described in Section 5.1, each BBASC has outline specific information needs. These are evaluated below.

8.6.1 Lavaca-Colorado Estuary Specific Outcomes

The CL-BBASC workplan (2012) identified several information needs. Below is a description on how the current work can be used by the CL-BBASC.

1. Describe relationships between physical habitat and flow. As shown here, salinity zones are defining key habitats in Lavaca and Matagorda Bays. These two bays have different long-term average salinities and different benthic communities
2. Identify improvements made in methods for determining environmental flow regimes for estuaries. The break-through in the current study is showing how a forecasting model can be used to evaluate the flood caused by hurricane Harvey. This same approach can be used to evaluate different salinity regimes.
3. Evaluate achievement of the BBEST freshwater inflow recommendations in Matagorda Bay (based on the Matagorda Bay Health Evaluation recommendations) and ecological response to those freshwater inflow quantities and distribution. As described in the above section this is considerably more difficult because of the complexity of the inflow standards. However, it has been shown that infauna in both Lavaca and Matagorda Bays are continuing to show signs of degradation, which is likely due to some kind of degradation in Bay health. It is not clear if the degradation is due to inflow alone, and it is likely that it is not. However, it is noted that salinity has increased over the time period as well, while both temperature and dissolved oxygen has declined. There are likely other stressors, such as pollutants, which are playing a role in the long-term degradation.
4. Implement a program to review effectiveness of strategies that could be used in areas where there may be inadequate amounts of water to support an ecologically sound stream or estuary. Benthos are excellent indicators of ecosystem health and an ecologically sound environment, as evidenced by the fact that five of seven BBEST committees used benthic indicators to recommend inflow standards. As such, the current research adds to the baseline of information regarding benthic ecosystem community structure.

8.6.2 Guadalupe Estuary Specific Outcomes

The GSA-BBASC (2012) work plan identifies several issues that the current research addresses.

1. Life cycle habitat and salinity studies for key faunal species. The word “key” is critical. Often the word key is used to mean important or species of interest. In ecological science “key” means a top predator that can control community structure via predation and regulating competitive interactions among prey species. Regardless, benthos are forage for commercially and recreationally important fish species, and are thus at the base of the food chain.
2. Rangia clam investigations. Rangia are key bioindicator of salinity effects and a member of the benthic community. The current study has explicitly sampled and

reported on Rangia. In fact, Rangia proved to be a key indicator in the recovery from the effects of the flood that followed Hurricane Harvey.

3. Nutrient load and concentration monitoring. Nutrient concentrations as indicators of water quality have been explicitly sampled and reported on in the current study. There is no better indicator of estuarine conditions resulting from freshwater inflow than nutrient concentrations.

8.6.3 Nueces Estuary Specific Outcomes

The Nueces-BBASC (2012) work plan identifies issues that are addressed by the current research.

1. Re-examination of the 2001 Agreed Order monthly targets in the context of biological responses. Information is provided in the current study regarding biological responses to inflow.
2. Describe and design studies to address relationships between abundance of fish and shellfish in the bay and bay salinities. Information is provided in the current study regarding mollusk and crustacean responses to salinity. Typically people mean oysters, crabs, and shrimps when they refer to shellfish, but those are the larger members of the broader community of benthic mollusks and crustaceans, all of which are sensitive to salinity distributions.
3. Relationship between freshwater inflow and ecological health. Ecological health is indicated by the condition of water and sediment quality, and both are measured explicitly in the current study.
4. Define ecological effects of zero flow event duration, intervals between periods of zero flow, and long-term frequency of zero flow occurrences. It is demonstrated here that the high salinities associated with zero flows during droughts act as a disturbance.
5. Ecologically sound environment strategy effectiveness program. Soundness is another word for health, so the issue here is to identify indicators of ecological health, and strategies or maintain a healthy estuary condition.
6. Evaluate probable effects of climate change (a greenhouse warmed future) on water resources including supply, demand, and the ecological condition of rivers and streams and associated bays in the Nueces Basin. The current long-term studies are explicitly aimed at understanding climate change responses and effects on bay health because it can only be assessed with long-term measurements. It is now clear that the entire Texas coast is trending hotter, saltier, and more hypoxic, and these combined effects are leading to degradation of ecosystem health.

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10 TWDB Review Comments and Responses

10.1 Response to Review

All comments in the review have been addressed. All required and recommended changes have been performed. There is one exception, for comment # 16 (and other similar requests) to change commas to semicolons in citations, the commas were retained and the few instances where semicolons were used were changed to commas.

Most changes were minor, but a few of the suggestions required extensive revisions. Those suggestion numbers were as follows:

#2) Expand on SOW Task 5: A new section, 8.3 on salinity bioindicators, is added to the discussion, and a new paragraph is added to the executive summary.

#28) Confirm and correct text regarding chemistry: This required extensive new descriptions of the average nutrient values in different bays.

#44) Include means of bivalves: The average abundance and shell sizes of bivalves has been added to the descriptions of the results.

#66) Restate complexity of standards: Deleted the word "problem" and expanded the discussion of the complexity of flow standards and difficulty in applying them to biotic responses.

10.2 Review of Draft Report

This review of the Draft Report was received April 12, 2022.

Texas Water
Development Board

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Phone (512) 463-7847, Fax (512) 475-2053

Paul A. Montagna, Ph.D.
Texas A&M University – Corpus Christi
Harte Research Institute – Gulf of Mexico Studies
6300 Ocean Drive, Unit 5869
Corpus Christi, Texas 78412

RE: Contract 2000012436 with Texas A&M University – Corpus Christi; Comments on Draft Report Entitled "Long-Term Benthic Data: Adaptive Management of Three Basins"

Dear Mr. Montagna:

Texas Water Development Board (TWDB) staff completed a review of the draft report prepared under the above-referenced contract. Attachment 1 provides the comments resulting from this review.

As stated in the TWDB contract, Texas A&M University – Corpus Christi will consider revising the final report in response to comments. If applicable, please also submit an electronic copy of any computer programs, models, or operations manuals developed under the terms of this contract.

TWDB staff looks forward to receiving an electronic copy of the entire Final Report in Portable Document Format (PDF) format accompanied by a Transmittal Letter which identifies how the Executive Administrator's comments were addressed.

Note: The final deliverables must comply with the accessibility standards defined in the Texas Administrative Code (1TAC 213 & 1TAC 206.50). Contracted deliverables must meet the standards referenced in US Section 508 Appendix C Chapter 7 §702.10 (WCAG 2.0 Level AA, excluding Guideline 1.2 Time Based Media). WCAG guidelines are based on the standards set by the World Wide Web Consortium (W3C) and ensure all resources offer equal access opportunities to the public.

If you have any questions or need any further information, please feel free to contact your Contract Manager, Amanda Burke of the Surface Water staff at 512-463-6021, Amanda.Burke@twdb.texas.gov or Cameron Turner of the Procurement and Contract Services Division at (512) 936-6090, cameron.turner@twdb.texas.gov.

Sincerely,

John T. Dupnik, P.G.
Deputy Executive Administrator
Water Science and Conservation

Date: 4/12/2022

Attachment
c w/o att.: Amanda Burke, Surface Water

Long-Term Benthic Data: Adaptive Management of Three Basins

TWDB Contract #2000012436
Comments to Draft Final Report

REQUIRED CHANGES

General Draft Final Report Comments:

1) Please denote letter connotations in figures with multiple graphs as they are referenced in text and captions.
2) Please address or expand on SOW Task 5- Establish what the bioindicators of salinity zone habitats are and if the habitats change over time.
3) Please use "Gulf of Mexico" or "GoM" instead of "sea".
4) Consider reformatting document spacing to be left justified.
5) Please be consistent in how measurements are written, for example: umol versus µmol.
6) Measurements with a negative integer are confusing, please explain for example: (± 0.2 mg l-1)

Specific Draft Final Report Comments:

1) Pg 3. Under List of Figures. Add "p" in component: Figure 7. Principal component scores for seasons (winter, spring, summer, and fall) and estuaries.
2) Pg 4. Under List of Tables. Table 3. Add a space between "for" and "water" in the first sentence. "ANOVA results for water column metrics."
3) Pg 6. Second sentence under Acknowledgements. Evan Turner is the Subject Matter Expert, Amanda Burke is the Contract Manager.
4) Pg 7. Paragraph 3. Sentence 1. Please include date of Hurricane Harvey landfall in Executive Summary.
5) Pg 7. Third paragraph. Second sentence. Please write out the word "three" instead of using "3"
6) Pg 7. Third paragraph. Last sentence. Please change to read: "This indicates that the benthos are resistant to disturbances, resilient, and recover over time".
7) Pg 8. First paragraph. Last sentence. Please change the last sentence to read: Benthic indicators (including oysters, clams, crab, and shrimp) were used by five of the seven BBESTs during the SB3 process to create inflow regimes.
8) Pg 7. Second paragraph. Last sentence. Please change "secondary" to "primary".
9) Pg 8. First sentence. Add "the" in front of TWDB.
10) Pg 8. Last paragraph. Last sentence. Please reword this sentence to make clear what influence with distance from the river means.
11) Pg 9. First sentence. Please add "the" in front of TWDB.

12) Pg 10. First paragraph under 5.1. Please change "This study has one objective…" to "This study had one objective…" to keep report in same tense throughout.
13) Pg 10. Second paragraph under 5.1 Please remove "work" after (Cl-BBASC 2012).
14) Pg 11. First sentence after Guadalupe Estuary Specific Outcomes. Please remove "work" after (GSA-BBASC 2012).
15) Pg 12. Last sentence. Please remove "is thus simple, and this", it is redundant.
16) Pg 13. Second sentence under 6.1. Please change commas to semi-colons between references to be consistent with the rest of the report. (Montagna and Kalke 1995; Kim and Montagna 2012; Van Diggelen and Montagna 2016)
17) Pg 13. Third sentence. Please change "(among estuary)" to "(among estuaries)"
18) Pg 17. Second sentence under 6.3.1. These values do not seem correct. For the accuracies, please refer to YSI or Hydrolab manual or site or previous article or standard operating procedures. Please specify depths that the measurements were taken."
19) Pg 17. First sentence under 6.3.3. Please change "(<0.4 °C)" to "(< 4.0 °C)" as referenced in the previous paragraph.
20) Page 19. Paragraph 1. Sentence 1. Sampling date is previously deemed a random effect (Pg 18. Last sentence) but are described as a main fixed effect here. Please clarify.
21) Pg 19. Fourth sentence under 6.5.4. Please add "Multidimensional scaling" before "(MDS) was used to compare…" or add an "n" to "MDS" as appropriate.
22) Pg 19. Last paragraph. First sentence. Please change "environmental" to "environment"
23) Pg 19. Last paragraph. Second sentence. Please explain what water column structure is being referred to here and what "each" is referencing.
24) Pg 19. Last paragraph. Fourth sentence. Please define what the "first two principal components" are.
25) Page 20. Paragraph 3. Sentence 1. Please clarify what was averaged and used in the exponential smoothing model.
26) Pg 24. First sentence. Please add a zero before the decimal for the P-value.
    a. "(P-value = < 0.0001)
27) Pg 28. Last sentence under 7.3. According to Table 5, the upper San Antonio Bay does not have the highest values for these variables stated (PO4, SiO4, and NOx) - East Matagorda appears to have the highest values for these variables. Please confirm and correct.
28) Pg 28. Last sentence under 7.3 states that Corpus Christi Bay has the lowest values for dissolved oxygen, pH, PO4, SiO4, NOx, and NH4, but Lavaca has the same values for PO4, SiO4, NOx, and NH4. Also, Nueces appears to have the lowest NH4 value, not Corpus Christi- according to Table 5. Please confirm and correct.
29) Pg 28. Last sentence under 7.3 references that the information coming from Table 3, but this should be Table 5.
30) Pg 29. First sentence. Please change "abundance" to "abundant".
31) Pg 29. Second sentence. Please change "with" to "which".
32) Pg 29. First paragraph. Last sentence. Please change "…is *Mulinia*…" to " …was *Mulinia*…" to keep a consistent tense throughout the report.
33) Pg 29. First paragraph. Last sentence. Please remove "is" before "a bivalve mollusk".
34) Page 30. Paragraph 1. Sentence 6. Please expand on or reword this sentence or move it to the discussion.
35) Pg 31. First sentence. References Table 5, but should be Table 7. Please change.

36) Pg 40. First sentence. Please change "but no the Nueces Estuary" to "but not the Nueces Estuary"
37) Page 45. Paragraph 1. Sentence 1. Please expand on what "best" means in the BIO-ENV analysis.
38) Pg 45. Second paragraph. Second sentence. Please add the word "the" before "highest salinities and three bays"
39) Pg 45. Second paragraph. Last sentence. Please change "is the location" to "was the location" to keep the tense consistent throughout the report.
40) Pg 48. First paragraph. Third sentence. Please change "wind storm" to "windstorm".
41) Pg 48. First paragraph. Fifth sentence. Please change "drive" to "drove" to keep the tense consistent throughout the report.
42) Pg 48. First paragraph. Sixth sentence. Please change "The biological responses are" to "The biological responses were" to keep the tense consistent throughout the report.
43) Pg 48. First paragraph. Seventh sentence. Please change "…dissolved oxygen deficits could kill…" to "…dissolved oxygen deficits, which could kill…".
44) Page 52. Paragraph 1. Please include means of bivalves in this paragraph as an average abundance is referenced. Please review and rework this paragraph.
45) Pg 53. First paragraph. First sentence. Please remove "a" before "devastating effect…"
46) Pg 53. Second paragraph. Third sentence. Please change "would have went…" to "would have gone …"
47) Pg 54. First paragraph. First sentence. Please change "There were only two periods…" to "There were only three periods…"
48) Page 55. Please remove figure from the margin (Richness vs. Date across stations across stations A, B, C, D before and after Hurricane Harvey).
49) Pg 55. First paragraph. First sentence. Please change "would have went…" to "would have gone …"
50) Pg 55. First paragraph. First sentence. Please use a lowercase "u" in "upper" to keep consistency throughout the report.
51) Pg 55. First paragraph. Second sentence. Please specify the location of "The biomass of the spring 2019 recruitment event", for example: The biomass of the spring 2019 recruitment event in the upper San Antonio Bay was also higher than expected and almost reached beyond the expected bounds.
52) Pg 56. First paragraph. First sentence. Please change "out of the bounds or the 95% confidence interval" to "out of the bounds of the 95% confidence interval".
53) Pg 56. First paragraph. Second sentence. Please change "In contrast, The recovery…" to "In contrast, the recovery".
54) Pg, 57. First paragraph. Third sentence. Please change "frequencies over 4- to 6-year periods to "frequencies over 4 to 6-year periods".
55) Pg 57. First paragraph. Fourth sentence. Please add the word "is" between "There" and "little"- "There is little in common…"
56) Pg 57. First paragraph. Seventh sentence. Please change "attainment frequencies base on 6 consecutive years" to "attainment frequencies based on six consecutive years".
57) Pg 57. First paragraph. Next to last sentence. Please change the sentence to read "For Nueces Bay and Delta, there are attainment frequencies for three time periods (November to February, March to June, and July to October) at three different "levels" where levels are defined as three different inflow regimes (wet, average, and dry).

58) Pg 57. First paragraph. Last sentence. Please add a period to the end of the sentence.
59) Pg 57. First paragraph under 8.1. First sentence. Please clarify this statement. "While the information generated is useful for evaluations made in each basin, we also learn about general ecological effects by comparing bays and estuaries than by investigating them individually."
60) Pg 57. First paragraph under 8.1. Second sentence. Please use a semicolon between references to keep consistency throughout the report. (Alber 2002; Montagna et al. 2013).
61) Pg 57. First paragraph under 8.1. Third sentence. Please use a semicolon between references to keep consistency throughout the report. (Montagna and Li 2010; Kim and Montagna 2012).
62) Pg 57. Paragraph under 8.1. Last sentence. Please check and correct Figure references, "Figure 7 for water quality differences, and Figure 4 for sediment quality differences." Figure 1. is the average monthly gauged inflow within estuaries. Figure 2. is principal component scores for seasons (winter, spring, summer, and fall) and estuaries.
63) Pg 58. Third paragraph. Please clarify the conclusions made here. On Pg 53 it states, "The short-term view makes it appear as if the Hurricane had a large devastating effect on benthos in San Antonio Bay" … "However, the long-term view makes it appear as if the storm did not matter at all".
64) Pg 58. Second paragraph under 8.3. Second sentence. Please use a semicolon between references, "(Kim et al. 2014; Pollack et al. 2011; Tolan 2007)."
65) Pg 58. Last paragraph. First sentence. Please add a comma after "development".
66) Page 59. Paragraph 3. Sentence 2. The complexity of the environmental flow standards can be recognized without explicitly stating it as a "problem". Please re-state.
67) Pg 59. First paragraph. Third sentence. Please change to read "In Tees Bay, United Kingdom, long-term changes in macrobenthos abundance, diversity, and community structure changed differently near the river mouth compared to far from it (Warwick et al. 2002).
68) Pg 59. First paragraph. Last sentence. Please remove. Please state findings not recommendations.
69) Pg 59. First paragraph under 8.4. Sixth sentence. Please remove the words "are identified".
70) Pg 60. Last paragraph. Next to last sentence. Please add an "s" to "standard" to make it plural.
71) Pg 60. Last paragraph. First sentence. Please change to "seven levels of summer"
72) Pg 63. Number 4. Please change to "as evidenced by the fact that five out of seven BBEST committees"
73) Pg 64. Work Plan Item 6. Please include climate change in introduction if it was an explicit topic in this report.
74) Pg 64. Number 2. Last sentence. Please add the word "of" between "all" and "which".
75) Pg 64. Number 4. Last sentence. Please remove the "s" at the end of "acts" to make it singular.

Figures and Tables Comments:

1) Figure 3. Please include how stations are divided into bays (Table 1).
2) Figure 7. Please include corresponding names of estuaries abbreviated in the legend in the caption. Please denote figure as "A)" and "B)" with appropriate text in caption.

3) Table 10. Please include units in caption and/or table.
4) Figure 16. Please use arrows to indicate landfall of hurricane and its path back to the GoM.
5) Figure 20. Please include more information regarding this figure in the caption.
6) Pg 24. Table 3 heading. Please add a space between "for" and "water".
7) Pg 25. Table 4 heading. Please check that this is correct (umol l^{-1})
8) Pg 27. Figure 7. Please add "p" to "component".
9) Pg 27. Figure 7. Please add symbols to the caption to denote which one is associated with winter, spring, summer, and fall.
10) Pg 39. Figure 12 caption. Please add a comma between "July" and "October".
11) Pg 42, Figure 13 caption. Please add a comma between "July" and "October".
12) Pg 42, Figure 13 caption. Please change the reference to "Figure 13" to "Figure 12".
13) Pg 44, Figure 14 caption. Please change the reference to "Figure 13" to "Figure 12".
14) Pg 55, Figure 22 caption. Please change the reference to "Figure 20", to "Figure 21".
15) Pg 56, Figure 23 caption. Please change the reference to "Figure 20", to "Figure 21".

SUGGESTED CHANGES

Specific Draft Final Report Comments:

1) Please include use of exponential smoothing model (ESM) in executive summary.
2) Pg 7. Paragraph 2. Sentence 2. Please clarify whether this supposed to be a comparison in size between the Guadalupe and Colorado-Lavaca Estuary. Also, limited exchange with the Gulf of Mexico may be additional explanations as to why San Antonio Bay has a lower long-term average salinity than Lavaca Bay.
3) Pg 15. Next to last sentence. Consider changing "25 August 2017" to "August 25, 2017".
4) Pg 41. First sentence. Please remove "only".
5) Pg 48. First sentence. Consider changing "25 August 2017" to "August 25, 2017"
6) Pg 48, First paragraph. Fourth sentence. Add a hyphen between "1:1000" and "year event", making it "1:1000-year event".
7) Pg 49. First paragraph. Last sentence. Consider changing "6 October 2017" to "October 6, 2017".
8) Pg 49. First paragraph. Last sentence. Consider changing "9 October 2017" to "October 9, 2017".
9) Pg 54. First paragraph. First sentence. Please clarify the meaning of "the abundance forecast was off", such as, "the abundance forecast fell outside of the 95% confidence band".
10) Pg 57. First paragraph. Second sentence. Consider changing "30 August 2012" to "August 30, 2012,".
11) Pg 57. First paragraph. Second sentence. Consider changing "6 March 2014" to "March 6, 2014,…"

Figures and Tables Comments:

1) Pg 26. Figure 6 caption. Consider adding a space before "A)" and "B)" for better readability.

10.3 Review of Draft Final Report

This review of the final report was received May 26, 2022.

Long-Term Benthic Data: Adaptive Management of Three Basins

TWDB Contract #2000012436
Comments to Draft Final Report

REQUIRED CHANGES

General Draft Final Report Comments:

Specific Draft Final Report Comments:

1) Pg 7. First paragraph. Last sentence. Please add a space between "and" and "291 from Nueces Estuary".
2) Pg 7. Second paragraph. Third sentence. Please change this sentence to read "San Antonio Bay is small and has limited exchange with the Gulf of Mexico, therefore it has lower long-term average salinity than Lavaca Bay."
3) Pg 7. Third paragraph. Second sentence. Please write out the word "three" instead of using "3"
4) Pg 8. Second paragraph. First sentence. Please remove "between relationship".
5) Pg 12. Please add a comma after each Task and Priority #. For example: "Task 11, Refine estimates…" and "Priority 1, Life Cycle Habitat…"
6) Pg 18. First sentence under 6.3.3. Please change "(<0.4 °C)" to "(< 4.0 °C)" as referenced in the previous paragraph.
7) Pg 20. Last paragraph. Second sentence. Please change "was analyzed" to "were analyzed".
8) Pg 20. Last paragraph. Next to last sentence. Please remove "order to discover".
9) Pg 22. First full sentence. Please change "patterns is tested" to "patterns was tested".
10) Pg 53. First paragraph. Last sentence. Please delete the word "**Error!**"
11) Pg 54. Second paragraph. Last sentence. Please change "implying" to "implies".
12) Page 57. Please remove figure from the margin (Richness vs. Date across stations across stations A, B, C, D before and after Hurricane Harvey).
13) Pg 59. First paragraph. Seventh sentence. Please spell out the number 6 "attainment frequencies based on six consecutive years".
14) Pg 59. First paragraph under 8.1. Last sentence. Please add a space between "Figure" and "7".
15) Pg 62. First paragraph. Fifth sentence. Please change "brough" to "brought".
16) Pg 62. First paragraph. Seventh sentence. Please add an "in" between "occur" and "East Matagorda".
17) Pg 62. Second paragraph. Last sentence. Please change "and it found primarily" to "and is found primarily".
18) Pg 63. Second paragraph. Third sentence. Please remove "along" from the end of the sentence "…to far from it along (Warwick et al. 2002)."

Figures and Tables Comments:

1) Pg 53. Figure 19. Each graph is labeled twice (A., A); B. B); C., C)). Please delete one set of labels.
2) Pg 53. Figure 19. In the caption, please delete "**Reference source not found**.".
3) Pg 56. Figure 21 caption. Last line. Please remove the space between "Low" and "er" to connect the word Lower.
4) Pg. 57. Figure 22 caption. Last line. Please remove the space between "Low" and "er" to connect the word Lower.
5) Pg. 58. Figure 23 caption. Last line. Please remove the space between "Low" and "er" to connect the word Lower.

SUGGESTED CHANGES

Specific Final Report Comments:

Figures and Tables Comments: