CONTRACT No. 1800012223
FINAL REPORT RECIEVED: 02/26/20

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

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TWDB Contract # 1800012223

January 2020

Pursuant to Senate Bill 1 as approved by the 85th Texas Legislature, this study report was funded for the purpose of studying environmental flow needs for Texas rivers and estuaries as part of the adaptive management phase of the Senate Bill 3 process for environmental flows established by the 80th Texas Legislature. The views and conclusions expressed herein are those of the author(s) and do not necessarily reflect the views of the Texas Water Development Board.

Cite as:

Montagna, P.A. and P.M. Cockett, and M. Rohal. 2020. Using Comparative Long-term Benthic Data for Adaptive Management of Freshwater Inflow to Three Basins. Final Report to the Texas Water Development Board, Contract # 1800012223. Texas A&M University-Corpus Christi, Corpus Christi, Texas, 87 pp.

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

Table of Contents

1 List of Figures ... 3
2 List of Tables ... 5
3 Acknowledgements ... 6
4 Executive Summary ... 7
5 Introduction ... 8
  5.1 Objectives ... 10
  5.2 Approach ... 12
6 Methods ... 13
  6.1 Study Area ... 13
  6.2 Sediment Samples ... 16
    6.2.1 Sample Collection ... 16
    6.2.2 Laboratory Analyses ... 16
  6.3 Water Samples ... 17
    6.3.1 Hydrographic Measurements ... 17
    6.3.2 Chlorophyll ... 17
    6.3.3 Nutrients ... 17
  6.4 Hydrology ... 17
  6.5 Analytics ... 18
    6.5.1 Diversity Indicators ... 18
    6.5.2 Estuary and Bay Differences ... 18
    6.5.3 Community Structure ... 19
    6.5.4 Conditions ... 19
    6.5.5 Time Series Identification ... 20
    6.5.6 Time Series Analysis ... 21
    6.5.7 Linking Inflow Events and Communities ... 21

7 Results ... 22
7.1 Bioindicator Identification ... 23
7.2 Condition Identification ... 29
7.3 Inflow Identification ... 31
7.4 Time Series Identification ... 33
7.4.1 Physical Setting ... 33
7.4.2 Macrofauna ... 37
7.4.3 Multivariate Autoregressive State Space (MARSS) Model ... 41
7.5 Linking Inflow Events and Communities ... 48
7.5.1 Long-term Dynamics ... 48
7.5.2 Hurricane Harvey ... 49
8 Discussion ... 54
8.1 Spatial Considerations ... 54
8.2 Temporal Considerations ... 54
8.3 Linking Inflow, Salinity, and Ecological Response ... 55
8.4 Evaluating Inflow Standards ... 56
8.5 Using Benthic Data in the Adaptive Management Process ... 59
8.5.1 Lavaca-Colorado Estuary Specific Outcomes ... 59
8.5.2 Guadalupe Estuary Specific Outcomes ... 60
8.5.3 Nueces Estuary Specific Outcomes ... 60
9 References ... 62
10 TWDB Review Comments and Responses ... 70
10.1 Review ... 70
10.2 Response to Comments ... 80

1 List of Figures

Figure 1. Long-term benthic sampling stations overlaid with the track of Hurricane Harvey (August 2017)....................9

Figure 2. Conceptual model of the Domino Theory of inflow effects on estuary biological resources (from Montagna et al. 2013)....................10

Figure 3. The three Texas Coastal Bend estuaries sampled. Station locations are along a climatic (among estuaries) and estuarine (within estuaries) gradients....................14

Figure 4. nMDS Plot of community structure by estuary and bay. Each symbol on the nMDS is representative of an estuary....................24

Figure 5. nMDS Plot of community structure by estuary and bay with PCA of hydrodynamic measurements overlaid....................25

Figure 6. Principal Components (PC) Analysis of estuary condition indicators. A) PC1 versus PV2. B) PC2 versus PC3....................30

Figure 7. Principal comonent scores for seasons (winter, spring, summer, and fall) and estuaries....................30

Figure 8. Average monthly gauged inflow within estuaries. Each point represents a monthly average inflow estuary-wide....................31

Figure 9. Average monthly inflow in three estuaries from January 1986 to December 2015. 32

Figure 10. Average monthly temperature estuary-wide, with a linear regression over time and 95% confidence limits....................34

Figure 11. Average monthly dissolved oxygen (DO) concentrations estuary-wide with a linear regression over time and with 95% confidence limits....................35

Figure 12. Average monthly salinity practical salinity unites (psu) estuary-wide with a linear regression over time and 95% confidence limits....................36

Figure 13. Average quarterly (January, April, July October) $\log_{10}$ transformed benthic infauna abundance by bay from 1987-2018....................37

Figure 14. Average quarterly (January, April, July October) log10 transformed benthic infauna biomass by bay from 1987-2018....................39

Figure 15. Average quarterly (January, April, July October) log10 transformed benthic infauna Hill's N1 diversity by bay from 1987-2018....................40

Figure 16. Time series for taxa group log abundances in the Lavaca-Colorado Estuary....................42

Figure 17. Time series for taxa group log abundances in the Guadalupe Estuary....................43

Figure 18. Time series for taxa group log abundances in the Nueces Estuary. 44

Figure 19. Stability metrics for benthic infauna communities in estuaries and bays. 47

Figure 20. Continuous salinity measurements at station GE-A in the Guadalupe Estuary (From: Walker et al. 2019). 49

Figure 21. Continuous dissolved oxygen measurements at station GE-A in the Guadalupe Estuary (From: Walker et al. 2019). 50

Figure 22. Benthic metrics three quarters before and three quarters after Hurricane Harvey. 51

Figure 23. Long-term benthic dynamics used to predict benthic metrics in October 2018 to July 2019.. 53

2 List of Tables

Table 1. Locations of bays and stations within the Guadalupe (GE), Lavaca-Colorado (LC), and Nueces (NC) estuaries. 15

Table 2. Archived samples analyzed during the current study. 16

Table 3. Averages for all macroinfauna and hydrographic variables sampled quarterly in each estuary from 1987-2018. 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. 22

Table 4. Average infauna species abundance (n m^{-2}) measured in each bay over all samples collected from 1987-2018. Abbreviation: Cum%= cumulative percent. 23

Table 5. ANOVA results for macrofauna total abundance (n/m^2), biomass (g/m^2), diversity (Hill N1), and evenness (Pielou J′). DF = degrees of freedom. 25

Table 6. Benthic metrics (average and standard error) by stations within estuaries. 26

Table 7. ANOVA results for dissolved oxygen (DO), salinity (Sal), temperature (Temp), pH, NH4, PO4, SiO4, and NOx. DF = degrees of freedom. 27

Table 8. Water column constituent concentration (umol l^{-1}) average and standard error by stations within estuaries. 28

Table 9. Linear regression for abundance ($\log_{10}$ n + 1), biomass ($\log_{10}$ g +1), diversity (N1) over time by bay. 38

Table 10. Strength of taxa interactions for the primary bays in three estuaries. 45

Table 11. Strengths of taxa interactions for secondary bays in three estuaries. 46

Table 12. Spearman correlations (r) and probability that the correlation equals zero (p) for the relationship between macrofauna abundance, biomass, and diversity and salinity, DO, and temperature by estuary from 1987-2018. 48

Table 13. Bay and estuary freshwater inflow standards for Lavaca Bay System [30 TAC §298.330(a)(2)]. 57

Table 14. Bay and estuary freshwater inflow standards for Matagorda Bay Inflows from the Colorado River Basin [30 TAC §298.330(a)(2)]. 57

Table 15. 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)]. 58

Table 16. Bay and estuary freshwater inflow standards for Nueces Bay and Delta [TAC §298.430(a)(3)]. 59

3 Acknowledgements

Funding for the project was supplied by the Texas Water Development Board (TWDB), General Revenue Fund under Interagency Cooperation Contract # 1800012223. The authors thank the TWDB program manager, Evan L. Turner, for guidance and support.

Many people at the Harte Research Institute helped in the analysis of this work, this includes Richard Kalke, Larry Hyde, and Elani Morgan. Parts of this report are derived from Master Theses from Meaghan Hardegree and Elaine Kurr.

4 Executive Summary

This goal of this project is to extend the long-term dataset of benthos (i.e., bottom-dwelling) species/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 (Matagorda, San Antonio, and Corpus Christi), but since 2009 there have been insufficient funds to complete the analysis of collected samples. This study extended those initial efforts to document benthic conditions by analyzing 324 archived samples from all three basins.

The bay systems have different long-term characteristic fauna that reflects the long-term average salinity conditions in each bay system. San Antonio Bay is small, so it has a lower long-term average salinity than Lavaca Bay even though they have about the same amounts of freshwater inflow. 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 systems, the secondary bays have distinct communities compared to the primary bays. This is because the secondary bays are closer to freshwater inflow sources and are more oligohaline and brackish in nature than the secondary bays, which can be more marine influenced.

The time period analyzed included the effects of the flood caused by Hurricane Harvey in San Antonio Bay. When taking a short-term view, i.e., analyzing data from 3 quarters prior and 3 quarters after the hurricane induced flood, it appears as if the benthos were devastated by the flood and then recovered slowly. However, taking a long-term view by analyzing the data from 2004 to 2018, it is noted that there is 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. This indicates that the benthos are both resistant to disturbances, and resilient and recover over time.

The time-series of benthic data is critical information for the Senate Bill 3 environmental flows adaptive management process, because it will provide a rich, multi-decade dataset from which to evaluate the effectiveness of current freshwater inflow standards in three basin-bay systems along the mid-Texas coast.

5 Introduction

Since the early 1970's, 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 to create inflow regimes by five of the seven BBESTs during the SB3 process. Only two basins (Brazos River and Lower Laguna Madre) did not use these benthic indicators, because these systems are unique, and datasets were unavailable. The Brazos is a riverine habitat and the Lower Laguna Madre is a high-salinity seagrass habitat.

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 estuary is distinct, they share similar geographical features. Estuaries form at the mouth of a river, where freshwater from a river flows into a secondary bay. The secondary bays are connected to primary bays, which are open to the Gulf of Mexico and influenced by tides. Thus, within each estuary there is a salinity gradient from lower salinity secondary bays to higher salinity primary bays, and this is demonstrated by sampling stations A – D along this gradient in each estuary (Figure 1). To identify effects of the Colorado River, stations E and F were added in January 1993 to Matagorda Bay. Although each estuary shares common geographical attributes with the others, these sites offer a spatial comparison, because salinity within each bay varies due to differences in freshwater inflow. All the long-term stations in Figure1 have been sampled quarterly since 2004. In 2017, 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, so identifying effects and recovery from Harvey is a critical part of the analyses.

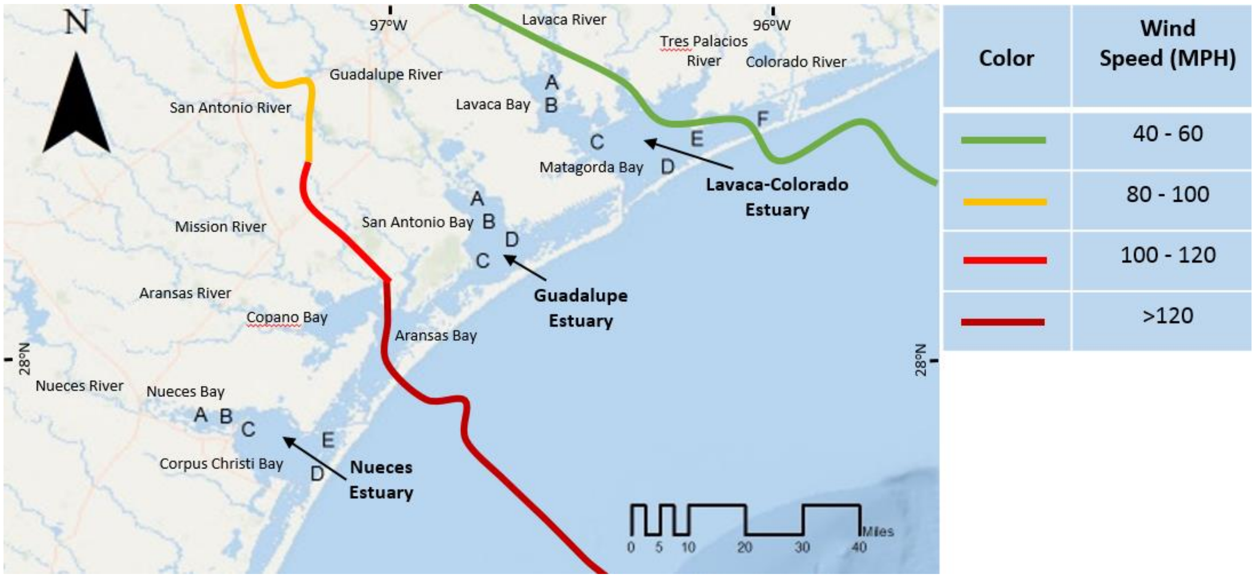

Figure 1. Long-term benthic sampling stations overlaid with the track of Hurricane Harvey (August 2017).

The long-term benthic studies sponsored by TWDB have helped change the fundamental understanding of how freshwater inflow affects living marine resources. 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).

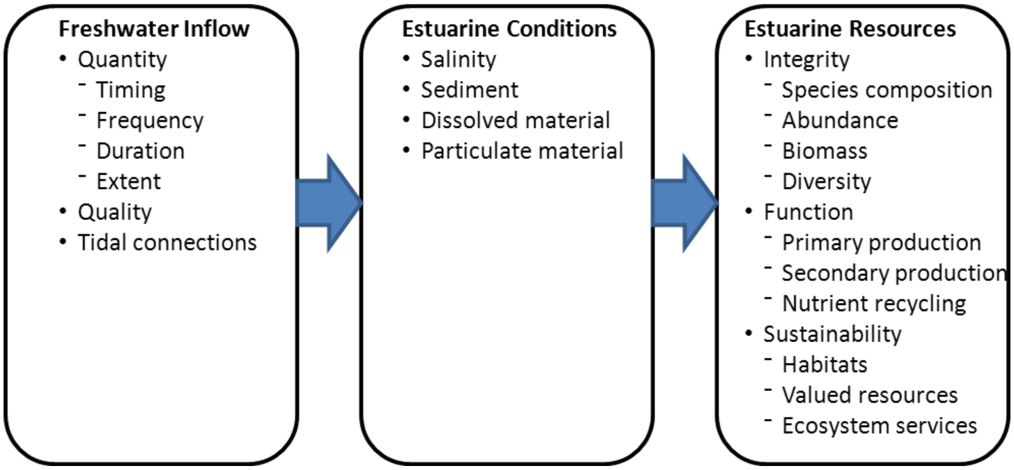

Figure 2. Conceptual model of the Domino Theory of inflow effects on estuary biological resources (from Montagna et al. 2013).

5.1 Objectives

This study has have 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) work 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.

Guadalupe Estuary Specific Outcomes: 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) work 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.

Nueces Estuary Specific Outcomes: 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 1). 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 thus simple, and this 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 all stations in the Lavaca-Colorado Estuary, Guadalupe Estuary, Nueces Estuaries during two other projects: 1) in January, April, July, and October 2017, and January, April, July 2018 using funds from a National Oceanic and Atmospheric Administration award # NA15NOS4780185, entitled "The Hydrological Switch: A Novel Mechanism Explains Eutrophication and Acidification of Estuaries;" and 2) in October 2018, and January, April, and July 2019 using funding from the National Science Foundation award #1760006, entitled "RAPID: Capturing the Signature of Hurricane Harvey on Texas Coastal Lagoons." The original Scope of Work for the present study was to analyze older archived benthic samples, however in addition the 2018 benthic samples were also analyzed to capture the effect of the hurricane.

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 (Montagna and Kalke 1995, Kim and Montagna 2012, Van Diggelen and Montagna 2016). This is because there is a climatic gradient (among estuary) 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.

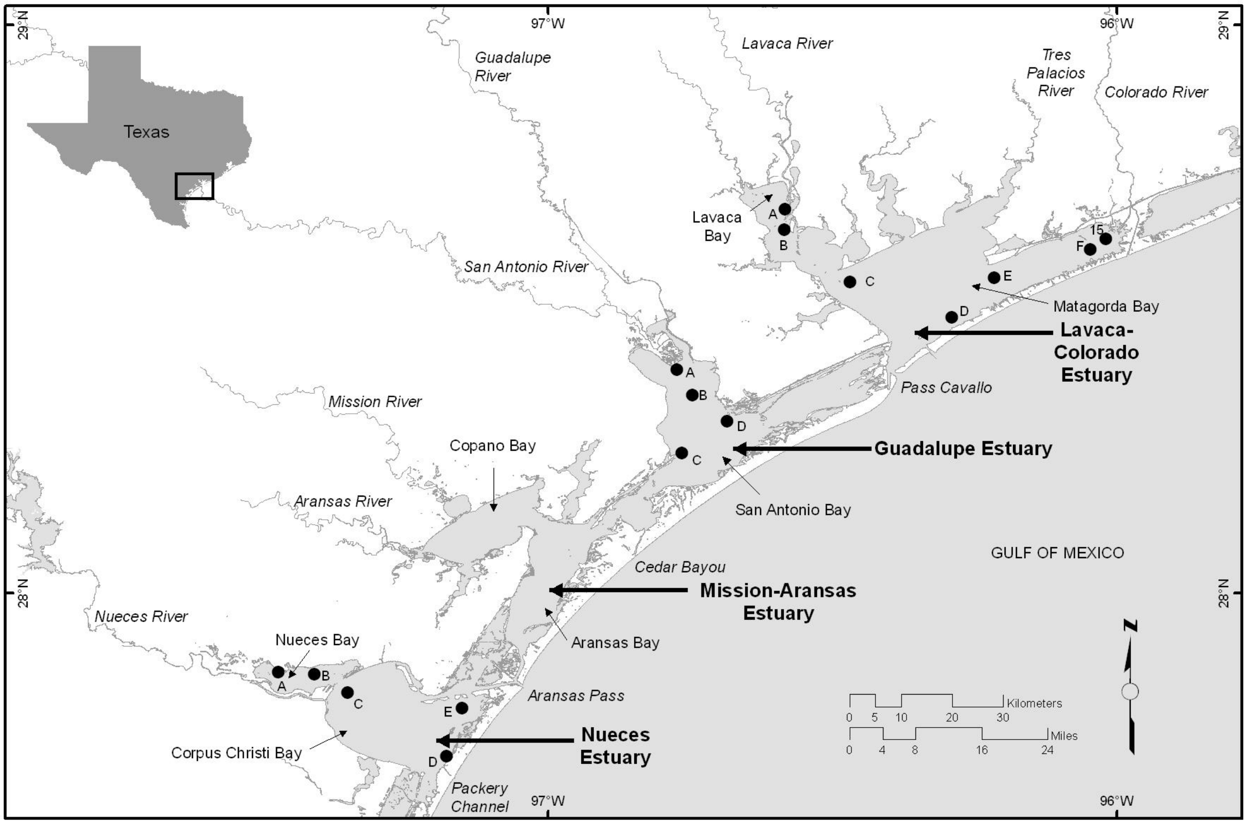

Figure 3. The three Texas Coastal Bend estuaries sampled. Station locations are along a climatic (among estuaries) and estuarine (within estuaries) gradients.

Stations were located in primary bays closer to the Gulf of Mexico exchange point, and in secondary bays closer to the freshwater inflow sources (Table 1). Four stations were sampled for macrofauna and water quality in the Guadalupe Estuary, seven 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	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	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 471 archived samples were analyzed during the current study. Of these, 402 were considered part of the Hurricane Harvey study because they were collected from 2017 and 2018. Hurricane Harvey hit the Texas coast in 25 August 2017, so the Scope of Work was to analyze samples for a two-year period, one year before and one year after the storm (Table 2A). The large number of samples analyzed was due to the concurrent running of two other projects: 1) a National Oceanic and Atmospheric Administration project to study the effects of freshwater inflow on the eutrophication and acidification of the same three estuaries plus Baffin Bay (Montagna et al. 2019), and a National Science Foundation project to examine the effects of the flooding caused by Hurricane Harvey. Together, the three concurrent projects enabled us to accomplish more work than originally planned, and this benefits the TWDB and BBASCs. An additional 69 archived benthic samples were analyzed that were from the period 2009 to 2012 (Table 2B).

Table 2. Archived samples analyzed during the current study.

Estuary	Period	Quarters	Stations	Archived Samples
A. Hurricane Harvey				
Lavaca-Colorado	10/2016 - 10/2018	9	7	189
Guadalupe	10/2016 - 10/2018	9	4	108
Nueces	10/2016 - 4/2018	7	5	105
Subtotal		*25*	*16*	*402*
B. Archives				
Lavaca-Colorado	4/2009 - 10/2012	15	1	45
Guadalupe		0	4	0
Nueces	1/2010 - 10/2011	8	1	24
Subtotal		*23*	*6*	*69*
Total all Samples				*471*

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 YSI 6600 multi parameter instrument by lowering the sonde into the water. The following parameters were read from the digital display unit (accuracy 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 (<0.4 °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: bioindicator identification, condition identification, and identification the flow regimes necessary to maintain those conditions.

6.5.1 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 *i*th 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':

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

6.5.2 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 full random variable effect. 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 $j=1, 2, 3, \ldots, 133$ 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.

6.5.3 Community Structure

Community structure of macrofauna species was analyzed by non-metric multidmensional scaling (MDS) 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. MDS 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 MDS plot to elucidate grouping of station-date combinations. The group average cluster mode was used for the cluster analysis along with a SIMPROF test to identify statistically different groups.

Multivariate analyses were used to analyze how the physical-chemical environmental changes over time. The water column structure was each analyzed using Principal Component Analysis (PCA). PCA reduces multiple environmental variables into component scores, which describe the variance in order to discover the underlying structure in a data set (Clarke and Warwick 2001). In this study, only the first two principal components were used.

6.5.4 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 studies (Arismendez et al. 2009; Pollack et al. 2009, 2011; Palmer et al. 2011, 2016; Paudel and Montagna 2014).

6.5.5 Time Series Identification

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. To examine and identify the time series, lag, and autocorrelation responses, we use the multivariate autoregressive state space (MARSS) modeling framework (Holmes et al. 2012a, 2012b). This approach has been used successfully to identify flow needs to maintain fishery harvest in the Mekong River (Sabo et al. 2018) and has been used examine blue crab response to inflow in Mission-Aransas and Guadalupe Estuaries (Buskey et al. 2015). The multivariate technique can also be used to investigate the effects of other abiotic and biotic variables that could be driving the biological responses (Hampton et al. 2013). Confounding factors such as concentrations of toxic materials, low dissolve oxygen, or low pH can thus be identified as having a role in the response. In this way, we identify response complexities, inter-connectedness, and factors that could confound the relationship between inflow and biological responses. The model formulation is:

$$X_t = A + BX_{t-1} + CU_{t-1} + E_t \sim MVN(0,Q)$$

Where X = variates (standardized abundance), A = intrinsic growth, B = interaction coefficients, C = effect of covariates on variates, E = process errors, and Q = variance covariance.

An analysis of eigen values ($\det(B)^2$) of the estimated interaction strengths (B matrix of MARSS model) can provide information on the stability of the bay systems. Stability refers to the return time to the stationary distribution of taxa (i.e., the average long-term benthic abundance) following a perturbation. Thus, the response of taxa abundance to environmental fluctuations can be determined for specific bays to estimate the stability or resilience of the benthic infauna community.

6.5.6 Time Series Analysis

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, all replicates for all stations for each quarter were averaged to create one value for the whole bay for each quarter. 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. 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.

6.5.7 Linking Inflow Events and Communities

Community structure is linked with environmental variables using the non-metric multivariate BIO-ENV procedure 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.

7 Results

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 3). The highest diversity was found in Corpus Christi bay with the lowest values in Lavaca Bay (Table 3). The highest evenness was found in Corpus Christi Bay and the lowest value was found in Upper San Antonio Bay (Table 3). Therefore, Lavaca Bay contained the lowest values for all macrofauna community metrics. With regard to hydrographic variables the highest values for dissolved oxygen, pH, PO4, SiO4, and NOx were found in Upper San Antonio Bay and the lowest values were found in Corpus Christi Bay which also had the lowest NH4 values (Table 3)

Table 3. Averages for all macroinfauna and hydrographic variables sampled quarterly in each estuary from 1987-2018. 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**	**Lower San Antonio**	**Upper San Antonio**	**Corpus Christi**	**Nueces**
Abundance (n m^{-2})	5,852	11,892	10,515	9,701	19,255	16,140	11,670
Biomass (g m^{-2})	1.23	5.61	3.15	6.07	12.12	9.19	7.87
Diversity (N1 35 cm $^{-2}$)	2.87	5.76	3.52	3.78	2.99	8.45	5.56
Evenness (J´ 35 cm $^{-2}$)	0.67	0.75	0.67	0.66	0.63	0.76	0.74
DO (mg l^{-1})	8.00	7.48	8.60	8.04	8.61	6.91	7.48
Salinity	17.44	25.90	20.75	18.88	11.55	32.12	27.62
Temperature (°C)	22.13	22.20	22.83	22.65	22.80	22.59	22.89
pH	8.13	8.13	8.25	8.20	8.31	8.12	8.13
NH4 (µmol l $^{-1}$)	2.62	1.53	3.21	1.64	2.52	1.31	2.07
PO4 (µmol l $^{-1}$)	1.91	0.83	1.89	1.73	2.95	0.55	1.69
SiO4 (µmol l $^{-1}$)	94.08	45.38	59.27	98.45	139.41	46.47	104.14
NOx (µmol l $^{-1}$)	4.77	1.45	9.38	4.36	21.24	0.73	2.04

7.1 Bioindicator Identification

The 13 most abundance species all had at least 1% of the total abundance (Table 4). The most abundant species was *Mediomastus ambiseta* with accounted for 39.1% of total species abundance. *Mediomastus ambiseta* was most abundant in Upper San Antonio Bay and least abundant in Lavaca Bay. *Streblospio benedicti* is the second most abundant species which accounted for 11.6% of total species abundance. *Streblospio benedicti* was most abundant in Upper San Antonio Bay and least abundant in Matagorda Bay.

Table 4. Average infauna species abundance (n m^{-2}) measured in each bay over all samples collected from 1987-2018. 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*	3,387	4,079	7,389	7,425	4,892	3,863	3,653	4,955	39.2%	39%
2	*Streblospio benedicti*	867	282	1,203	4,971	928	1,267	588	1,444	11.4%	51%
3	*Mulinia lateralis*	382	457	1,077	1,829	662	1,081	104	799	6.3%	57%
4	*Dipolydora caulleryi*	0	839	868	1	213	526	2,351	685	5.4%	62%
5	*Texadina sphinctostoma*	11	0	0	2,839	245	0	0	442	3.5%	66%
6	*Tharyx setigera*	2	101	1	0	16	516	1,925	366	2.9%	69%
7	Oligochaeta (unidentified)	16	520	382	240	11	12	713	270	2.1%	71%
8	Nemertea (unidentified)	88	315	207	174	170	138	345	205	1.6%	73%
9	*Apseudes* sp. A	0	1,294	0	0	0	0	0	185	1.5%	74%
10	*Cossura delta*	176	515	159	54	69	88	228	184	1.5%	75%
11	*Ampelisca abdita*	183	10	171	258	30	286	35	139	1.1%	77%
12	*Gyptis brevipalpa*	11	216	61	14	53	242	350	135	1.1%	78%
13	*Clymenella torquata*	2	19	0	0	74	469	323	127	1.0%	79%
	Subtotal dominant species	5,124	8,647	11,518	17,804	7,364	8,488	10,616	9,937		79%
	Subtotal other Species	688	3,210	1,658	1,480	2,335	3,314	6,212	2,700		21%
	Total	5,813	11,857	13,175	19,284	9,699	11,802	16,828	12,637		100%

The nMDS analysis of macrofauna community metrics found three different statistical groupings of bays (Figure 4). The first group contains Upper San Antonio, East Matagorda, and Lavaca Bays. The second group contains Nueces and Lower San Antonio Bays. The third group contains Corpus Christi and Matagorda Bays. None of the bays within each of the three estuaries grouped all together. The groups were based on distance from a river or Gulf of Mexico inlet.

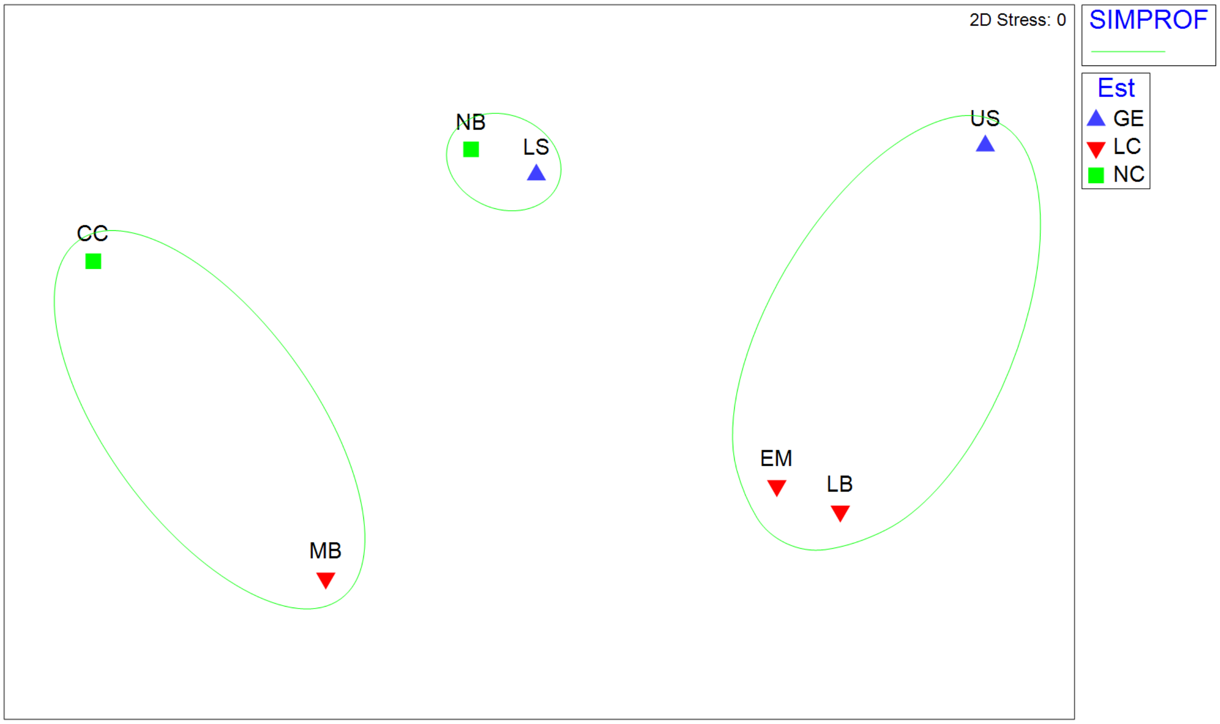

Figure 4. nMDS Plot of community structure by estuary and bay. Each symbol on the nMDS is representative of an estuary.
Bay symbol abbreviations: CC = Corpus Christ, EM = East Matagorda, LB = Lavaca Bay, LS = lower San Antonio, MB = Matagorda Bay, NB = Nueces Bay, US = Upper San Antonio.

The nMDS analysis of macrofauna community metrics was overlaid with a PCA of the water quality variables (Figure 5). Three bays (Matagorda, East Matagorda, and Lavaca Bays) had higher ammonia (NH4) and dissolved oxygen (DO). Corpus Christi and Nueces Bays had highest salinities.

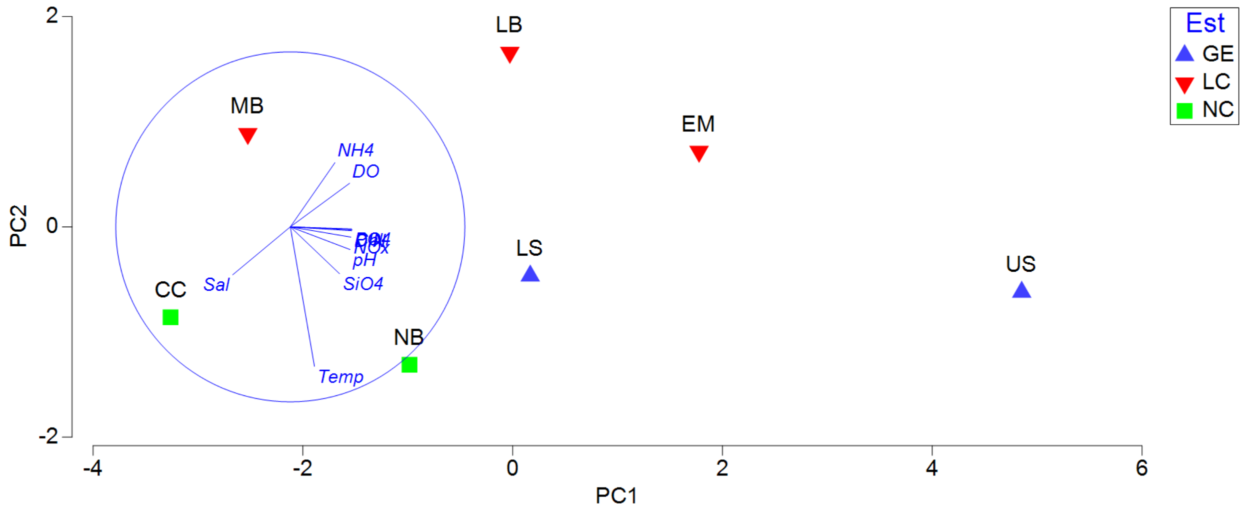

Figure 5. nMDS Plot of community structure by estuary and bay with PCA of hydrodynamic measurements overlaid.
Each symbol on the nMDS is representative of an estuary, and bay labels as in Figure 4.

An ANOVA of macrofauna metrics of abundance, biomass, diversity, and evenness were statistically different by date (P-Value = <.0001), station (P-Value = <.0001), and the station*date*bay interaction (P-Value = <.0001) (Table 5). 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 5. ANOVA results for macrofauna total abundance (n/m^2), biomass (g/m^2), diversity (Hill N1), and evenness (Pielou J´). DF = degrees of freedom.

				P-Value			
	F-Test	**Source**	**DF**	**Abundance**	**Biomass**	**N1**	**J´**
1	1/5	Date	125	<.0001	0.0015	<.0001	0.0007
2	2/(3+4+5)	Est	2	0.6920	0.2393	0.1059	0.0718
3	3/(4+5)	Bay(Est)	4	0.0986	0.7597	0.3543	0.3783
4	4/5)	Sta(Est*Bay)	9	<.0001	<.0001	<.0001	<.0001
5	5/6	Date*Sta(Est Bay)	1285	<.0001	<.0001	<.0001	<.0001
6		Error	2937				

Table 6. Benthic metrics (average and standard error) by stations within estuaries.

Estuary-Bay	Abundance ($n\ m^{-2}$) Mean	StdErr	Biomass ($g\ m^{-2}$) Mean	StdErr	Diversity (N1/sample) Mean	StdErr
LC-A	6,356	307	1.39	0.14	2.8	0.1
LC-B	5,269	242	1.04	0.08	2.9	0.1
LC-C	9,638	475	4.90	0.49	5.7	0.2
LC-D	16,258	1,065	7.41	0.64	6.4	0.2
LC-E	9,691	688	4.36	0.94	5.0	0.2
LC-F	9,499	670	2.92	0.40	3.6	0.1
GE-A	21,975	1,026	20.96	2.25	3.3	0.1
GE-B	16,535	1,191	3.27	0.24	2.7	0.1
GE-C	8,600	534	2.48	0.33	2.9	0.1
GE-D	10,802	532	9.66	2.55	4.7	0.2
NC-A	8,838	398	3.87	0.47	3.4	0.1
NC-B	14,287	735	12.64	0.82	7.8	0.2
NC-C	11,978	416	10.13	0.63	9.1	0.2
NC-D	12,930	919	3.58	0.39	4.9	0.2
NC-E	24,935	717	15.55	0.85	12.6	0.2

Patterns of benthic metrics among stations are different in different estuaries (Table 6). In the Lavaca-Colorado estuary, abundance biomass and diversity increase from the rivers (stations A, B, E, and F) to the sea (stations C and D). In the Guadalupe Estuary, abundance and biomass decrease from near the river (A and B) toward the sea (stations C and D). In the Nueces Estuary, abundance biomass and diversity increase from the rivers (stations A, B) to the sea (stations C and E). In Nueces, station D, metrics are lower because of hypoxia, which occurs every summer.

An ANOVA of hydrographic metrics of dissolved oxygen, salinity, temperature, pH, NH4, PO4, SiO4, and NOx were different by date (P-Value = <.0001), and bay (Table 6). There was no difference across estuaries.

Table 7. ANOVA results for dissolved oxygen (DO), salinity (Sal), temperature (Temp), pH, NH4, PO4, SiO4, and NOx. DF = degrees of freedom.

			P-Value							
N	**F-Test**	**Source**	**DO**	**Sal**	**Temp**	**pH**	**NH4**	**NOx**	**PO4**	**SiO4**
1	1/5	Date	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
2	2/(3+4)	Est	0.177	0.0682	0.2371	0.1579	0.4110	0.3723	0.3988	0.3537
3	3/4	Bay(Est)	0.0004	0.0009	0.0075	<.0050	0.0037	0.0480	0.0035	0.0008
4	4/5	Sta(Est*Bay)	0.0001	<.0001	0.7318	0.0936	0.1396	<.0001	0.0175	<.0001
5	5/5	Error								

As mentioned above, dissolved oxygen concentration is lowest at station D in the Nueces estuary (Table 8). Salinity increases from the rivers (A and B) to the sea (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 8. Water column constituent concentration (umol l^{-1}) average and standard error by stations within estuaries.

Estuary-Bay	DO		Salinity		Temperature		pH		NH4		NOx		PO4		SiO4	
	Mean	StdErr	Mean	StdErr	Mean	StdErr	Mean	StdErr	Mean	StdErr	Mean	StdErr	Mean	StdErr	Mean	StdErr
LC-A	8.07	0.14	15.99	0.88	22.22	0.60	8.13	0.05	2.22	0.26	5.08	1.00	1.60	0.13	102.0	6.3
LC-B	7.93	0.13	18.88	0.81	22.04	0.60	8.13	0.04	3.02	0.86	4.46	0.98	2.23	0.94	86.2	5.9
LC-C	7.53	0.12	24.39	0.61	22.05	0.60	8.08	0.03	1.50	0.15	1.62	0.39	0.78	0.07	54.7	4.1
LC-D	7.28	0.13	27.82	0.40	22.06	0.57	8.12	0.02	1.54	0.18	1.04	0.18	0.71	0.06	38.1	2.9
LC-E	7.49	0.18	25.39	0.58	22.33	0.67	8.15	0.03	1.67	0.23	1.43	0.28	0.99	0.09	45.6	4.0
LC-F	8.42	0.29	20.73	0.87	22.75	0.65	8.25	0.04	3.23	0.52	7.71	1.52	1.76	0.18	61.5	4.8
GE-A	8.75	0.23	9.33	0.72	22.93	0.58	8.32	0.04	3.05	0.35	31.76	3.99	3.50	0.30	151.1	12.6
GE-B	8.46	0.22	13.77	0.77	22.67	0.58	8.31	0.04	2.00	0.23	10.82	1.45	2.39	0.24	127.7	10.6
GE-C	8.09	0.16	18.52	0.85	22.66	0.59	8.24	0.03	1.66	0.23	4.82	1.11	1.81	0.18	102.6	7.6
GE-D	7.98	0.15	19.24	0.85	22.65	0.58	8.16	0.03	1.62	0.21	3.91	0.76	1.64	0.17	94.3	6.1
NC-A	7.52	0.13	25.73	0.93	22.85	0.57	8.13	0.03	2.41	0.30	2.34	0.33	2.08	0.12	124.0	6.9
NC-B	7.44	0.12	29.50	0.67	22.92	0.57	8.13	0.03	1.73	0.23	1.75	0.28	1.31	0.09	84.3	5.5
NC-C	7.09	0.12	31.56	0.42	22.79	0.56	8.12	0.02	1.33	0.23	0.79	0.11	0.63	0.06	49.6	3.6
NC-D	6.62	0.17	32.96	0.45	22.39	0.57	8.15	0.02	1.54	0.21	0.87	0.17	0.55	0.07	46.2	3.3
NC-E	7.03	0.13	31.86	0.41	22.60	0.59	8.08	0.02	1.04	0.11	0.51	0.08	0.48	0.06	43.4	3.4

7.2 Condition Identification

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.

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.

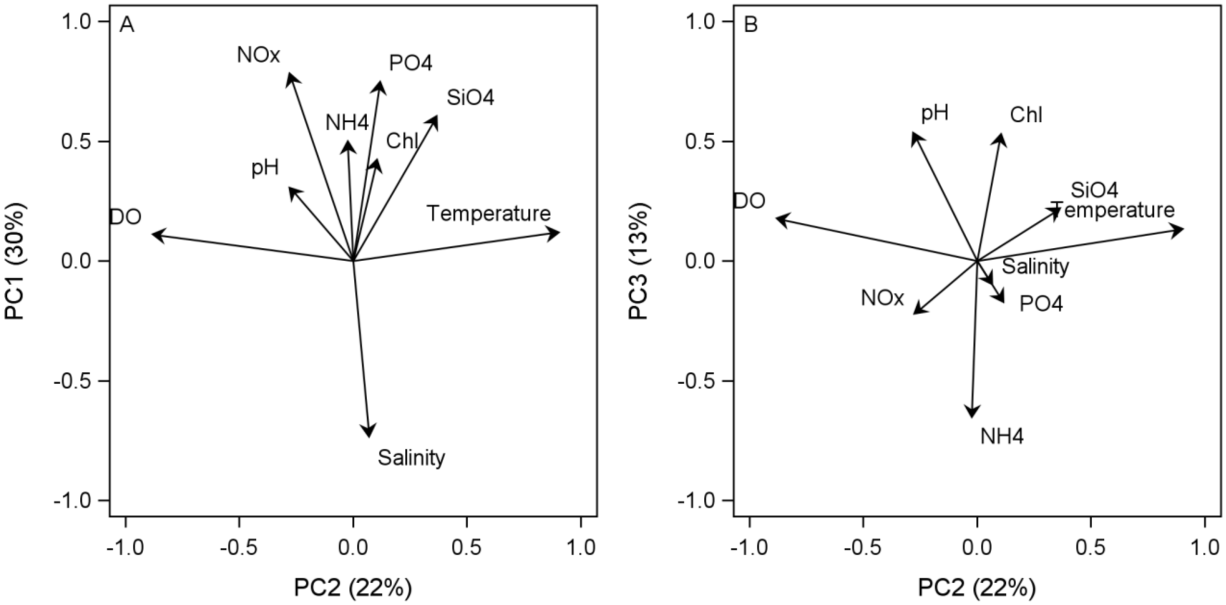

Figure 6. Principal Components (PC) Analysis of estuary condition indicators. A) PC1 versus PV2. B) PC2 versus PC3.

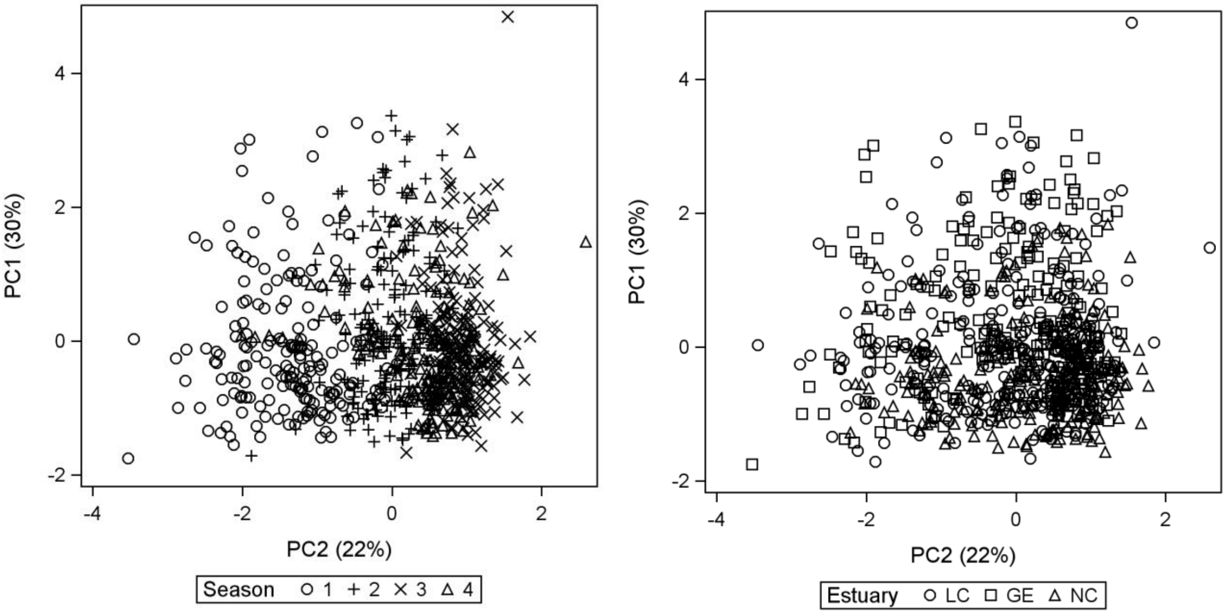

Figure 7. Principal comonent scores for seasons (winter, spring, summer, and fall) and estuaries.

7.3 Inflow Identification

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 8). 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.

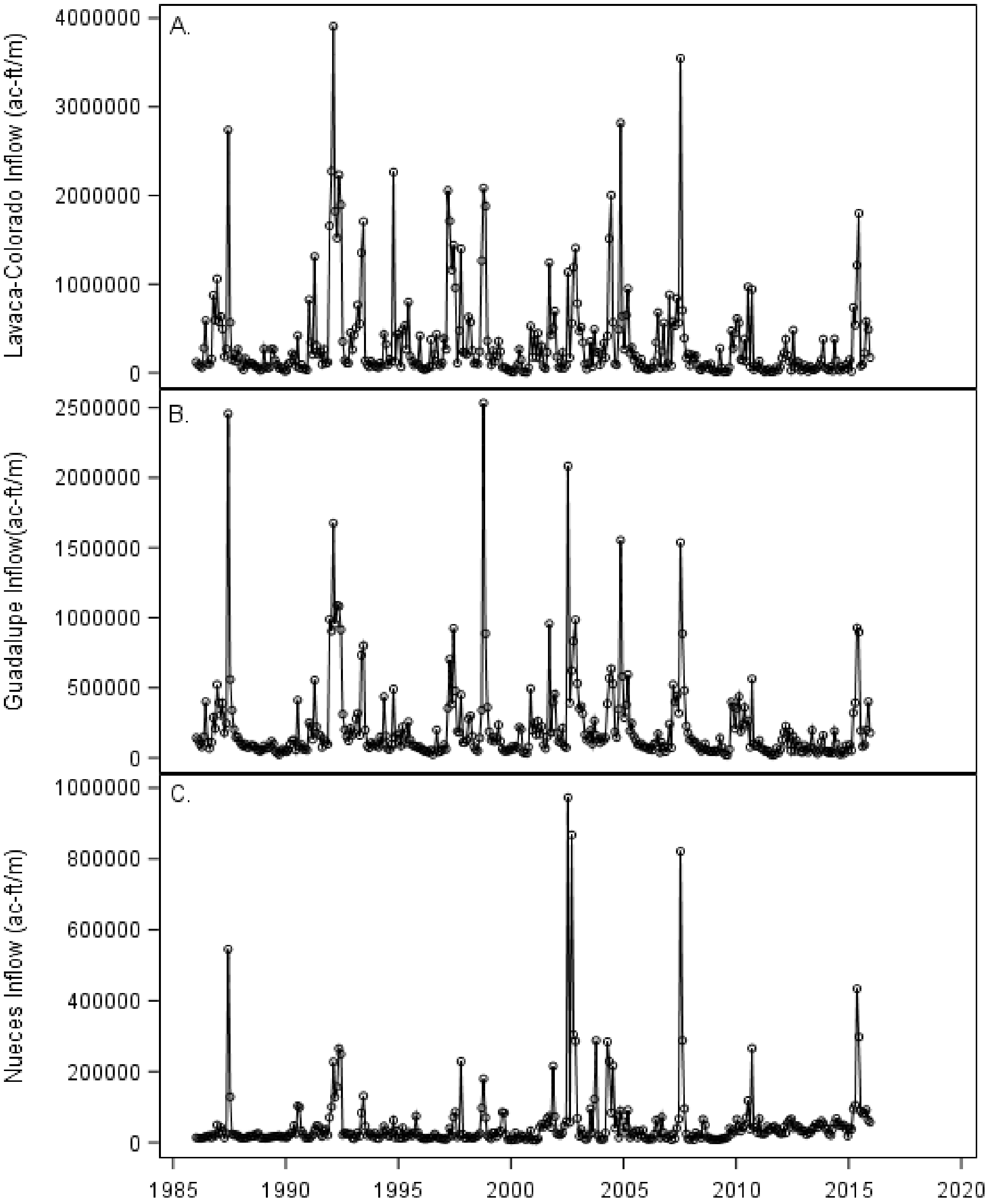

Figure 8. Average monthly gauged inflow within estuaries. Each point represents a monthly average inflow estuary-wide.

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 9). All of the estuaries have the lowest average monthly inflow in August.

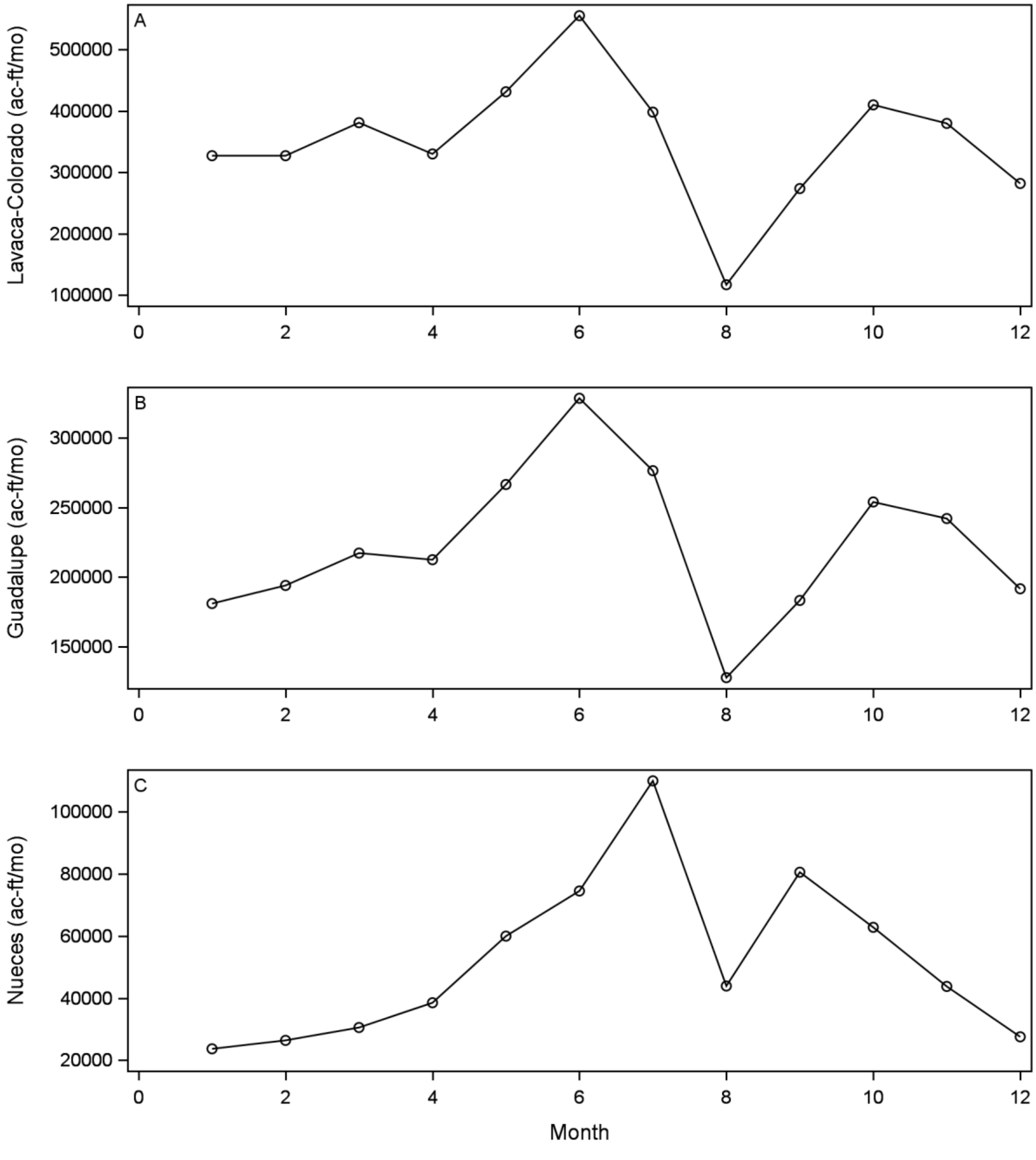

Figure 9. Average monthly inflow in three estuaries from January 1986 to December 2015.

7.4 Time Series Identification

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 10). 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).

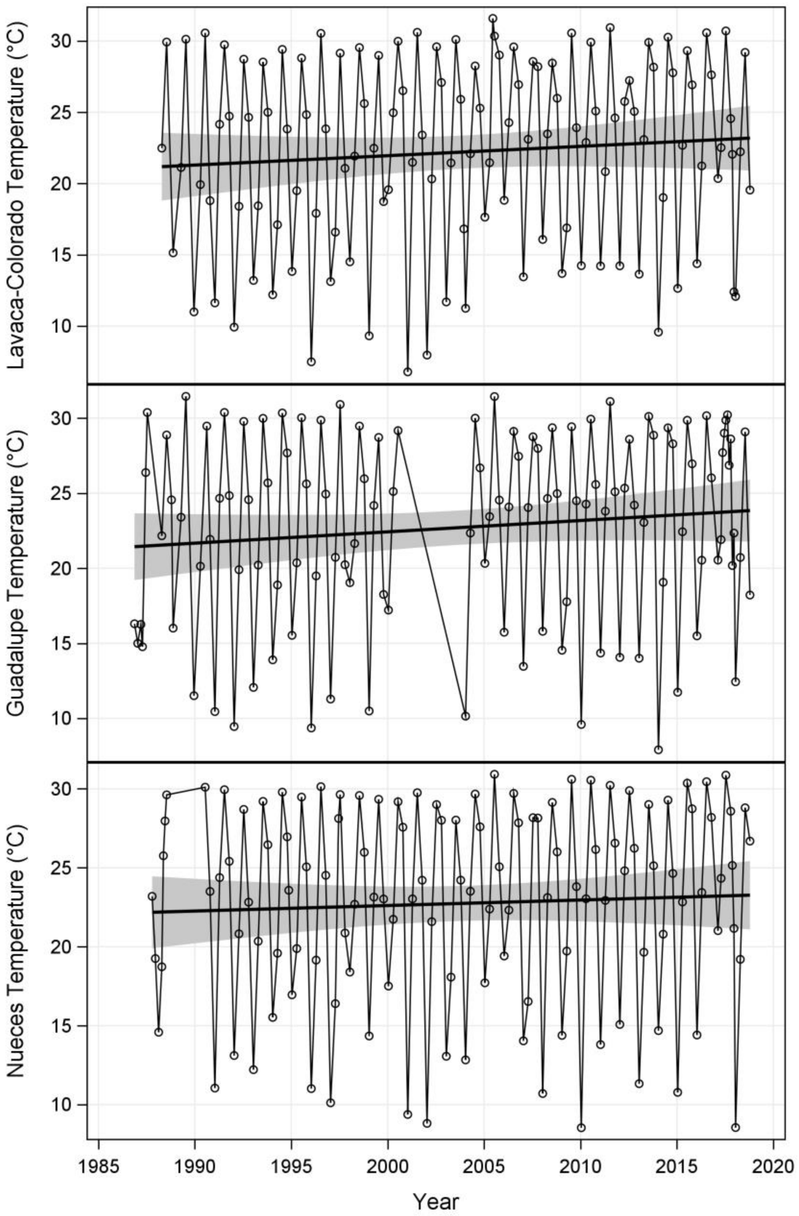

Figure 10. Average monthly temperature estuary-wide, with a linear regression over time and 95% confidence limits.

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 11). 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.

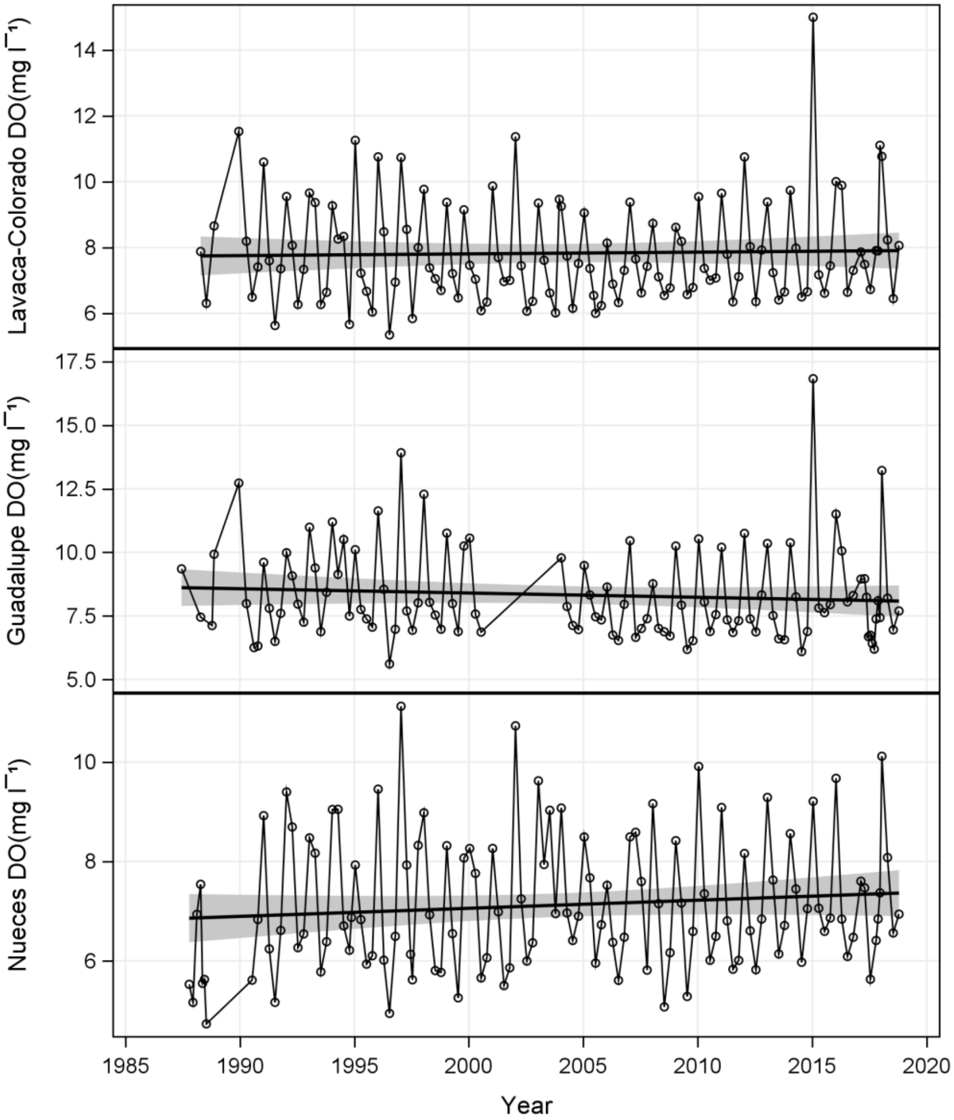

Figure 11. Average monthly dissolved oxygen (DO) concentrations estuary-wide with a linear regression over time and with 95% confidence limits.

Salinity slightly increased over the course of the study within each estuary (Figure 12). 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.

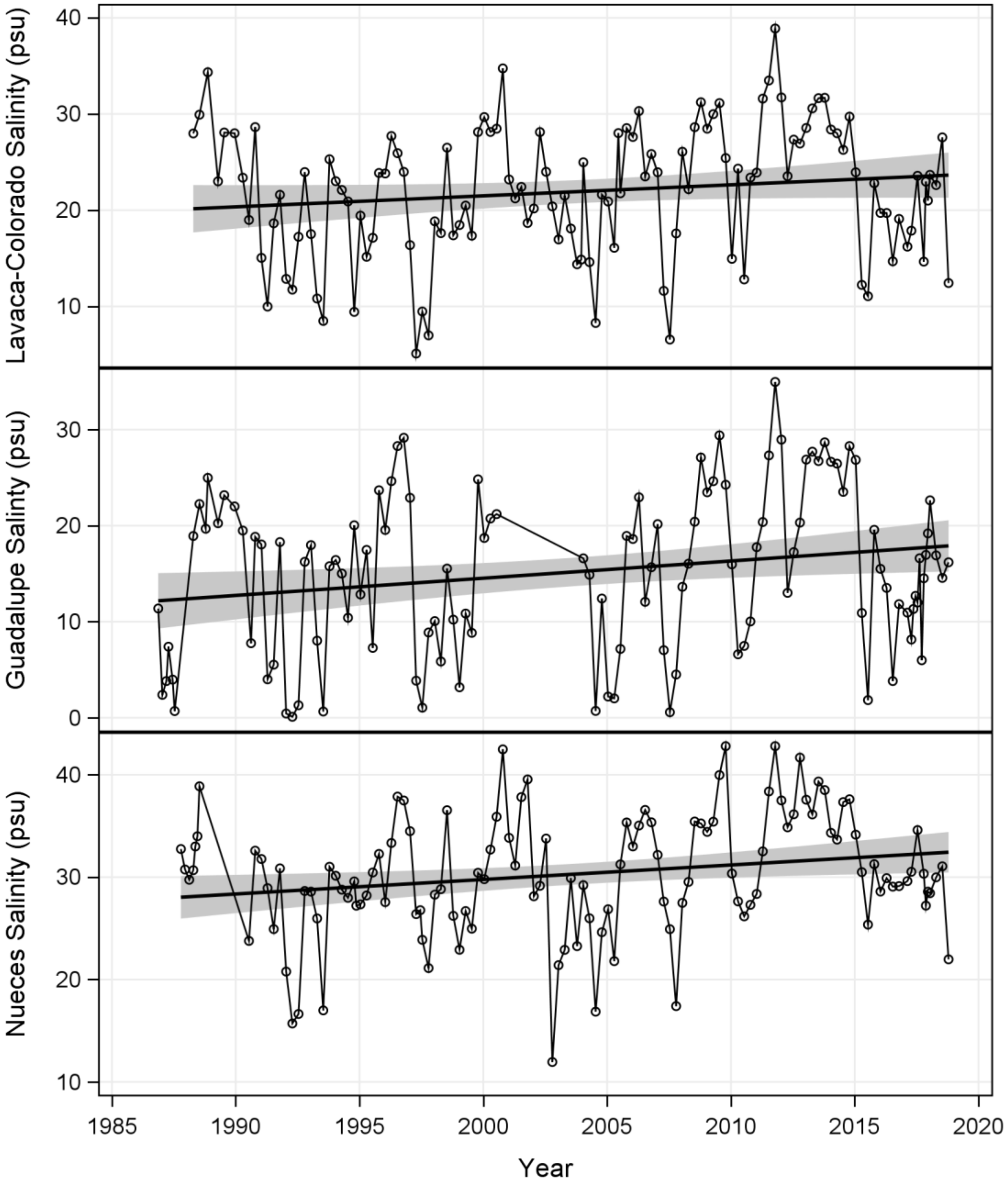

Figure 12. Average monthly salinity practical salinity unites (psu) estuary-wide with a linear regression over time and 95% confidence limits.

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 13).

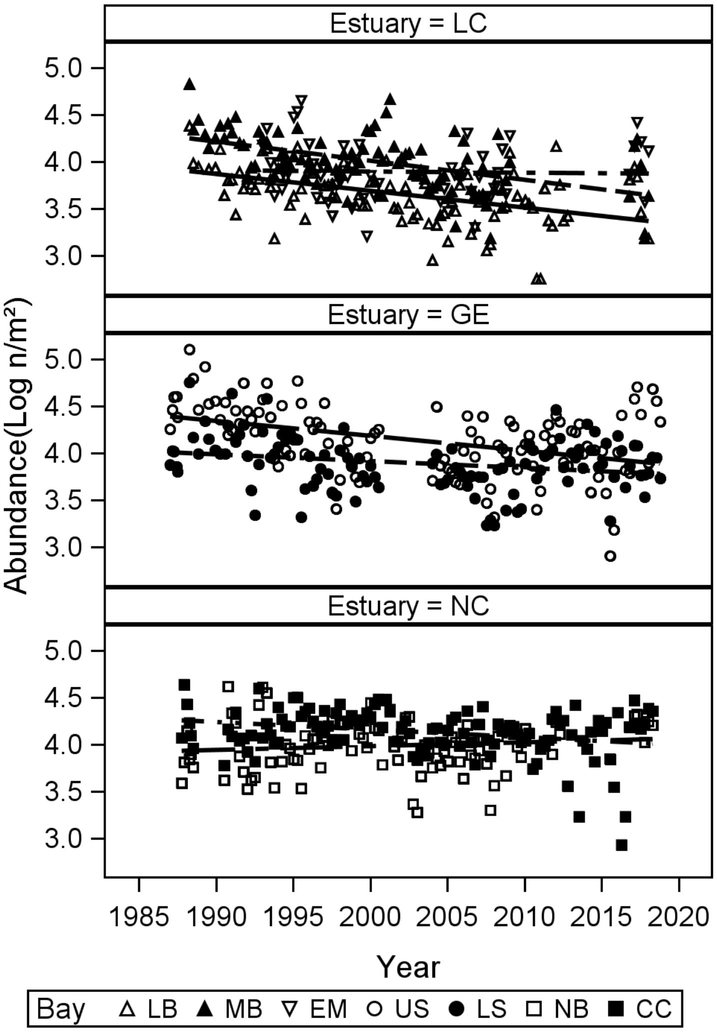

Figure 13. Average quarterly (January, April, July October) $\log_{10}$ transformed benthic infauna abundance by bay from 1987-2018.
Lavaca-Colorado Estuary (LC) includes Lavaca Bay (LB, open triangles), Matagorda Bay (MB, closed triangles), and East Matagorda Bay (EM, open upside down triangles). Guadalupe Estuary (GE) includes Upper San Antonio Bay (US, open circles) and Lower San Antonio Bay (LS filled circles). 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 no 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.

	Abundance			Biomass		
***Bay**	**Model**	**R2**	**p**	**Model**	**R2**	**p**
LB	Y = 47.34 - 0.02183 X	21%	< 0.0001	Y = 57.55 - 0.02884	17%	0.0001
MB	Y = 54.67 - 0.02532 X	30%	< 0.0001	Y = 57.19 - 0.02829	23%	0.0001
US	Y = 65.09 - 0.03049 X	34%	< 0.0001	Y = -46.55 + 0.02374	10%	0.0042
LS	Y = 55.66 - 0.02592 X	34%	< 0.0001	Y = 67.65 - 0.03375	19%	0.0001
NB	Y = 9.91 - 0.00298 X	1%	0.5476	Y = 0.587 + 0.00003	0%	0.9967
CC	Y = 15.15 - 0.00549 X	3%	0.0917	Y = -5.30 + 0.00310	1%	0.5053

	Diversity		
***Bay**	**Model**	**R2**	**p**
LB	Y = 396.45 - 0.1943 X	11%	0.0029
MB	Y = 1321.6 - 0.6529 X	39%	< 0.0001
US	Y = 184.62 - 0.0881 X	8%	0.0143
LS	Y = 404.4 - 0.1975 X	11%	0.0036
NB	Y = -246.14 + 0.1308 X	2%	0.2462
CC	Y = -980.32 + 0.5029 X	17%	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.

Benthic infauna biomass declined only in both bays of the Lavaca-Colorado Estuary (Figure 14, 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.

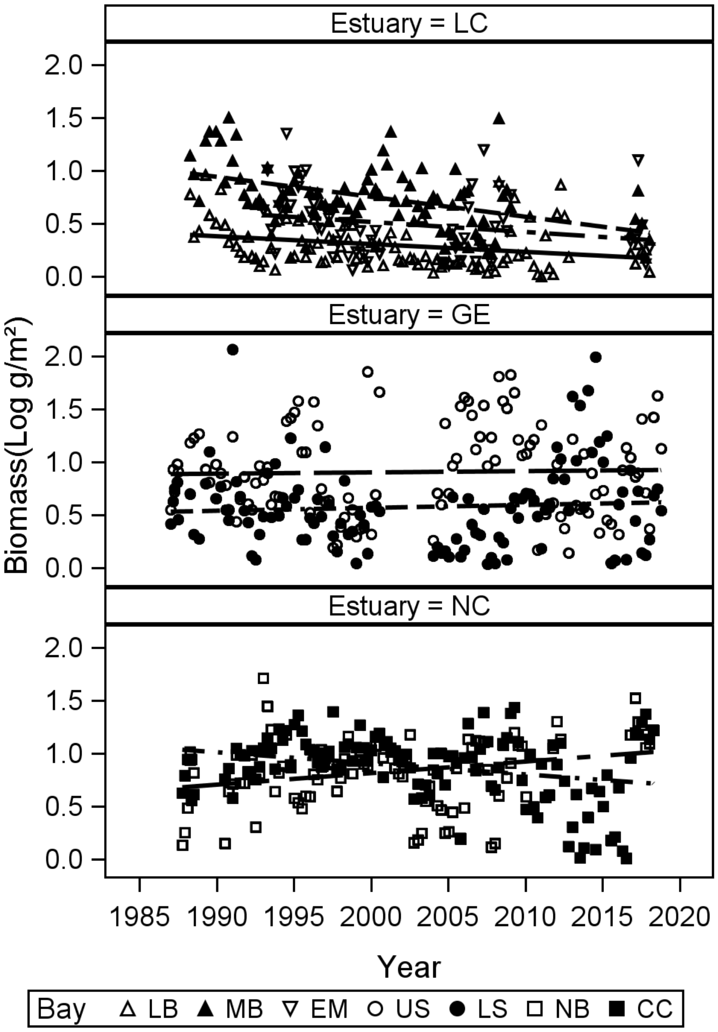

Figure 14. Average quarterly (January, April, July October) log10 transformed benthic infauna biomass by bay from 1987-2018.
Lavaca-Colorado Estuary (LC) includes Lavaca Bay (LB, open triangles), Matagorda Bay (MB, closed triangles), and East Matagorda Bay (EM, open upside down triangles). Guadalupe Estuary (GE) includes Upper San Antonio Bay (US, open circles) and Lower San Antonio Bay (LS filled circles). Nueces Estuary (NC) includes Nueces Bay (NB, open squares) and Corpus Christi Bay (CC, filled squares).

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 15). Primary bays had higher diversity than secondary bays for all estuaries.

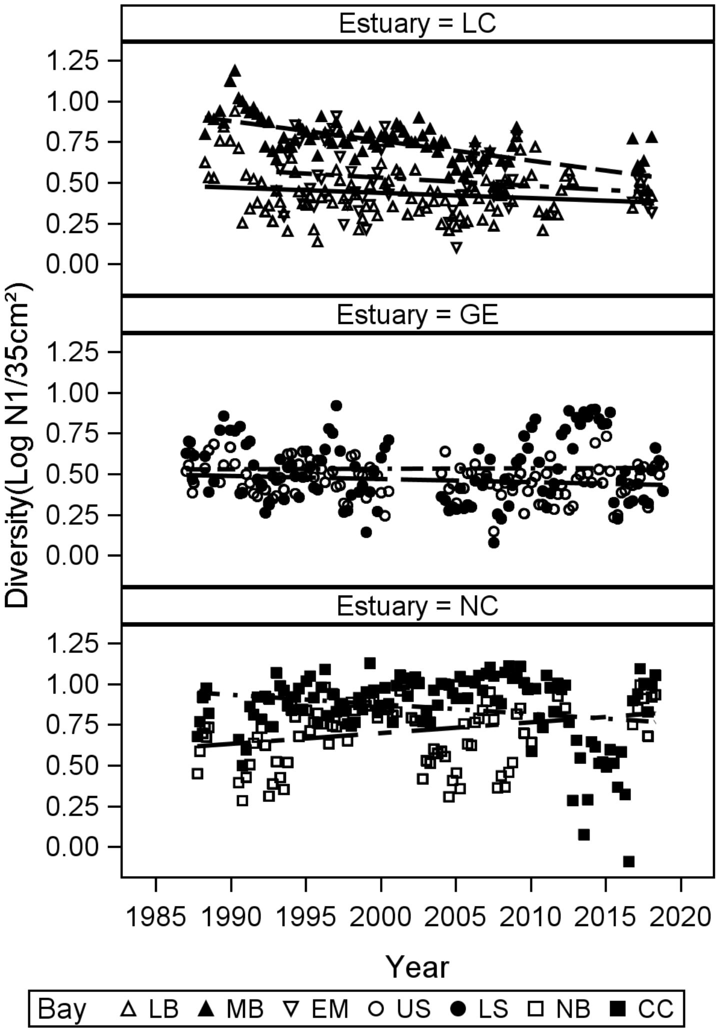

Figure 15. Average quarterly (January, April, July October) log10 transformed benthic infauna Hill's N1 diversity by bay from 1987-2018.
Lavaca-Colorado Estuary (LC) includes Lavaca Bay (LB, open triangles), Matagorda Bay (MB, closed triangles), and East Matagorda Bay (EM, open upside down triangles). Guadalupe Estuary (GE) includes Upper San Antonio Bay (US, open circles) and Lower San Antonio Bay (LS filled circles). Nueces Estuary (NC) includes Nueces Bay (NB, open squares) and Corpus Christi Bay (CC, filled squares).

7.4.3 Multivariate Autoregressive State Space (MARSS) Model

A multivariate autoregressive state space (MARSS) model was fit to time series data of five taxa. A MARSS model can be used to measure the stability of a system which is the response of taxa to long-term change in the environment, such as those caused by natural seasonal effects or perturbations such as low dissolved oxygen. The stability is indicated by analyzing the eigen values of the estimated taxa interaction coefficients or B matrix of the fit MARSS models. Species were pooled prior to analysis to produce four taxa groups (Crustacea, Mollusca, Nemertea, Polychaeta, and other taxa. The analyses were also performed on the primary bays and the secondary bays (Figures 16 - 18).

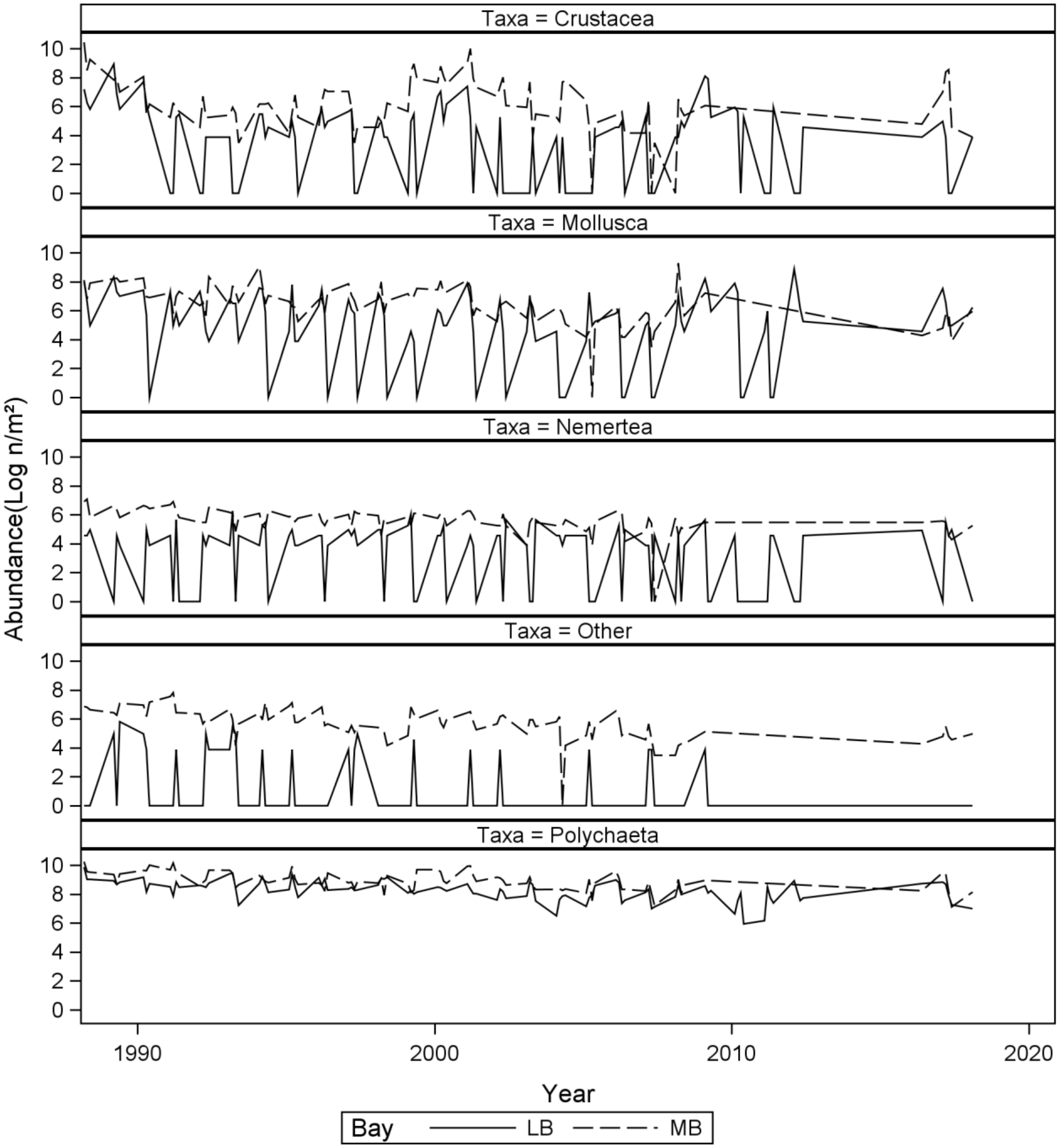

Figure 16. Time series for taxa group log abundances in the Lavaca-Colorado Estuary. LB = Lavaca Bay and MB = Matagorda Bay.

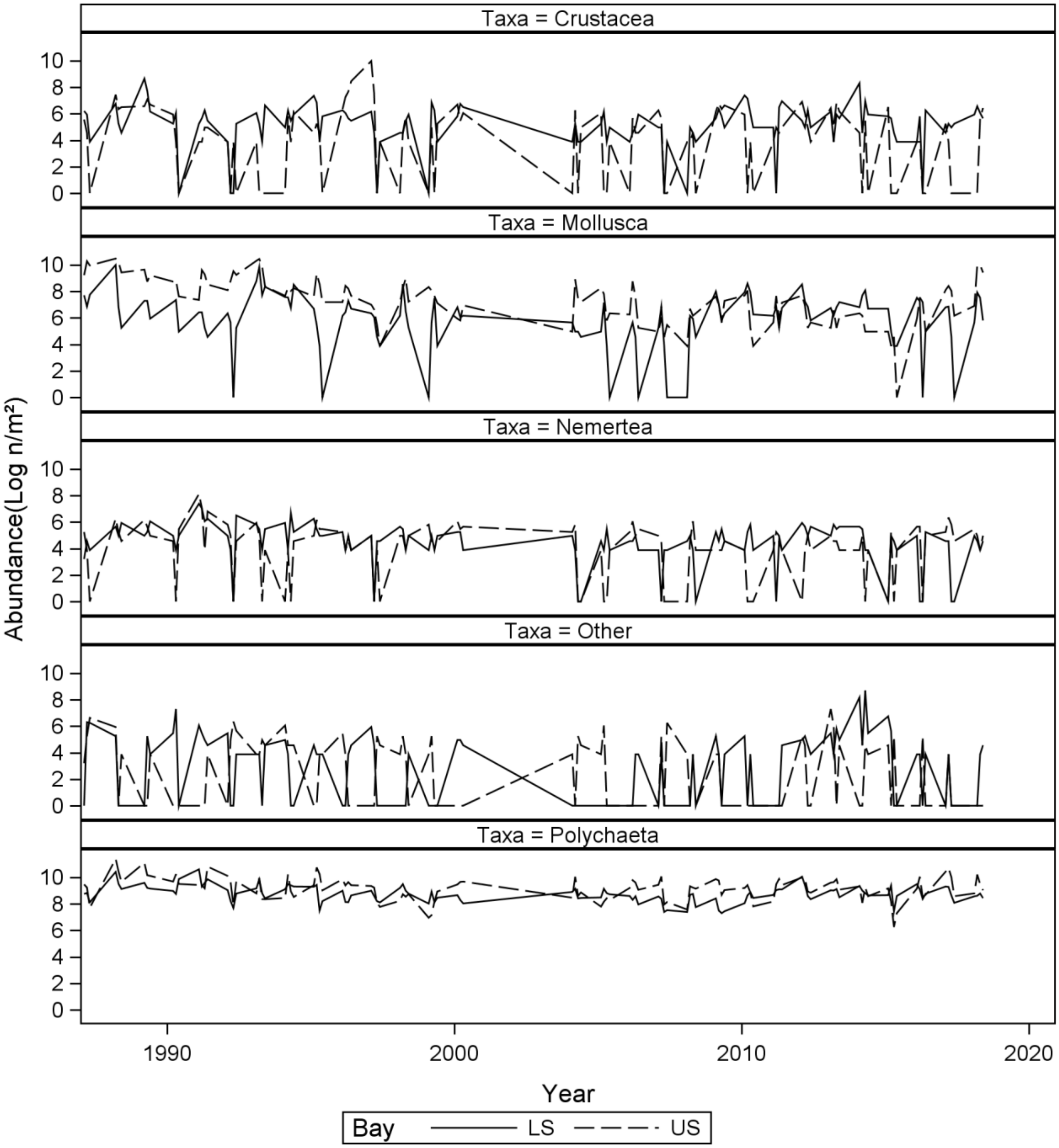

Figure 17. Time series for taxa group log abundances in the Guadalupe Estuary. LS = Lower San Antonio Bay, US = Upper San Antonio Bay.

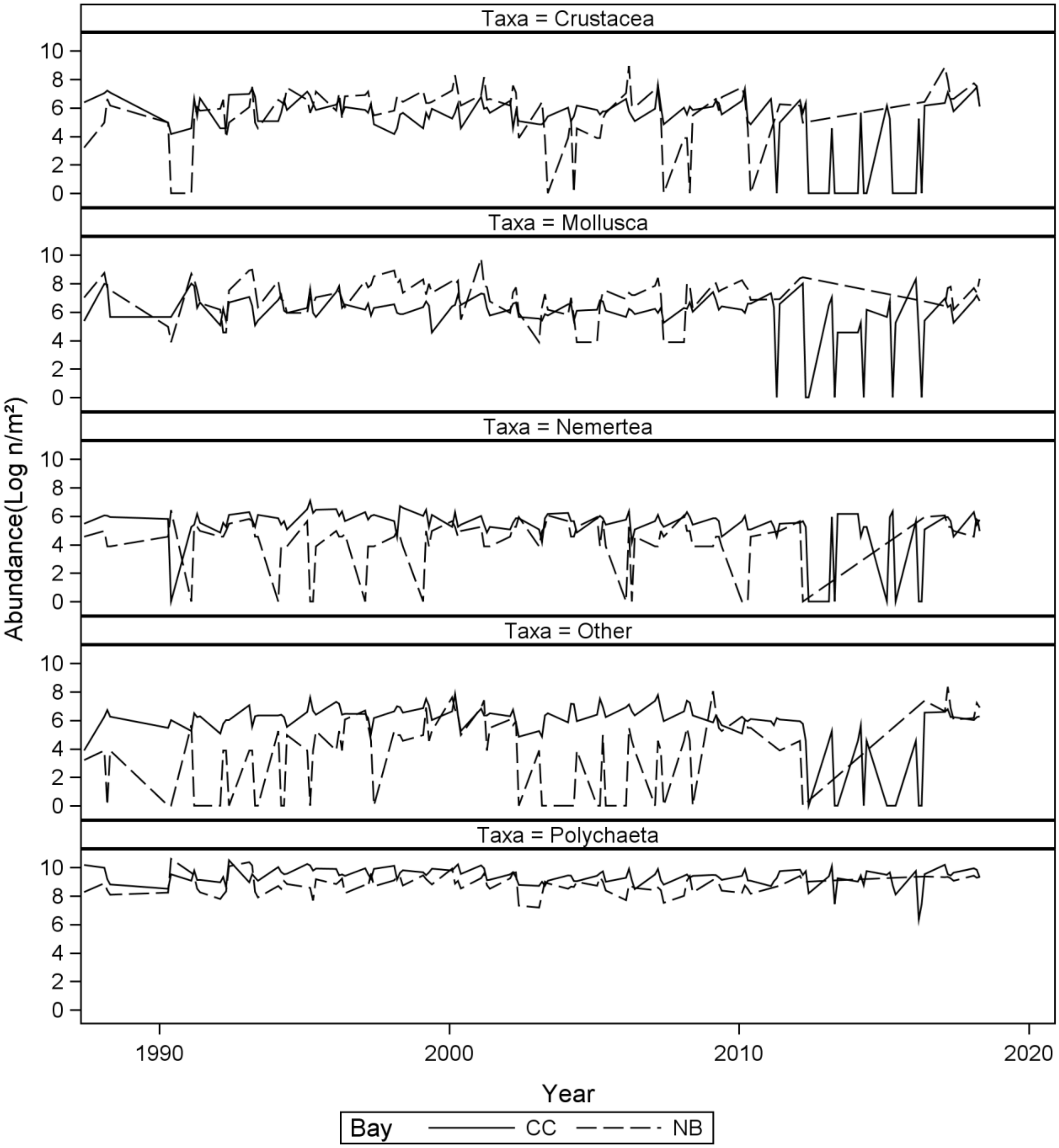

Figure 18. Time series for taxa group log abundances in the Nueces Estuary. CC = Corpus Christi Bay, NB = Nueces Bay.

Using the MARSS package in R statistical software, the strengths of taxa interactions were estimated for primary bays (Table 10) and secondary bays (Table 11). The strengths of the interactions (B matrix of MARSS models) are shown in colors: red represents a positive interaction effect of a variate on a lag with itself and another variate or the effect of a covariate on a variate, blue represents a negative interaction effect, and white represents little or no interaction. The strengths of seasonal effects were modeled using a brute force method by including seasons (quarters 1 – 4, i.e., Q1 – Q4) as a factor. The strengths of interactions can be thought of as the density dependence (red) or density of independence of variate or covariates in response to densities at the previous time step. The response of taxa within secondary and primary bays exhibit different levels of interaction action strengths in response to environmental drivers (salinity and dissolved Oxygen).

Table 10. Strength of taxa interactions for the primary bays in three estuaries.

***Primary Bays**		**VARIATES**					**COVARIATES**					
		Crus	**Moll**	**Poly**	**Nerm**	**Oth**	**Sal**	**DO**	**Q1**	**Q2**	**Q3**	**Q4**
LC	Crustacea	0.24	0.17	0.01	-0.09	0.11	0	-0.35	0	-0.66	0.09	0.28
	Mollusca	-0.03	0.21	0.01	0.1	-0.02	0.33	0.27	0.56	-0.19	-0.1	-0.25
	Polychaeta	0.07	0.16	0.24	-0.09	0.45	0.07	-0.08	0.17	-0.89	0.28	0.31
	Nermertinea	0.23	0.1	0.09	0.1	0.28	0.05	0.1	-0.21	0.04	-0.1	0.16
	Other	0	0.16	-0.04	0.15	0.53	0.08	0.21	0.26	-0.37	-0.09	0.15
GE	Crustacea	0.55	0.22	-0.4	0.42	0.03	0.01	-0.38	0.1	-0.66	0.02	0.56
	Mollusca	0.05	0.26	-0.24	0.23	-0.1	-0.03	0.21	0.23	-0.04	-0.23	-0.28
	Polychaeta	0.03	-0.08	0.44	-0.08	0.13	0.17	0.45	0.22	0.12	-0.35	-0.29
	Nermertinea	-0.12	-0.43	0.83	-0.08	-0.09	0.31	0.42	-0.01	0.27	-0.2	-0.06
	Other	-0.1	-0.23	0.28	-0.05	0.1	0.23	0.06	-0.14	0.35	-0.35	0.13
NC	Crustacea	-0.19	0.25	0.24	0.07	-0.11	0.15	-0.08	0.16	-0.31	-0.24	0.33
	Mollusca	-0.2	0	0.2	0.06	0.23	0.04	0.04	0.2	-0.53	0.12	0.22
	Polychaeta	0.14	-0.18	0.08	0.07	-0.02	-0.07	0.06	0.27	-0.21	-0.09	0
	Nermertinea	-0.13	-0.28	0.11	0.16	0.39	-0.09	0.06	0.77	-0.27	-0.42	-0.16
	Other	-0.13	-0.28	0.11	0.16	0.39	-0.09	0.06	0.77	-0.27	-0.42	-0.16

*Abbreviations: LC=Lavaca-Colorado, GE=Guadalupe, NC=Nueces.

Table 11. Strengths of taxa interactions for secondary bays in three estuaries.

*Secondary Bays		VARIATES					COVARIATES					
		Crus	**Moll**	**Poly**	**Nerm**	**Oth**	**Sal**	**DO**	**Q1**	**Q2**	**Q3**	**Q4**
LC	Crustacea	0.14	0.3	-0.13	0.3	0.12	0.32	0.22	0.27	-0.24	-0.19	0.25
	Mollusca	0.11	0.13	0.02	0.05	0.17	0.28	0.25	0.61	-0.28	-0.64	0.42
	Polychaeta	-0.04	0.09	0.38	-0.09	0.03	0.06	-0.01	0.34	-0.4	-0.27	0.16
	Nermertinea	0.19	-0.5	0.5	-0.24	0.05	0.04	0.1	0.63	-0.08	-0.29	0.08
	Other	-0.02	0.06	0.13	0.19	0.23	0.01	0.25	0.34	0.08	-0.02	-0.28
GE	Crustacea	0.29	0.01	0	-0.02	-0.04	0.13	-0.09	-0.22	-0.19	-0.05	0.43
	Mollusca	-0.05	0.71	-0.04	0.16	0.11	-0.01	-0.16	0.22	-0.39	-0.26	0.21
	Polychaeta	-0.04	0.09	0.32	-0.04	-0.02	0.22	0.08	0.52	-0.26	-0.29	-0.27
	Nermertinea	-0.08	-0.05	0.08	0.26	-0.11	0.04	0.09	0	-0.21	-0.15	0.3
	Other	-0.11	-0.07	-0.04	-0.13	0.06	-0.23	0.52	0.3	0.51	-0.22	-0.72
NC	Crustacea	0.01	0.11	0.33	-0.07	-0.05	0.11	-0.01	-0.02	-0.18	-0.39	0.56
	Mollusca	-0.05	0.02	0.32	-0.05	-0.19	0.05	-0.28	0.03	-0.12	-0.04	0.11
	Polychaeta	-0.14	-0.11	0.15	0	0.01	-0.12	-0.07	-0.07	-0.13	0.17	0.05
	Nermertinea	0.03	0.23	-0.12	-0.03	0.27	0.14	0.04	-0.04	-0.32	-0.17	0.66
	Other	0.03	0.23	-0.12	-0.03	0.27	0.14	0.04	-0.04	-0.32	-0.17	0.66

*Abbreviations: LC=Lavaca-Colorado, GE=Guadalupe, NC=Nueces.

Stability metrics were determined by performing an eigen value analysis on the estimated taxa interactions, $\det(B)^2$ = return time to stationary distribution of taxa (Figure 19). A bay is considered stable or more resilient the lower the value of $\det(B)^2$. The secondary bays of the Guadalupe and Nueces estuaries are the most stable of the secondary bays. The secondary bay of the Lavaca-Colorado estuary is less stable than it's primary bay compared to the Guadalupe and Nueces estuaries. The Nueces estuary's primary bay exhibits greater stability than both the secondary and primary bays within the Lavaca-Colorado estuary. The Guadalupe estuary's primary bay is the least stable of all the bays.

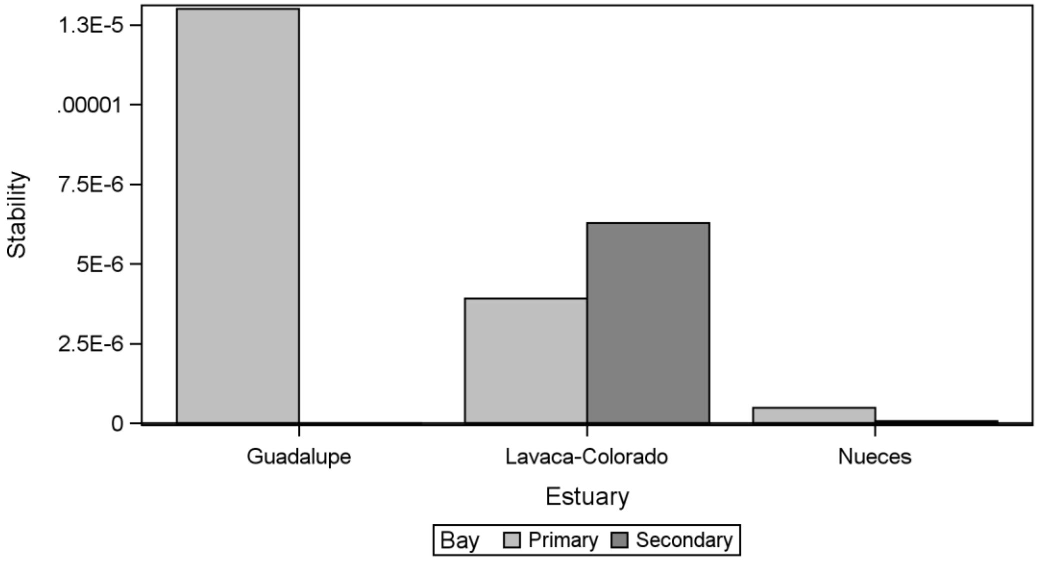

Figure 19. Stability metrics for benthic infauna communities in estuaries and bays.

7.5 Linking Inflow Events and Communities

7.5.1 Long-term Dynamics

The BIO-ENV analysis between the macrofauna community and hydrographic measurements found that a combination of variables was the best. 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).

Macrofauna abundance and diversity were negatively correlated to temperature in Lavaca-Colorado estuary (Table 12). 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 12. Spearman correlations (r) and probability that the correlation equals zero (p) for the relationship between macrofauna abundance, biomass, and diversity and salinity, DO, and temperature by estuary from 1987-2018.

		Lavaca-Colorado			**Guadalupe**			**Nueces**		
Variable	**Stat**	**Abundance $n\ m^{-2}$**	**Biomass $g\ m^{-2}$**	**Diversity N1**	**Abundance $n\ m^{-2}$**	**Biomass $g\ m^{-2}$**	**Diversity N1**	**Abundance $n\ m^{-2}$**	**Biomass $g\ m^{-2}$**	**Diversity N1**
Salinity	r	0.16	0.18	0.16	0.09	0.42	0.44	0.02	0-0.03	0.07
	p	0.10	0.06	0.09	0.35	<0.0001	<0.0001	0.85	0.77	0.46
DO	r	0.16	0.12	0.18	0.12	-0.11	0.05	0.24	0.07	0.07
	p	0.12	0.22	0.07	0.22	0.27	0.62	0.01	0.43	0.43
Temperature	r	-0.24	-0.19	-0.23	-0.18	-0.003	-0.22	-0.37	-0.06	-0.09
	p	0.01	0.07	0.02	0.05	0.97	0.02	<0.0001	0.54	0.31

7.5.2 Hurricane Harvey

Hurricane Harvey made landfall Friday 25 August 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 1). This is the strongest hurricane to hit the middle Texas coast since Carla in 1961. After the wind storm 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 drive primary production of coastal "blue carbon." The biological responses are 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 could kill or stress many estuarine and marine organisms. Harvey provides an opportunity to study the effects of a very large inflow event.

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. As the storm approached, storm surge pushed salinities over 30 psu with in-rushing sea water (Figure 20). 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 6 October 2017, and to 10 psu by 9 October 2017.

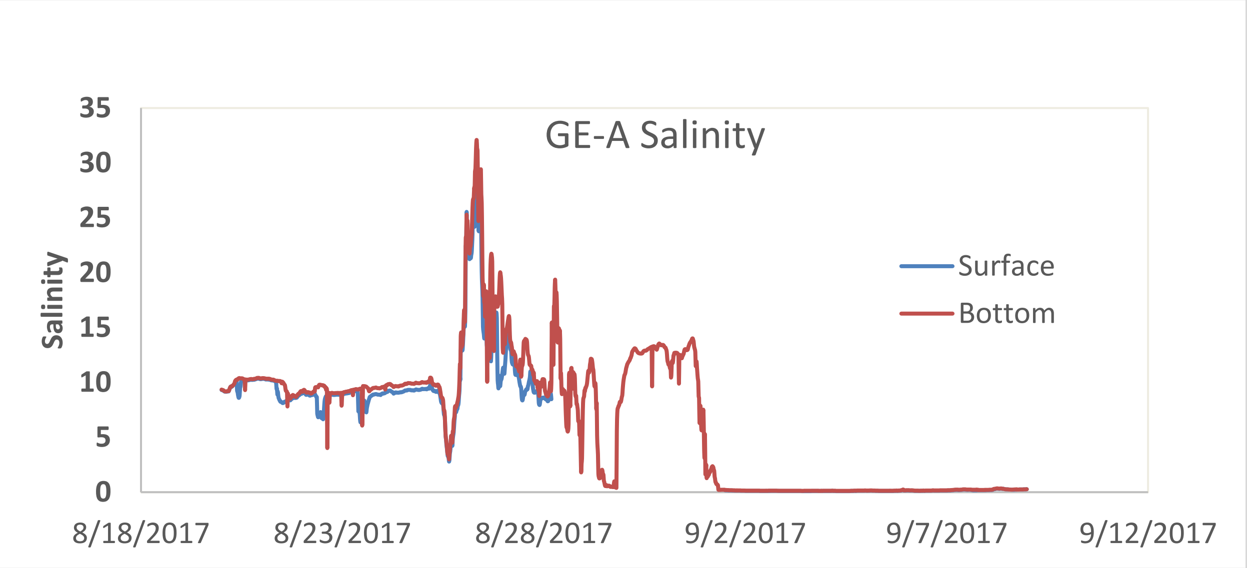

Figure 20. Continuous salinity measurements at station GE-A in the Guadalupe Estuary (From: Walker et al. 2019).

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. The DO did not recover until 15 days after the storm.

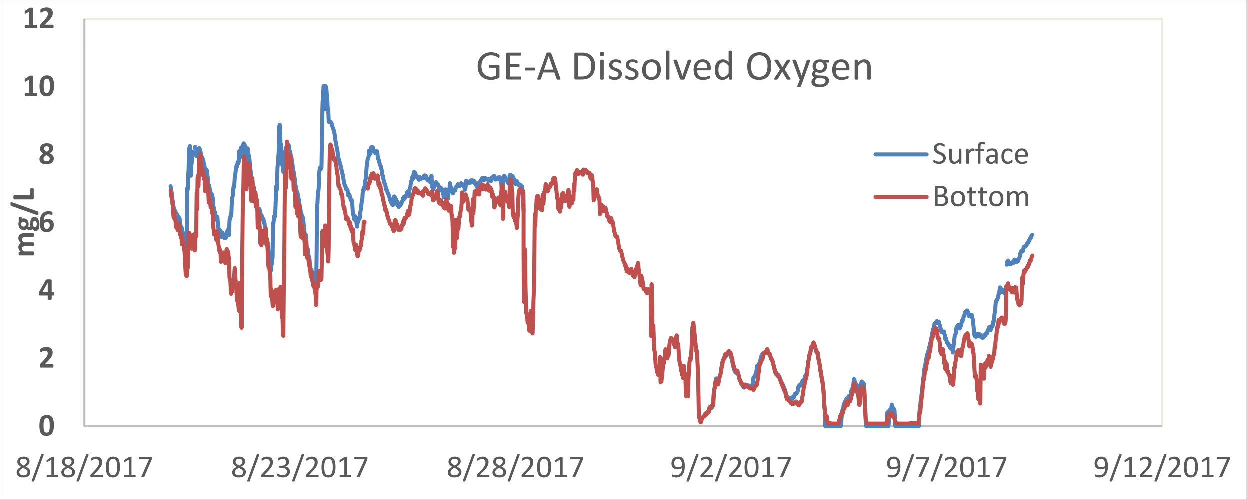

Figure 21. Continuous dissolved oxygen measurements at station GE-A in the Guadalupe Estuary (From: Walker et al. 2019).

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 (Figure 22). Community structure also changed. The bivalves had an average abundance and size distribution 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 bloom of small *Mulinia lateralis* and *Rangia cuneata* by April 2018 (Figure 22). These newly recruited mollusks grew by July 2018, and a second bloom occurred. This short-term view makes it appear as if there was a large loss, but a recovery within nine months after the storm, implying that benthos are vulnerable but resilient.

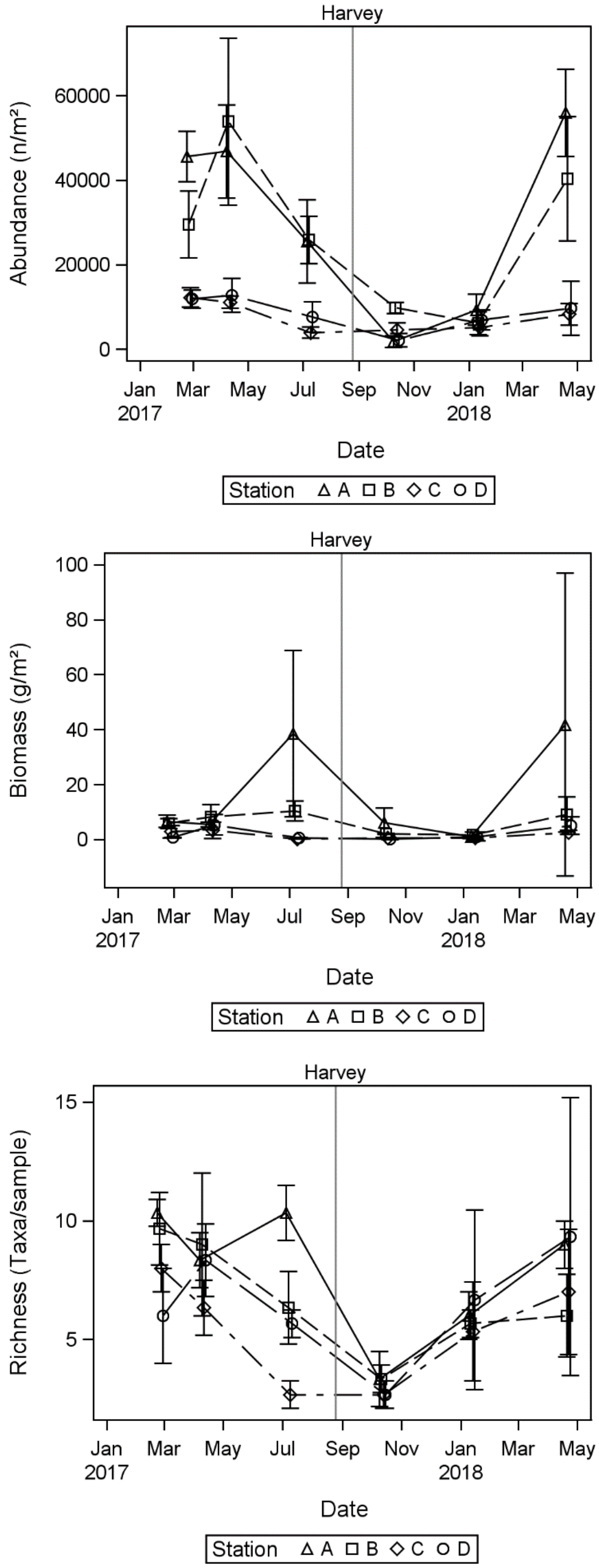

Figure 22. Benthic metrics three quarters before and three quarters after Hurricane Harvey.

The short-term view makes it appear as if the Hurricane had a large a 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 (Figure 23). 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 (Figure 23). However, the long-term view makes it appear as if the storm did not matter at all. The forecast model predicts that benthic abundance would have went down anyway as it does every fall and recover as it does every spring (Figure 23A). The abundance recovery after the storm was greater than expected but within bounds of error.

There were three other periods when the forecast was off, and this was in July 2007 to January 2008, July 2009, and July 2015. The periods in 2008 and 2015 were also flood periods with very low salinities near zero. However, the middle period in July 2009 was a drought when salinities were very high (Figure 12B), around 35. So, it does appear the extreme events (both floods and droughts) can disturb benthic communities.

The forecast model predicts that benthic biomass would have went down as well, but the decline was lower than expected, although not out of error bounds (Figure 23B). The spring bloom was also higher than expected and almost reached beyond the expected bounds.

The forecast model predicts that benthic diversity went down more than expected (Figure 23C). The recovery was as expected, with values that were nearly exactly as predicted. However, even though the number of species were as predicted, the community structure was very different.

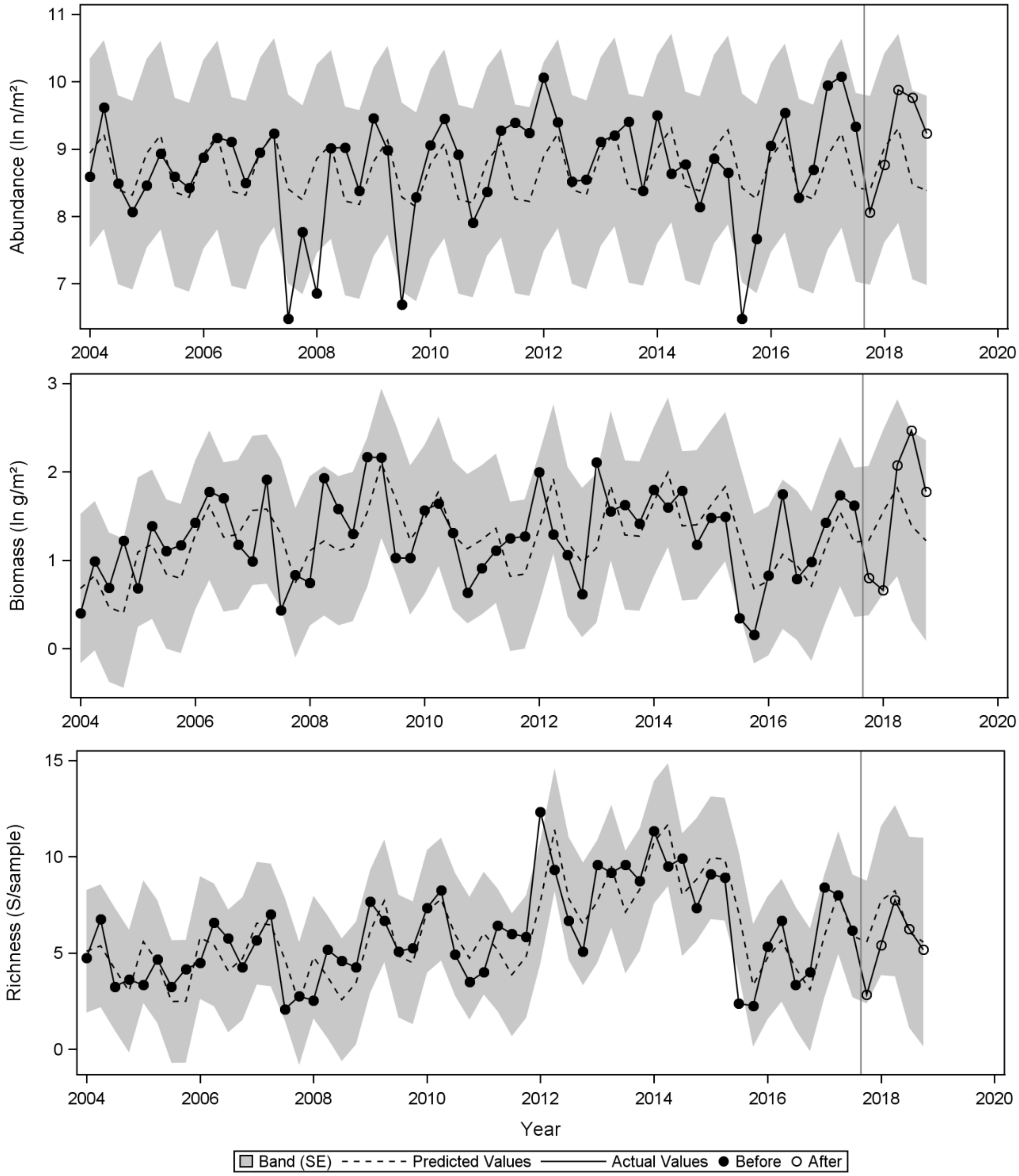

Figure 23. Long-term benthic dynamics used to predict benthic metrics in October 2018 to July 2019.

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.

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 30 August 2012 for Matagorda and Lavaca Bays (TCEQ §298.330) and for San Antonio Bay (TCEQ §298.380), and on 6 March 2014 for Nueces Bay and Delta (TCEQ §298.430). The rules are quite complex and describe different attainment frequencies over 4- to 6-year periods of time, in different seasons, and under different conditions. There 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 base on 6 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 3 different “levels” where levels are defines as 3 different inflow regimes (wet, average, dry). It is impossible to try and link

8.1 Spatial Considerations

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. This is because the domino theory suggests community structure and function is controlled by long-term 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 7 for water quality differences, and Figure 4 for sediment quality 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 response after hurricanes. The short-term view leads to the conclusion that benthos are vulnerable but resilient, meaning they die off but bounce back. On the other hand, the long-term view is very different, and leads to the conclusion that the benthos responses are a bit more extreme, but within the range of error, of what one would expect. Thus, the long-term view is that benthos are actually both resistant (meaning they bend without breaking) and resilient (meaning they can recover when knocked down).

8.3 Linking Inflow, Salinity, and Ecological Response

We have learned that salinity is an important driver. 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. Elsewhere, long-term changes in macrobenthos abundance, diversity and community structure changed differently near the river mouth compared to far from it along in Tees Bay, UK (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 & Montagna, 2009; Montagna et al. 2002; Palmer et al. 2002). Therefore, it may be useful to adopt different inflow standards for primary and secondary bays, just as we develop different environmental flow standards for different stream segments.

8.4 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 (Fig. 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 that resource are identified 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. The problem with the rules is that the flow requirements are inordinately complex. The flow standards consist of multiple tables that describe complex flow regimes that vary in time, and attainment frequencies vary as well. So, it is not possible to know which flow regime you are in until the future and you evaluate the past for attainment frequency. Consider the following examples.

The Lavaca Bay standards are the simplest (Table 13). There are standards for two seasons, spring and fall, under for different climatic regimes (subsistence, dry, average, and wet).

Table 13. 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 14) 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 14. 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, 7 levels of summer, and combined levels (Table 15). The standard are also for two specific periods: February, and March through May. Zero flows are allowed under certain circumstances.

Table 15. 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)

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)

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 16). 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 16. 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%)

8.5 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.

8.5.1 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. <u>Describe relationships between physical habitat and flow</u>. 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. <u>Identify improvements made in methods for determining environmental flow regimes for estuaries</u>. 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. <u>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</u>. 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 5 of 7 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.

8.5.2 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 explicityly 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.

8.5.3 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 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 acts 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. It is now clear that the entire Texas coast is getting hotter, saltier and more hypoxic, and these combined effects are leading to degradation of ecosystem health.

9 References

Alber, M. 2002. A conceptual model of estuarine freshwater inflow management. *Estuaries* 25: 1246–1261.

Arismendez, S.S, Kim, H.-C., Brenner, J., Montagna, P.A. 2009. Application of watershed analyses and ecosystem modeling to investigate land–water nutrient coupling processes in the Guadalupe Estuary, Texas. *Ecological Informatics* 4: 243-253.

Buskey, E.J., Scheef, L.P., Xue, J. 2015. Assessing the effects of freshwater inflows and other key drivers on the population dynamics of blue crab and white shrimp using a multivariate time-series modeling framework. Final report to the Texas Water Development Board, project 1400011712. The University of Texas at Austin, Port Aransas, Texas.

Clarke, K.R. 1993. Non-parametric multivariate analyses of changes in community structure. *Australian Journal of Ecology* 18: 117-143.

Clarke, K.R., Gorley, R.N. 2015. PIMER v7: User Manual/Tutorial. PRIMER-E, Plymouth, U.K.

Clarke, K.R., Warwick, R.M. 2001. Change in Marine Communities: An Approach to Statistical Analysis and Interpretation. 2nd Edition. PRIMER-E: Plymouth, United Kingdom.

Colorado and Lavaca Rivers and Matagorda and Lavaca Bays Basin and Bay Stakeholder Committee and Expert Science Team (CL-BBEST). 2011. Environmental Flows Recommendation Report. https://www.tceq.texas.gov/assets/public/permitting/watersupply/water_rights/eflows/sn_bbest_recommendationsreport.pdf

Freese and Nichols 2019. Twenty-sixth Annual Report, Receiving Water Monitoring Program, Lavaca Bay, May 2018 to May 2019, Calhoun County, Texas. Report to Formosa Plastics Corporation, Point Comfort, Texas. Freese and Nichols, Inc., Austin, TX, 378 pp.

Hampton, S.E., Holmes, E.E., Scheef, L.P., Scheuerell, M.D., Katz, S.L., Pendleton, D.E., Ward, E.J. 2013. Quantifying effects of abiotic and biotic drivers on community dynamics with multivariate autoregressive (MAR) models. *Ecology* 94: 2663-2669.

Hampton, S.E., Scheuerelll, M.D. Church M.J., and Melack, J.M. 2019. Long-term perspectives in aquatic research. *Limnology and Oceanography* 64: S2-S10.

Hanson, H.C. 1962. Dictionary of Ecology. Crown Publishers, Inc.

Hardegree, M.N. 2018. Effect of climate on estuarine benthos at regional scales along the Texas coast. M.S. Thesis, Environmental Science Program, Physical and Environmental Sciences Department, Texas A&M University-Corpus Christi, Corpus Christi, TX.

Hedges, J.I., Stern, J.H. 1984. Carbon and nitrogen determinations of carbonate-containing solids. *Limnology and Oceanography* 29:657-663.

Hill, M. O. 1973. Diversity and evenness: a unifying notation and its consequences. *Ecology*. 54:427-432.

Holmes, E.E., Ward, E.J., Scheuerell, M.D. 2012a. Analysis of multivariate time-series using the MARSS package. Version 3.4. http://cran.r-project.org/web/packages/MARSS

Holmes, E.E., Ward, E.J. Wills, K. 2012b. MARSS: multivariate autoregressive state-space models for analyzing time series data. *R Journal* 4:11–19.

Hu, X., Beseres-Pollack, J. McCutcheon, M.R., Montagna, P.A., Ouyang, Z. 2015. Long-term alkalinity decrease and acidification of estuaries in Northwestern Gulf of Mexico. *Environmental Science & Technology* 49: 3401-3409.

Hu, X., Cai, W.-J. 2013. Estuarine acidification and minimum buffer zone - A conceptual study. *Geophysical Research Letters* 40: 5176-5181.

Kalke, R.D., Montagna, P.A. 1991. The effect of freshwater inflow on macrobenthos in the Lavaca River Delta and Upper Lavaca Bay, Texas. *Contributions to Marine Science* 32: 49-72.

Kim, H.-C., Montagna, P.A. 2009. Implications of Colorado River freshwater inflow to benthic ecosystem dynamics: a modeling study. *Estuarine, Coastal and Shelf Science* 83:491-504.

Kim, H.-C., Montagna, P.A. 2010. Effect of Climatic Variability on Freshwater Inflow, Benthic Communities and Secondary Production in Texas Lagoonal Estuaries. Final report to the Texas Water Development Board, contract number 08-483-0791.Harte Research Institute for Gulf of Mexico Studies, Texas A&M University-Corpus Christi, Corpus Christi, Texas.119 pages.

Kim, H.-C., Son, S., Montagna. P., Spiering, B., Nam, J. 2014. Linkage between freshwater inflow and primary productivity in Texas estuaries: Downscaling effects of climate variability. *Journal of Coastal Research* 68:65–73

Kim, H.-C., Montagna, P.A. 2012. Effects of climate-driven freshwater inflow variability on macrobenthic secondary production in Texas lagoonal estuaries: A modeling study. *Ecological Modelling* 235– 236: 67– 80.

Kotta, J., Kotta, I., Simm, M., Põllupüü, M. 2009. Separate and interactive effects of eutrophication and climate variables on the ecosystem elements of the Gulf of Riga. *Estuarine, Coastal and Shelf Science* 84:509–518

Longley, W.L. (ed.). 1994. Freshwater inflows to Texas bays and estuaries: ecological relationships and methods for determination of needs. Texas Water Development Board and Texas Parks and Wildlife Department, Austin, Texas. 386 p.

Martinez-Andrade, F., Campbell, P., Fuls, B.. 2005. Trends in relative abundance and size of selected finfishes and shellfishes along the Texas Coast: November 1975-December 2003. Management Data Series No. 232, Texas Parks and Wildlife Department, Coastal Fisheries Division, Austin, Texas. 140 pp.

Matagorda Bay Health Evaluation (MBHE) 2007a. Final Report, Matagorda Bay Health Evaluation – Habitat Assessment. Prepared for Lower Colorado River Authority and San Antonio Water System. July 2007.

Matagorda Bay Health Evaluation (MBHE) 2007b. Final Report, Matagorda Bay Health Evaluation Bio-statistical Analyses. Prepared for Lower Colorado River Authority and San Antonio Water System. September 2007.

Matagorda Bay Health Evaluation (MBHE) 2007c. Final Report, Matagorda Bay Health Evaluation – Bay Food Supply, Nutrient and Chlorophyll-a Modeling. Prepared for Lower Colorado River Authority and San Antonio Water System. July 2007.

Matagorda Bay Health Evaluation (MBHE) 2008. Final Report, Matagorda Bay Inflow Criteria (Colorado River), Matagorda Bay Health Evaluation. Prepared for Lower Colorado River Authority and San Antonio Water System. December 2008.

Montagna, P.A, Hill, E.M. Moulton, B. 2009. Role of science-based and adaptive management in allocating environmental flows to the Nueces Estuary, Texas, USA. In: Brebbia, C.A. and E. Tiezzi (eds.), *Ecosystems and Sustainable Development VII,* WIT Press, Southampton, UK, pp. 559-570.

Montagna, P.A. 1989. Nitrogen Process Studies (NIPS): the effect of freshwater inflow on benthos communities and dynamics. Technical Report No. TR/89-011, Marine Science Institute, The University of Texas, Port Aransas, TX, 370 pp.

Montagna, P.A. 1999. Predicting long-term effects of freshwater inflow on macrobenthos and nitrogen losses in the Lavaca-Colorado and Guadalupe Estuaries. Final Report to Texas

Water Development Board. Technical Report No. TR/99-001, Marine Science Institute, The University of Texas, Port Aransas, TX, 68 pp.

Montagna, P.A. 2000. Effect of freshwater inflow on macrobenthos productivity and nitrogen losses in Texas estuaries. Final report to Texas Water Development Board, Contract No. 2000-483-323, University of Texas Marine Science Institute Technical Report Number TR/00-03, Port Aransas, Texas. 78 pp.

Montagna, P.A. 2013. Macrobenthos Monitoring in Mid-Coastal Estuaries - 2013.Final Report to the Texas Water Development Board, Contract # 1248311357.Harte Research Institute, Texas A&M University-Corpus Christi, Corpus Christi, Texas, 34 pp.

Montagna, P.A. 2014. Macrobenthos Monitoring in Mid-Coastal Estuaries - 2014. Final Report to the Texas Water Development Board, Contract # 1448311638. Harte Research Institute, Texas A&M University-Corpus Christi, Corpus Christi, Texas, 39 p.

Montagna, P.A., Estevez, E.D., Palmer, T.A., Flannery, M.S. 2008. Meta-analysis of the relationship between salinity and molluscs in tidal river estuaries of southwest Florida, U.S.A. *American Malacological Bulletin* 24: 101-115.

Montagna, P.A., Hu, X., Palmer, T.A., Wetz, M. 2018. Effect of hydrological variability on the biogeochemistry of estuaries across a regional climatic gradient. *Limnology and Oceanography* 63:2465-2478.

Montagna, P.A., Hu, X., Wetz, M., Byrne, R., Liu, Z., Kim, H.-C. 2019. The Hydrological Switch: A Novel Mechanism Explains Eutrophication and Acidification of Estuaries. Final Report to NOAA, NOS, National Center for Coastal Ocean Science (NCCOS) for project # NA15NOS4780185. Texas A&M University-Corpus Christi, Corpus Christi, TX. 28 pp

Montagna, P.A., Kalke, R.D. 1992. The effect of freshwater inflow on meiofaunal and macrofaunal populations in the Guadalupe and Nueces Estuaries, Texas. *Estuaries* 15:266-285.

Montagna, P.A., Kalke, R.D. 1995. Ecology of infaunal Mollusca in south Texas estuaries. *American Malacological Bulletin* 11:163-175.

Montagna, P.A., Kalke, R.D., Ritter, C. 2002. Effect of restored freshwater inflow on macrofauna and meiofauna in upper Rincon Bayou, Texas, USA. *Estuaries* 25:1436-1447.

Montagna, P.A., Li, J. 1996. Modeling and monitoring long-term change in macrobenthos in Texas estuaries. Final Report to the Texas Water Development Board. University of Texas at Austin, Marine Science Institute, Technical Report No. TR/96-001, Port Aransas, Texas, 149 pp.

Montagna, P.A., Li., J. 2010. Effect of Freshwater Inflow on Nutrient Loading and Macrobenthos Secondary Production in Texas Lagoons. In: *Coastal Lagoons: Critical Habitats of Environmental Change*, M. J. Kennish and H. W. Paerl (eds.), CRC Press, Taylor & Francis Group, Boca Raton, FL, pp. 513-539.

Montagna, P.A., Palmer, T.A. 2012. Impacts of Droughts and Low Flows on Estuarine Health and Productivity. Final Report to the Texas Water Development Board, Project for Interagency Agreement 1100011150. Harte Research Institute, Texas A&M University-Corpus Christi, Corpus Christi, Texas. 142 pp.

Montagna, P.A., Palmer, T.A., Beseres Pollack, J. 2007. Effect of Freshwater Inflow on Macrobenthos Productivity. In: Minor Bay and River-Dominated Estuaries - Synthesis. Final Report to the Texas Water Development Board, Contract No. 2006-483-026. Harte Research Institute, Texas A&M University-Corpus Christi, Corpus Christi, Texas.

Montagna, P.A., Palmer, T.A., J. Beseres Pollack, J. 2013. *Hydrological Changes and Estuarine Dynamics*. SpringerBriefs in Environmental Sciences, New York, New York. 94 pp. doi 10.1007/978-1-4614-5833-3

Montagna, P.A., Palmer, T.A. 2009. Effect of Freshwater Inflow on Macrobenthos Productivity in the Guadalupe Estuary 2008-2009. Final Report to the Texas Water Development Board, Contract # 0904830893. Harte Research Institute, Texas A&M University-Corpus Christi, Corpus Christi, Texas, 12 pp.

Montagna, P.A., Palmer, T.A. 2011. Effect of Freshwater Inflow on Macrobenthos Productivity in the Guadalupe Estuary 2009-2010. Final Report to the Texas Water Development Board, Contract # 1004831015. Harte Research Institute, Texas A&M University-Corpus Christi, Corpus Christi, Texas, 17 pp.

Montagna, P.A., Ward, G., Vaughan, B. 2011. The importance and problem of freshwater inflows to Texas estuaries. In: *Water Policy in Texas: Responding to the Rise of Scarcity*, R.C. Griffin (ed.), The RFF Press, Washington, D.C. pp. 107-127.

Montagna, P.A., Yoon, W.B. 1991. The effect of freshwater inflow on meiofaunal consumption of sediment bacteria and microphytobenthos in San Antonio Bay, Texas USA. *Estuarine and Coastal Shelf Science* 33: 529-547.

Mulik, J., Sukumaran, S., Srinivas, T. 2020 Factors structuring spatio-temporal dynamics of macrobenthic communities of three differently modified tropical estuaries. *Marine Pollution Bulletin* 150:110767.

Nueces River and Corpus Christi and Baffin Bays Basin and Bay Area Stakeholder Committee and Expert Science Team (N-BBEST). 2011. Environmental Flows Recommendation Report. https://www.tceq.texas.gov/assets/public/permitting/watersupply/water_rights/eflows/20110301guadbbest_transmission.pdf

Palmer, T.A., Montagna, P.A. 2015. Impacts of droughts and low flows on estuarine water quality and benthic fauna. *Hydrobiologia* 753:111–129.

Palmer, T.A., Montagna, P.A., Chamberlain, R.H., Doering, P.H., Wan, Y., Haunert, K. Crean, D.J. 2016. Determining the effects of freshwater inflow on benthic macrofauna in the Caloosahatchee Estuary, Florida. *Integrated Environmental Assessment and Management* 12:529-539.

Palmer, T.A., Montagna, P.A., Pollack, J.B., Kalke, R.D., DeYoe, H.R. 2011. The role of freshwater inflow in lagoons, rivers and bays. *Hydrobiologia* 667: 49-67.

Paudel, B., Montagna, P.A. 2014. Modeling inorganic nutrient distributions among hydrologic gradients using multivariate approaches. *Ecological Informatics* 24:35-46.

Patillo, M.E., T.E. Czapla, D.M. Nelson, and M.E. Monaco. 1997. Distribution and Abundance of Fishes and Invertebrates in Gulf of Mexico Estuaries. Species Life History Summaries. ELMR Report No. 11, vol. II, NOAA/NOS Strategic Environmental Assessment Division, Silver Spring, MD, 377 pp.

Paudel, B., Montagna, P.A., Adams, L. 2019. The relationship between suspended solids and nutrients with variable hydrologic flow regimes. *Regional Studies in Marine Science* 29: 100657. doi: 10.1016/j.rsma.2019.100657

Pielou, E.C. 1975. *Ecological Diversity*. Wiley, New York.

Pollack, J.B., Kinsey, J.W., Montagna, P.A. 2009. Freshwater Inflow Biotic Index (FIBI) for the Lavaca-Colorado Estuary, Texas. *Environmental Bioindicators* 4: 153-169.

Pollack, J.B., Palmer, T.A., Montagna, P.A. 2011. Long-term trends in the response of benthic macrofauna to climate variability in the Lavaca-Colorado Estuary, Texas. *Marine Ecology Progress Series* 436: 67–80. doi: 10.3354/meps09267

Russell, M.J., Montagna, P.A. 2007. Spatial and temporal variability and drivers of net ecosystem metabolism in western Gulf of Mexico estuaries. *Estuaries and Coasts* 30: 137-153.

Sabo, J.L., Ruhi, A., Holtgrieve, G.W., Elliott, V., Arias, M.E., Ngor, P.B., Räsänen, T.A., Nam, S. 2017. Designing river flows to improve food security futures in the Lower Mekong Basin. Science 358 (6368): eaao1053.

SAS Institute Inc. 2017. SAS/ETS® 14.3 User's Guide. Cary, NC: SAS Institute Inc.

Science Advisory Committee. 2009. Methodologies for Establishing a Freshwater Inflow Regime for Texas Estuaries Within the Context of the Senate Bill 3 Environmental Flows Process. Report # SAC-2009-03-Rev1., June 5, 2009.Available at http://www.tceq.state.tx.us/assets/public/permitting/watersupply/water_rights/eflows/fwi20090605.pdf

Shank, G.C., Nelson, K. Montagna, P.A. 2009. Importance of CDOM distribution and photoreactivity in a shallow Texas estuary. *Estuaries and Coasts* 32: 661-677.

Shannon, C. E., Weaver, W. 1949. *The Mathematical Theory of Communication*. University of Illinois Press. Urbana, IL.

Sklar, F.H., Browder, J.A.. 1998. Coastal environmental impacts brought about by alterations to freshwater flow in the Gulf of Mexico. *Environmental Management* 22:547–562.

Standard Methods for the Examination of Water & Wastewater. 5310 Total organic carbon (TOC), B. High-temperature combustion method. (Online Reference)

Tolan, J.M. 2007. El Niño-Southern Oscillation impacts translated to the watershed scale: estuarine salinity patterns along the Texas Gulf Coast, 1982 to 2004. *Estuarine Coastal and Shelf Science* 72: 247-260

Trinity and San Jacinto Rivers and Galveston Bay Basin and Bay Expert Science Team (T-BBEST). 2009. Environmental Flows Recommendation Report. https://www.tceq.texas.gov/assets/public/permitting/watersupply/water_rights/eflows/trinity_sanjacinto_bbestrecommendationsreport.pdf

Turner, E.L., Bruesewitz, D.A., Mooney, R.F., Montagna, P.A., McClelland, J.W., Sadovski, A. Buskey, E.J. 2014. Comparing performance of five nutrient phytoplankton zooplankton (NPZ) models in coastal lagoons. *Ecological Modelling* 277: 13–26.

Turner, E.L., Montagna, P.A. 2016. The max bin regression method to identify maximum bioindicators responses to ecological drivers. *Ecological Informatics* 36:118–125.

TWDB (Texas Water Development Board) 2017. 2017 State Water Plan. Water for Texas. Texas Water Development Board, Austin, Texas. Accessed 12 December 2017, http://www.twdb.texas.gov/waterplanning/swp/2017/doc/SWP17-Water-for-Texas.pdf?d=1513113355867

Van Diggelen, A.D., Montagna, P.A. 2016. Is salinity variability a benthic disturbance in estuaries? *Estuaries and Coasts* 39:967-980.

Walker, L., Wetz, M., Montagna, P.A., Hu, X., Hayes, K. 2019. Timescales of water quality change in 3 Texas estuaries induced by passage of Hurricane Harvey. Coastal and Estuarine Research Federation, Biennial Meeting, Mobile, AL, 3-7 November 2019.

Wetz, M.S., Hu, X., 2015. Final Report to the Texas Water Development Board, Contract #1448311639. Department of Life Sciences, Texas A&M University-Corpus Christi, Corpus Christi, TX, 14 pp.

Wu, F., Tong, C., Feng, H., Gu, J., and Song, G. 2019. Effects of short-term hydrological processes on benthic macroinvertebrates in salt marshes: A case study in Yangtze Estuary, China. *Estuarine, Coastal and Shelf Science* 218: 48-58.

10 TWDB Review Comments and Responses

10.1 Review

DRAFT REPORT

CONTRACT # 1800012223	CONTRACTOR Texas A&M University - Corpus Christ	DATE AND INITIALS
Assignment Date	01/15/20	sr 020620
Contract Administration Stephen A. Ross Name and Phone #	☑ Draft Report received ☑ Date stamp, label with contract info ☑ Request/Receive reviewers names from CM ☑ Prepare Draft Report Memo Review language (draft report review memo) and SOW to insert in Task for reviewers. Send Task to reviewers for review with 2-3 week due date (flexible). Print Task ☑ Create Draft Report folder ☑ Enter in receipt of draft report in Worklog ☑ Enter in CAS on Contracts Reports that draft report was received. Scan transmittal letter into CAS if received. ☑ Place Draft Report Folder in pending	02/06/20 sr
Contract Administration Stephen A. Ross Name	Once comments are received from CM ☑ Pull Draft Report folder ☑ Prepare comment letter and comments for routing (draft report comment letter template)	02/06/20 sr
Angela Wallace	Manager, Contracting and Purchasing review & approval.	2/10/2020 aw
Evan Turner, Ph.D.	Contract Manager review & approval	2/10/2020 ETP
Caimee Schoenbaechler	Manager or Team Lead review & approval	2/12/2020 CS
☐ Mark Wyatt ☐ Larry French ☑ Carla Guthrie ☐ Kevin Kluge ☐ Temple McKinnon	Director review & approval	2/12/2020 CGG
☑ John Dupnik ☐ Jessica Zuba ☐ Edna Jackson ☐ Richard Wade	Deputy Executive Administrator review & approval	2/12/2020 JTD
Contract Administration Stephen A. Ross Name	☑ Scan comment letter and comments to add to CAS under Contract Reports ☑ Mail letter to entity ☑ Update WorkLog ☑ Mark Task for draft report review complete and email new task to CM & SS-CA calendar with 30-day Final Report due date or Expiration Date of contract ☑ File all documents into Report Folder of rotating file	02/06/20 sr

Texas Water
Development Board

P.O. Box 13231, 1700 N. Congress Ave.
Austin, TX 78711-3231, www.twdb.texas.gov
Phone (512) 463-7847, Fax (512) 475-2053

Paul A. Montagna, Ph.D.
Texas A&M University - Corpus Christi
6300 Ocean Drive, Unite 5844
Corpus Christi, TX 78412-5844

RE: INTERAGENCY COOPERATION CONTRACT with TEXAS A&M UNIVERSITY – CORPUS CHRISTI; Contract No. 1800012223, Comments on Draft Report Entitled "*Using Comparative Long-term Benthic Data for Adaptive Management of Freshwater Inflow to Three Basins*"

Dear Dr. Montagna:

Staff members of the Texas Water Development Board (TWDB) have 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 from the Executive Administrator and other reviewers. In addition, Texas A&M University – Corpus Christi will include a copy of the Executive Administrator's draft report comments in the Final Report.

Please note: The TWDB logo should not be used in the Final Report.

The TWDB's Contract Administration staff looks forward to receiving one (1) electronic copy of the entire Final Report in Portable Document Format (PDF) and five (5) bound double-sided copies. **Please further note, that in compliance with Texas Administrative Code Chapters 206 and 213 (related to Accessibility and Usability of State Web Sites), the digital copy of the final report must comply with the requirements and standards specified in statute. For more information, visit http://www.sos.state.tx.us/tac/index.shtml.** If you have any questions on accessibility, please contact David Carter with the Contract Administration Division at (512) 936-6079 or david.carter@twdb.texas.gov.

Texas A&M University – Corpus Christi shall also submit one (1) electronic copy of any computer programs or models, and, if applicable, an operations manual developed under the terms of this Contract.

If you have any questions or need any further information, please feel free to contact Dr. Evan Turner of our Water Science and Conservation staff at 512-936-6090 or Evan.Turner@twdb.texas.gov .

Sincerely,

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

Date: 2/12/2020

Attachment
c w/o att.: Evan Turner, Ph.D., TWDB

Attachment 1

TWDB Comments to Draft Final Report

Contract No. 1800012223
Texas A&M University – Corpus Christi
Using Comparative Long-term Benthic Data for Adaptive Management of Freshwater Inflow to Three Basins

REQUIRED CHANGES

General Draft Final Report Comments:

1. Please add the following statement to the cover page of the final report:

   Pursuant to Senate Bill 1 as approved by the 85th Texas Legislature, this study report was funded for the purpose of studying environmental flow needs for Texas rivers and estuaries as part of the adaptive management phase of the Senate Bill 3 process for environmental flows established by the 80th Texas Legislature. The views and conclusions expressed herein are those of the author(s) and do not necessarily reflect the views of the Texas Water Development Board.

2. Please check the final report for grammar, typographical, spacing, and spelling errors and ensure the final report adheres to the formatting guidelines for Texas Water Development Board reports. See "Helpful Contracting Documents at the following link: http://www.twdb.texas.gov/about/contract_admin/index.asp.

3. The report lacks a discussion section that provides coherence between the analysis, results, summary of key findings, linkages to peer reviewed or grey literature, and ties back to the adaptive management process for environmental flows. Please provide this discussion with the final report.

4. Throughout the document the authors refer to the "plan" for the present study. Please refer to the "scope of work" rather than the "plan" to avoid confusion with other plans mentioned in the report.

Specific Draft Final Report Comments:

1. Table of Contents, page i: Please correct the title on the Table of Contents page to reflect the appropriate study.

2. Abstract, Page 7: Please summarize the relevant findings of the report to encapsulate the text and relevant findings. Please clarify what is interesting about the samples that were analyzed from Hurricane Harvey.

3. Section 5.2 Approach, page 11, Study Area, page 13, and Table 1, page 15: Please use consistent reporting schemes when naming and listing the three estuaries. The TWDB prefers estuaries to be listed in geographic order from northeast to southwest.

4. Sections 6.2 and 6.3 Benthic and Water Quality Analyses, pages 16-17: Please provide sufficient detail for data collection methods to be replicated or provide a citation where detailed field sampling methods can be accessed.

5. Section 6.1 Study Area, page 15: The last paragraph states, "A total of 471 archived samples were analyzed during the current study. Of these, 402 were considered part of the Hurricane Harvey study." Please clarify what the "Hurricane Harvey study" refers to and whether the funding for the collection of those samples is what is being referred to.

6. Section 6.4.2 Estuary and Bay Differences, page 18: Please clarify that ANOVA is a statistical model and consider the revisions in bold to the following sentence, "Thus, the **ANOVA** model is a two-way, partially hierarchical design that can be described by the following **formula…**"

7. Section 6.4.3. Community Structure, page 18: Please spell out "sqrt" to "square root." Also, please provide clarification as to why only the first two principal components were used in this study and ensure the description is consistent with the analysis conducted in the study (i.e., Figure 6 on page 26 depicts three principal components).

8. Section 6.4.5 Time Series Identification, pages 19-20: Sabo et al. 2018 is cited in the text but is not listed in the Reference section. Please add the citation to the Reference section. Additionally, on page 20, stability is defined as the return time to the stationary distribution of taxa following a perturbation. Please clarify which specific environmental fluctuations are used to estimate the stability of the benthic communities in this study.

9. Section 7.1 Bioindicator Identification, page 24: Figure 5 on page 24 is not described nor referenced in the text. Please add a description of and reference to the plot in the body of the report. Please also explain what PC1 and PC2 represent as well as the significance of the grouping highlighted by the circle.

10. Section 7.1 Bioindicator Identification, page 24: It is stated that "An ANOVA of macrofauna metrics of abundance, biomass, diversity, and evenness were statistically different by date (P-Value = <.0001), station (P-Value = <.0001), and the station*date*bay interaction (P-Value = <.0001) (Table 5)." Please

provide additional detail describing how the metrics differed by date, station, and date/station/interaction variables.

11. Section 7.1 Bioindicator Identification, page 25: It is stated that "An ANOVA of hydrographic metrics of dissolved oxygen, salinity, temperature, pH, NH4, PO4, SiO4, and NOx were different by date (P-Value = <.0001), and bay (Table 6)." Please provide additional detail describing how the hydrographic metrics differed by date and bay.

12. Section 7.2 Condition Identification, page 25: In the first paragraph, please correct the following statement, "Thus, PC1 is the new variable that is related to seasonal effects" to "Thus, **PC2** is the new variable that is related to seasonal effects." In the second paragraph, please provide more detail by explaining the significance of samples clustering towards one end or the other of an axis.

13. Section 7.3 Inflow Identification, page 27: Please clarify the source of inflow data and the period of record corresponding to the inflow ranges reported in the first paragraph. Please also report annual average inflow for each estuary.

14. Section 7.4.1 Time Series Identification, Physical Setting, page 29: Please report whether the observed increasing trend in water temperature was statistically significant.

15. Section 7.4.2 Time Series Identification, Macrofauna, pages 29-34: Please report measures of statistical significance for the observed trends. Please also ensure the description of the trends observed in the data are accurately described in the text. The first paragraph on page 33 reports that benthic biomass declined in the Nueces Estuary, but the trend line for the Nueces Estuary in Figure 14 appears to be increasing.

16. Section 7.4.3. Multivariate Autoregressive State Space (MARSS) Model, pages 35-41: Earlier in the report, stability is defined as the return time to the stationary distribution of taxa following an environmental perturbation. Please provide clarification regarding which specific environmental perturbations are used to define stability of benthic communities in this study. Also, please define in the text on page 39 and Tables 7 and 8 which seasons corresponds to each of the Q1-Q4 designations.

17. Section 7.5.2 Hurricane Harvey, pages 43-46:
    a. Page 43, first paragraph: Please define "blue carbon."
    b. Page 43, second paragraph: Please report the recovery time for which salinity returned to pre-storm levels, if known.
    c. Page 44, last paragraph: Please clarify what "nearly nothing" refers to (e.g., bivalves).

   d. Page 44, last paragraph: Please refer to the Figure(s) with the data corresponding to the description of mollusk blooms in April and July 2018.
   e. Page 46, first paragraph: Please provide sufficient detail describing the method for forecasting benthic response such that the method could be replicated.
   f. Page 46, third paragraph: Please define "the first and last periods" to be July 2007 and July 2015. Please consider also commenting on how the model performed during the extreme drought year of 2011.
   g. Page 46, last paragraph: Please complete the final sentence.

18. Section 8, Discussion: This section of the report might be better described as a conclusion. Please provide a thorough discussion section that links the data analysis to the results and summary of findings as well as linkages to previous work and peer reviewed or grey literature. Please highlight key findings and relate a key finding of long-term benthic decline to the stability of benthic communities. Please ensure the discussion relates the key findings of the report to the adaptive management process for freshwater inflow standards. Specifically, describe how stakeholders might utilize the data and information from the study to evaluate the adequacy of the freshwater inflow standards adopted for three basins. Also discuss how the predictive benthic model could be utilized in the adaptive management process.

Figures and Tables Comments:

1. Figures 1 and 3: The scale bar in Figure 1 is in miles and the Figure 3 is in both kilometers and miles. Please ensure units are constant throughout the Figures.

2. Figure 2: The caption refers to a "Conceptual model" but the text on page 12 refers to the "Domino Theory." Please ensure consistency in the reporting of the diagram in Figure 2.

3. Figure 9: Please scale the label text so all labels are printed. Additionally, please present the X-axis label as a unit of time instead of decimal months.

4. Figure 10: Please provide r and p values for this result to match Figures 11 and 12 in the Figure caption.

5. Figure 11: The text on page 30 states that all bays have a strong decline in DO with $r < -.15$, however, the regression line for Nueces visually appears to increase. Please ensure the text and graphic are consistent in reporting the results.

6. Figures 13, 14, and 15: Please provide r and p value statistics for the regression lines presented in each of the subplots as part of the Figure caption. Also, please increase the size of the overall figure plot width to the maximum allowed within the page margin.

7. Figure 20: Please label "Date" on X-axis and adding unit of Salinity (PSU) on Y-axis.

8. Figure 21: Please label "Date" on X-axis and "Dissolved oxygen (mg/L)" on Y-axis.

9. Table 7: The MARSS model analysis states that the variates were analyzed to themselves for interactions. In the results benthos variate interactions with itself does not yield 0.0, or 1.0 interactions, however. Please discuss how the same-same interactions with the performed MARSS method approach yields values between 0 to 1.

SUGGESTED CHANGES

Specific Draft Final Report Comments:

1. Consider use of present tense when referring to the study in the report. For example, Section 5.1, page 10: "This study **has** ~~will have~~ one objective…", and "The work ~~proposed~~ **conducted** here ~~will meet~~ **meets** the needs…".

2. Section 5.3, Reporting, page 12: Consider omitting this section from the final report because the reporting requirements were specifications of the contract that do not inform the final results of the study.

3. Section 6.2 Benthic Analyses and Section 6.3 Water Quality Analyses, page 16: Consider naming these sections with "Sample Methods" or "Data Collection Methods" to more accurately reflect the descriptions provided.

Figures and Tables Comments:

1. Figures 10, 11, 12, 13, 14, 15: Consider including the r and p values for each regression line as an annotation overlay graphic for each subplot.

2. Figures 10, 11, 12, 13, 14, 15: Consider instituting similar plotting graphic settings (eg. font types, font sizes, line size, figure sizes) to create uniformity in the results. Additionally, please consider alternative methods to visualize the information as the annotation icon shapes overlap and are hard to differentiate.

3. Figure 19: Consider using alternative Y-tick labels (e.g. 0 2000000 4000000 6000000) instead of scientific notation.

4. Figure 20. Consider emphasizing the date of Hurricane Harvey landfall on the plot.

5. Figure 22: Consider arranging the subfigures horizontally and increasing the plot horizontal length.
6. Figure 23: Consider adding a legend at the top of the Figure.

10.2 Response to Comments

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

Paul Montagna, Ph.D., Patricia M. Cockett, M.S., and Melisa Rohal, Ph.D.

Contract #1800012223
Response to TWDB Comments to Draft Final Report

REQUIRED CHANGES

General Draft Final Report Comments:

1. Please add the following statement to the cover page of the final report:

   Pursuant to Senate Bill 1 as approved by the 85th Texas Legislature, this study report was funded for the purpose of studying environmental flow needs for Texas rivers and estuaries as part of the adaptive management phase of the Senate Bill 3 process for environmental flows established by the 80th Texas Legislature. The views and conclusions expressed herein are those of the author(s) and do not necessarily reflect the views of the Texas Water Development Board.

   Response: Added to the top of the back of the title page as it is shown in the file named "Formatting Guidelines for Texas Water Development Board Reports."

2. Please check the final report for grammar, typographical, spacing, and spelling errors and ensure the final report adheres to the formatting guidelines for Texas Water Development Board reports. See "Helpful Contracting Documents at the following link: http://www.twdb.texas.gov/about/contract_admin/index.asp.

   Response: The report was prepared using the file named "Formatting Guidelines for Texas Water Development Board Reports." It was checked and does conform to the specified format. Included a cover and title page.

3. The report lacks a discussion section that provides coherence between the analysis, results, summary of key findings, linkages to peer reviewed or grey literature, and ties back to the adaptive management process for environmental flows. Please provide this discussion with the final report.

   Response: The discussion in the draft report was short at 3 paragraphs and 242 words. Text has been added, and it is now 14 paragraphs, three additional tables, and 6 pages long.

4. Throughout the document the authors refer to the “plan” for the present study. Please refer to the “scope of work” rather than the “plan” to avoid confusion with other plans mentioned in the report.

   Response: “plan” was replaced with “Scope of Work” in four places.

Specific Draft Final Report Comments:

1. Table of Contents, page i: Please correct the title on the Table of Contents page to reflect the appropriate study.

   Response: Done

2. Abstract, Page 7: Please summarize the relevant findings of the report to encapsulate the text and relevant findings. Please clarify what is interesting about the samples that were analyzed from Hurricane Harvey.

   Response: Done.

3. Section 5.2 Approach, page 11, Study Area, page 13, and Table 1, page 15: Please use consistent reporting schemes when naming and listing the three estuaries. The TWDB prefers estuaries to be listed in geographic order from northeast to southwest.

   Response: Done. Now list LC, GE, and NC in order throughout the text and tables.

4. Sections 6.2 and 6.3 Benthic and Water Quality Analyses, pages 16-17: Please provide sufficient detail for data collection methods to be replicated or provide a citation where detailed field sampling methods can be accessed.

   Response: No need for a change. These methods are described in detail with citations in these methods sections.

5. Section 6.1 Study Area, page 15: The last paragraph states, “A total of 471 archived samples were analyzed during the current study. Of these, 402 were considered part of the Hurricane Harvey study.” Please clarify what the “Hurricane Harvey study” refers to and whether the funding for the collection of those samples is what is being referred to.

   Response: Added “… because they were collected from 2017 and 2018." study because they were collected from 2017 and 2018.”

6. Section 6.4.2 Estuary and Bay Differences, page 18: Please clarify that ANOVA is a statistical model and consider the revisions in bold to the following sentence, "Thus, the **ANOVA** model is a two-way, partially hierarchical design that can be described by the following **formula…"**

   Response: Done, now section 6.5.2.

7. Section 6.4.3. Community Structure, page 18: Please spell out "sqrt" to "square root." Also, please provide clarification as to why only the first two principal components were used in this study and ensure the description is consistent with the analysis conducted in the study (i.e., Figure 6 on page 26 depicts three principal components).

   Response: Done, now section 6.5.3.

8. Section 6.4.5 Time Series Identification, pages 19-20: Sabo et al. 2018 is cited in the text but is not listed in the Reference section. Please add the citation to the Reference section. Additionally, on page 20, stability is defined as the return time to the stationary distribution of taxa following a perturbation. Please clarify which specific environmental fluctuations are used to estimate the stability of the benthic communities in this study.

   Response: Citation added, now section 6.5.5. Added text to make it clear it is departure from the average long-term benthic abundance.

9. Section 7.1 Bioindicator Identification, page 24: Figure 5 on page 24 is not described nor referenced in the text. Please add a description of and reference to the plot in the body of the report. Please also explain what PC1 and PC2 represent as well as the significance of the grouping highlighted by the circle.

   Response: Sorry for oversight. This paragraph now added:
   The nMDS analysis of macrofauna community metrics was overlaid with a PCA of the water quality variables (Figure 5). Three bays (Matagorda, East Matagorda, and Lavaca Bays) had higher ammonia (NH4) and dissolved oxygen (DO). Corpus Christi and Nueces Bays had highest salinities.

10. Section 7.1 Bioindicator Identification, page 24: It is stated that "An ANOVA of macrofauna metrics of abundance, biomass, diversity, and evenness were statistically different by date (P-Value = <.0001), station (P-Value = <.0001), and the station*date*bay interaction (P-Value = <.0001) (Table 5)." Please provide additional detail describing how the metrics differed by date, station, and date/station/interaction variables.

Response: Added this " The differences by date are expected and dealt with in the time-series analysis section below."

11. Section 7.1 Bioindicator Identification, page 25: It is stated that "An ANOVA of hydrographic metrics of dissolved oxygen, salinity, temperature, pH, NH4, PO4, SiO4, and NOx were different by date (P-Value = <.0001), and bay (Table 6)." Please provide additional detail describing how the hydrographic metrics differed by date and bay.

    Response: Added a new Table 7 and paragraph with station metrics. Added a new Table 8 and a paragraph with station concentrations.

12. Section 7.2 Condition Identification, page 25: In the first paragraph, please correct the following statement, "Thus, PC1 is the new variable that is related to seasonal effects" to "Thus, **PC2** is the new variable that is related to seasonal effects." In the second paragraph, please provide more detail by explaining the significance of samples clustering towards one end or the other of an axis.

    Response: Done. Added: "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."

13. Section 7.3 Inflow Identification, page 27: Please clarify the source of inflow data and the period of record corresponding to the inflow ranges reported in the first paragraph. Please also report annual average inflow for each estuary.

    Response: Large oversight. A new section "6.4 Hydrology" is added to the methods to describe the data source.

14. Section 7.4.1 Time Series Identification, Physical Setting, page 29: Please report whether the observed increasing trend in water temperature was statistically significant.

    Response: Done, new paragraph added to page 32.

15. Section 7.4.2 Time Series Identification, Macrofauna, pages 29-34: Please report measures of statistical significance for the observed trends. Please also ensure the description of the trends observed in the data are accurately described in the text. The first paragraph on page 33 reports that benthic biomass declined in the Nueces

Estuary, but the trend line for the Nueces Estuary in Figure 14 appears to be increasing.

Response: Done. Added a new table for the regressions and new text. Also, text corrected, Nueces biomass is increasing.

16. Section 7.4.3. Multivariate Autoregressive State Space (MARSS) Model, pages 35-41: Earlier in the report, stability is defined as the return time to the stationary distribution of taxa following an environmental perturbation. Please provide clarification regarding which specific environmental perturbations are used to define stability of benthic communities in this study. Also, please define in the text on page 39 and Tables 7 and 8 which seasons corresponds to each of the Q1-Q4 designations.

    Response: As mentioned above, stability doesn't mean perturbation, it means the long-term average benthic metric response. So, stability is really a measure of variability over time, i.e., are there wide swings. Text is clarified.

17. Section 7.5.2 Hurricane Harvey, pages 43-46:
    a. Page 43, first paragraph: Please define "blue carbon."
    b. Page 43, second paragraph: Please report the recovery time for which salinity returned to pre-storm levels, if known.
    c. Page 44, last paragraph: Please clarify what "nearly nothing" refers to (e.g., bivalves).
    d. Page 44, last paragraph: Please refer to the Figure(s) with the data corresponding to the description of mollusk blooms in April and July 2018.
    e. Page 46, first paragraph: Please provide sufficient detail describing the method for forecasting benthic response such that the method could be replicated.
    f. Page 46, third paragraph: Please define "the first and last periods" to be July 2007 and July 2015. Please consider also commenting on how the model performed during the extreme drought year of 2011.
    g. Page 46, last paragraph: Please complete the final sentence.

    Response: All of these requests have been resolved by editing the text as suggested. Regarding e, it is an oversight that the EMS method was not described in the methods, so new section, "6.5.6 Time Series Analysis," is added to the methods section.

18. Section 8, Discussion: This section of the report might be better described as a conclusion. Please provide a thorough discussion section that links the data analysis to the results and summary of findings as well as linkages to previous work and peer reviewed or grey literature. Please highlight key findings and relate a key finding of long-term benthic decline to the stability of benthic communities. Please ensure the discussion relates the key findings of the report to the adaptive management process for freshwater inflow standards. Specifically, describe how stakeholders

might utilize the data and information from the study to evaluate the adequacy of the freshwater inflow standards adopted for three basins. Also discuss how the predictive benthic model could be utilized in the adaptive management process.

Response: This is now done. The discussion in the draft report was short at 3 paragraphs and 242 words. Text has been added, and it is now 14 paragraphs, three additional tables, and 7 pages long. There is an explicit discussion on standards, but it points out that it is difficult to assess standards because of the complexity of the standards themselves.

Figures and Tables Comments:

1. Figures 1 and 3: The scale bar in Figure 1 is in miles and the Figure 3 is in both kilometers and miles. Please ensure units are constant throughout the Figures.

   Response: Both figures have a miles scale. Can't edit Figure 1 right now.

2. Figure 2: The caption refers to a "Conceptual model" but the text on page 12 refers to the "Domino Theory." Please ensure consistency in the reporting of the diagram in Figure 2.

   Response: Changed figure caption to say "Conceptual model of the Domino Theory."

3. Figure 9: Please scale the label text so all labels are printed. Additionally, please present the X-axis label as a unit of time instead of decimal months.

   Response: Done.

4. Figure 10: Please provide r and p values for this result to match Figures 11 and 12 in the Figure caption.

   Response: Done in the text.

5. Figure 11: The text on page 30 states that all bays have a strong decline in DO with $r < -.15$, however, the regression line for Nueces visually appears to increase. Please ensure the text and graphic are consistent in reporting the results.

   Response: It does decrease, no change necessary.

6. Figures 13, 14, and 15: Please provide r and p value statistics for the regression lines presented in each of the subplots as part of the Figure caption. Also, please increase the size of the overall figure plot width to the maximum allowed within the page margin.

   Response: Done in Table 9.

7. Figure 20: Please label “Date” on X-axis and adding unit of Salinity (PSU) on Y-axis.

   Response: This figure is copied from another presentation and can’t be changed.

8. Figure 21: Please label “Date” on X-axis and “Dissolved oxygen (mg/L)” on Y-axis.

   Response: This figure is copied from another presentation and can’t be changed.

9. Table 7: The MARSS model analysis states that the variates were analyzed to themselves for interactions. In the results benthos variate interactions with itself does not yield 0.0, or 1.0 interactions, however. Please discuss how the same-same interactions with the performed MARSS method approach yields values between 0 to 1.

   Response: This is actually the lag, which is why it is not 1.0. Text added “…interaction effect of a variate on a lag with itself…”

SUGGESTED CHANGES

Specific Draft Final Report Comments:

1. Consider use of present tense when referring to the study in the report. For example, Section 5.1, page 10: “This study **has** ~~will have~~ one objective…”, and “The work ~~proposed~~ **conducted** here ~~will meet~~ **meets** the needs…”.

   Response: Done.

2. Section 5.3, Reporting, page 12: Consider omitting this section from the final report because the reporting requirements were specifications of the contract that do not inform the final results of the study.

   Response: Done.

3. Section 6.2 Benthic Analyses and Section 6.3 Water Quality Analyses, page 16: Consider naming these sections with “Sample Methods” or “Data Collection Methods” to more accurately reflect the descriptions provided.

   Response: Done.

Figures and Tables Comments:

1. Figures 10, 11, 12, 13, 14, 15: Consider including the r and p values for each regression line as an annotation overlay graphic for each sublpot.

   Response: This is included in the text.

2. Figures 10, 11, 12, 13, 14, 15: Consider instituting similar plotting graphic settings (e.g., font types, font sizes, line size, figure sizes) to create uniformity in the results. Additionally, please consider alternative methods to visualize the information as the annotation icon shapes overlap and are hard to differentiate.

   Response: Done.

3. Figure 19: Consider using alternative Y-tick labels (e.g. 0 2000000 4000000 6000000) instead of scientific notation.

   Response: the values are on the order of 0.0000001 and these labels are difficult to read. No change.

4. Figure 20. Consider emphasizing the date of Hurricane Harvey landfall on the plot.

   Response: This is a copied image from another publication and can’t be changed.

5. Figure 22: Consider arranging the subfigures horizontally and increasing the plot horizontal length.

   Response: No change.

6. Figure 23: Consider adding a legend at the top of the Figure.

   Response: No change.