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Assessment of the Relationship Between Freshwater Inflow and Biological Indicators in Lavaca Bay

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Assessment of the Relationship Between Freshwater Inflow and Biological Indicators in Lavaca Bay

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3. List of Abbreviations

Abbreviation	**Definition**
ANOVA	Analysis of Variance
BBASC	Bay and Basin Area Stakeholder Committee
BBEST	Basin and Bay Expert Science Team
Cl	Class
CL	Colorado-Lavaca
CPC	Climate Prediction Center
CPUE	Catch Per Unit Effort
DDD	Dichlorodiphenyldichloroethane -DDD is a metabolite of DDT
DDE	Dichlorodiphenyldichloroethylene - breakdown products of DDT
DDT	Dichlorodiphenyltrichloroethane
DF	Degrees of Freedom
DFFT	Discrete Fast Fourier Transform
e	Exponent
ENSO	El Niño-Southern Oscillation
ERM	Effects Range Median
Fa	Family
FPC	Formosa Plastics Corporation
FPExt	Flood Pulse Extent
H'	Shannon-Weiner diversity index
HMW	High Molecular Weight
HRI	Harte Research Institute
HSAF	high spectral anomaly frequency
HSAM	high spectral anomaly magnitude
IDI	interdrought interval
IFI	interflood interval
LCE	Lavaca-Colorado Estuary
LCRA	Lower Colorado River Authority
LMW	Low Molecular Weight
LSAF	low spectral anomaly frequency
LSAM	low spectral anomaly magnitude
MARSS	Multivariate Autoregressive State Space
Max	Maximum
MBHE	Matagorda Bay Health Evaluation
MDS	Non-metric Multidmensional Scaling
Min	Minimum
n	Number
n/m^2	Number of individuals per square meter

Abbreviation	**Definition**
N1	Hill's diversity number one
NAO	North Atlantic Oscillation
NOAA	National Oceanic and Atmospheric Administration
NPDES	National Pollutant Discharge Elimination System
NPI	North Pacific Index
ONI	Ocean Niño Index
Or	Order
P	Probability that the null hypothesis is zero
PAH	Polycyclic Aromatic Hydrocarbons
PCA	Principal Component Analysis
PCB	Polychlorinated Biphenyl
PEL	Probable Effects Levels
Ph	Phylum
PSR	Pressure–State–Response
psu	Practical Salinity Units
QAPP	Quality Assurance Project Plan
R	Richness, count of number of species in a sample
R^2	Coefficient of Determination, i.e., proportion of variability explained by a model
SAWS	San Antonio Water System
SVOC	Semivolatile Organic Compounds
SWQMP	Surface Water Quality Monitoring Program
TCEQ	Texas Commission on Environmental Quality
TDWR	Texas Department of Water Resources
TPWD	Texas Parks and Wildlife Department
TWDB	Texas Water Development Board
TxBLEND	Texas model to simulate water circulation and salinity conditions in estuaries
TxRR	Texas Rain and Runoff model
USGS	United States Geological Survey
VOC	Volatile Organic Compounds

4. Acknowledgements

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

Bill Harvey (Formosa Plastics Corporation) helped obtain the Formosa discharge data. The data was provided by Lisa Vitale of Freese and Nichols. Mark Fisher provided data from the Texas Parks and Wildlife, Coastal Fisheries Program.

5. Executive Summary

This goal of this project is to provide an understanding of the relationships between freshwater inflow and habitat in Lavaca Bay based on long-term monitoring data. It will also provide additional information for consideration by the Colorado-Lavaca Bay and Basin Area Stakeholder Committee (BBASC) and the Texas Commission on Environmental Quality (TCEQ) during future examination of environmental flow standards for Lavaca Bay. The approach was to assemble long-term data on inflow, water quality, sediment quality, and nekton communities. The data was obtained from Formosa Plastics, Harte Research Institute, Texas Commission on Environmental Quality, Texas Parks and Wildlife Department, Texas Water Development Board, and United States Geological Survey. The tasks included: 1) bioindicator identification, 2) condition identification, 3) inflow identification, 4) time series analysis, and 5) linking inflow events and communities.

Bioindicator identification: Bioindicators are organisms that exhibit sensitivity or dependence on low salinity conditions. Five of the seven Basin and Bay Expert Science Teams (BBESTs) identified benthic organisms as the most sensitive indicators of inflow effects because benthos are fixed in place and must tolerate overlying water conditions or perish. There are many candidate species because 18 benthic species of 255 are prevalent in Lavaca Bay than Matagorda Bay. Seven species are common and prefer low or moderate salinity conditions including the polychaetes *Capitella capitata* (8.2 psu), and *Hermundura ocularis* (21.6 psu), the gastropods *Eulimastoma* sp. (9.0 psu) and *Edotia triloba* (10.0 psu), the bivalve *Macoma mitchelli* (13.0 psu), and the amphipod *Ampelisca abdita* (25.3 psu). The eastern oyster *Crassostrea virginica* is a commercially valuable species that has an optimal salinity of 19.5 psu.

Inflow identification: Average inflow to Lavaca Bay (for the period from 1977 to 2016) was approximately 1.3 million acre-feet per year, with about 65% coming from the Lavaca River, about 20% from Garcitas and Placido Creeks and about 15% from the Keller, Cox and Chocolate Bayous. For the period from 1940-1980 approximately 28% of the inflow from the Lavaca-Navidad watershed came from the Lavaca river, 65% from the Navidad river and 7% from ungaged runoff downstream of gages on these two rivers. After the construction of Lake Texana these values changed only slightly to 32% came from the Lavaca, 61% from the Navidad and 7% from ungaged runoff downstream of gages. So, while there has been a reduction in the relative contribution of inflows from the Navidad River, from 65% to 61%, which might be attributed to Lake Texana it does not appear that the annual inflows have declined significantly since the construction of Lake Texana.

Condition identification: Over the 30-year period, nearly all the monthly average salinity throughout Lavaca Bay was in the range of 15 - 20 psu. As freshwater enters Lavaca Bay salinity is diluted, and dissolved nutrients and particulate matter is increased. Thus, there is a multivariate relationship between freshwater and water quality constituents that define estuary conditions. There are no seasonal relationships between inflow and water quality, except for lower dissolved oxygen being more prevalent during the summer.

Estuary conditions define the habitat in Lavaca Bay. The bay is fringed with marsh grass, and center of the bay has muddy and oyster reef habitat. More importantly, the Lavaca River flow maintains a salinity gradient within the bay where the long-term average salinity ranges from 12 psu at the river mouth, to 15 near the highway 35 causeway, to 19 between Alamo Beach and Cox Bay, to 21 near Magnolia Beach and the mouth of Matagorda Bay. The variance of salinity is higher closer to the river.

Time series analysis: While there is a great deal of variability in Lavaca River discharge over time, there is a long-term seasonal signal with highest discharge rates in spring (March) and lowest discharge rates in fall (September). Drought periods were also identified. The period between 1988 and 1992 was an extended drought. The period between 1992 and 2008 was an extended wet period. Then drought returned during the period between 2008 and 2013. Several species do not appear to be changing over time including white shrimp, brown shrimp, red drum, and spotted seatrout. Two species, eastern oyster and black drum, appear to be increasing over time. Two species, blue crab and southern flounder, and all benthic metrics (abundance, biomass, and diversity) are decreasing over time.

Linking inflow events and communities: Several approaches was used to link inflow and biological responses. Using time series analysis, global climatic events, such as the El Niño-Southern Oscillation (ENSO) is correlated to the extent of flood pulses (FPExt), as well as the interflood intervals. Benthic biomass and diversity is inversely correlated with ENSO and FPExt. All of the benthic metrics were inversely correlated to freshwater inflow water quality metrics meaning that increased nutrients and decreased salinity was related to macrofauna count and diversity decreases. Spatially, as the distance from freshwater inflow sources increases, larger and fewer individuals of brown and white shrimp and blue crab are caught. Infauna (i.e., sediment cores) and epifauna (i.e., trawls) had similar responses to dry and wet events. Dry conditions were salinities above the third quartile, and wet conditions were salinities below the first quartile. In Lavaca Bay, infauna and epifauna abundance and richness was greater during dry conditions than in wet conditions. This increase during dry periods is largely due to invasion by marine species, and both infauna and epifauna recover quickly after floods. The lower salinities and higher nutrients and chlorophyll after floods contributes to recruitment events, especially for shellfish (such as shrimp, crab, and bivalves) and this is evidenced by the larger number of small individuals in the upper reaches of the estuary.

While there are contaminants in Lavaca Bay, it is not likely that contaminants are confounding inflow effects. The contaminants are mainly restricted to the area adjacent to the Alcoa facility. There are toxic responses and plastic pellets in the sediments at the location of the Formosa Discharge site Lavaca Bay. However, the benthic communities at the discharge site are nearly indistinguishable from the communities in the reference stations in the bay. Because the contamination is confined to the lower part of the bay, and the benthic communities in the upper part of the bay are following similar trends over time, it appears that inflow change over time is the major driver of benthic bioindicators over time.

Management Implications: The high abundance of juveniles in the upper reaches of Lavaca Bay after flood conditions subside indicates the importance of Lavaca Bay as a nursery habitat. Changes in climate are predicted to decrease precipitation, but also increase water temperatures and storms. This has implications for water quality degradation because increased temperatures are related to lower dissolved oxygen concentrations. Projected population increases, especially in coastal areas could decrease freshwater availability and increase anthropogenic impacts on estuaries. Impacts from the human population along with increasing high flow and low flow events resulting from climate change can affect the resilience and health of organisms utilizing estuaries for nursery habitat. Establishing environmental flow standards that meet freshwater quality, quantity, and timing will preserve the nursery function in upper reaches, which will ensure the protection of estuarine resources for years to come.

6. Introduction

In recognition of the importance that the ecological soundness of riverine, bay, estuary and riparian areas has on the economy, health and well-being of the State, the 80th Texas Legislature enacted Senate Bill 3 in 2007. Senate Bill 3 called for creation of Basin and Bay Area Expert Science Teams (BBEST) to recommend environmental flow standards for bay and estuary inflows and Basin and Bay Area Stakeholder Committees (BBASC) charged with balancing environmental needs with the need for water for human uses. In the past, the State methodology depended on modeling inflow effects on fisheries harvest in Texas estuaries (Longley 1994). SB 3 however, requires an ecosystem management approach to provide environmental flows adequate to support a sound ecological environment and to maintain the productivity, extent and persistence of key aquatic habitats. SB3 also requires an adaptive management phase, in which the BBASC groups will have to review the inflow standards that were adopted by the Texas Commission on Environmental Quality (TCEQ). Thus, the BBASC groups will need information on freshwater inflow effects on water quality and biological indicator communities.

A previous Senate Bill 3 study (Colorado-Lavaca (CL)-BBEST 2011) to evaluate estuarine health of Lavaca Bay relied on work performed in the eastern arm of Matagorda Bay as part of the 2007 - 2008 Lower Colorado River Authority – San Antonio Water System (LCRA-SAWS) Matagorda Bay Health Evaluation (MBHE). The MBHE study determined the seasonal volumes of freshwater inflow needed to produce specific salinity conditions at locations downstream of the river mouth (MBHE 2008). The design salinities were determined based on an analysis of responses to salinity by several bioindicator species including finfish (Atlantic Croaker and Gulf Menhaden), shellfish (Brown Shrimp White Shrimp and Blue Crab) and estuarine marsh plant communities (Low Estuarine Marsh and High Estuarine Marsh) (MBHE 2007a; 2007b; 2007c). A simplified version of this approach was applied to Lavaca Bay by the CL-BBEST. In that process, design salinities and location in Lavaca Bay were assumed using best professional judgment and the relationship between freshwater inflow and salinity was derived through a simple statistical relationship. As part of the 2015 SB3 workplan study on Matagorda Bay (Anchor QEA et al. 2015), Joe Trungale updated the salinity and circulation model for Lavaca Bay and included analysis to make the flow-salinity relationships more consistent with the approach taken in Matagorda Bay. However, neither the 2015 Anchor QEA study nor the original 2011 BBEST report included a rigorous and comprehensive analysis of the biological indicators in Lavaca Bay, as has been done in many other Texas Bays, nor the specific confounding factors that may be important in Lavaca Bay.

There are several confounding factors that can obscure the effects of inflow alone, for example: the presence of a major industrial outfall from the Formosa Plastics plant directly into the Lavaca River, the mercury superfund site and dredge spoil island off of the Alcoa

Aluminum plant in Lavaca Bay, an active fishery that can deplete living marine resources in Lavaca Bay, and long-term climate change effects that drive salinity, temperature and dissolved oxygen conditions throughout the ecosystem. Thus, it is necessary to consider drivers other than freshwater that might affect the ecological health of Lavaca Bay.

6.1 Objectives

This study has one objective (i.e., task), and that is to analyze long-term data sets to assess the relationship between freshwater inflow and biological indicators in Lavaca Bay. This study supports the Senate Bill 3 adaptive management process. However, there are several steps to accomplish this objective including: obtaining data, perform statistical analyses, interpreting results, and report writing.

6.2 Approach

The current project analyzes long-term data sets to identify response of indicator species and habitats to freshwater inflow. A habitat is defined as the "sum total of environmental conditions of a specific place that is occupied by an organism, a population, or a community" (Hanson 1962). So, the task is to identify how inflow alters conditions that define habitat and support bioindicators. This approach has been pioneered by the Principal Investigator (PI) Paul Montagna in many similar peer reviewed studies in the past (Arismendez et al. 2009; Montagna et al. 2008; Palmer et al. 2016; Turner et al. 2014; Turner and Montagna 2016) and in Lavaca Bay in particular (Hu et al. 2015; Montagna and Kalke 1995; Montagna and Li 2010; Kim and Montagna 2009, 2012; Palmer and Montagna 2015; Pollack et al. 2009; 2011b; Van Diggelen and Montagna 2016).

A conceptual model called the Domino Theory (Montagna et al. 2013) has emerged that helps us identify 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 (Figure 1). 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 (Figure 1)

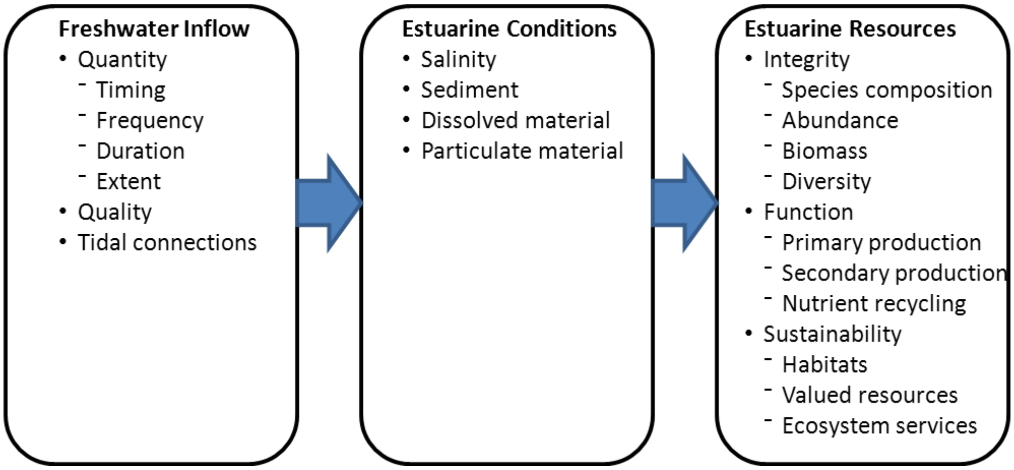

Figure 1. Conceptual model of inflow effects on estuary biological resources (Montagna et al. 2013).

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.

6.3 Reporting

An important output of this project is communication of results. Two meetings were held with the CL-BBASC: 1) to present the goals and objectives of the study on 1 March 2019, and 2) an update on progress on 2 August 2019.

Two additional public meetings were held where P. Montagna delivered a seminar entitled, “Importance of Environmental Flows to Lavaca Bay.” One was with the Lavaca Bay Foundation on 18 April 2019, and one was at the Formosa Plastics 26 June 2019.

Written deliverables were sent to the Texas Water Development Board (TWDB). Quarterly progress reports were sent to the TWDB on 12 December 2018, 11 March 2019, 14 June 2019, and 9 September 2019.

7. Methods

The methodology is primarily that of a meta-analysis and literature review. A meta-analysis is an analysis of combined datasets, which are of independent origins. Thus, datasets were collected from several independent sources and analyzed independently and as a whole where possible. The literature is based on existing literature.

7.1 What is Health and How is it Assessed?

The concept of ecological or environmental health has been with us since environmental protection was first considered. However, defining ecological health, particularly in the context of how freshwater inflow affects health, is a vexing issue (Montagna et al. 2013). Consider the analogy with human health. We know the normal human body temperature range is 36 to 38 ºC. If a person's body temperature is above this range, then the person has a fever and is likely sick. This example illustrates several important principles about human health as it relates to defining ecological health and how the definition has evolved for water quality assessment (Montagna et al. 2009).

Ecological health is assessed by determining if indicators of ecological conditions are within an acceptable range. Indicators are measures (or metrics) of ecological health for which sufficient information exists to establish an acceptable range of responses across broad spatial and temporal scales. Ecological condition is the status of ecological *function*, integrity, and sustainability. Ecological function is judged acceptable when the ecosystem provides important ecological processes. Ecological integrity is acceptable when the ecosystem has a balanced, resilient community of organisms with biological diversity, species composition, structural redundancy, and functional processes comparable to that of natural habitats in the same region. Ecological sustainability is acceptable when an ecosystem maintains a desired state of ecological integrity over time.

A common framework for environmental assessment is the simple Pressure–State–Response (PSR) model developed by the Organization for Economic Cooperation and Development (OECD 1993). The model is that variables that have cause and effect relationships with human activities exert pressure (P) on the environment, this changes the state (S) of the environment, and the management responses (R) to the change in conditions of the environment. The PRS model has been applied to the domino theory (Figure 1) where inflow was treated as a "pressure," estuary condition was treated as the "state," and change in biological indicators was the "response" (Montagna et al. 2013).

The PSR model was incomplete however, and it was enhanced by the European Environmental Agency (EEA 1999) to become the Driving force–Pressure–State–Impact–Response (DPSIR) framework (Jago-on et al. 2009). This is a systems approach for analyzing environmental problems where socio-economic development is the common driving force (D) that exerts pressure (P) on the environment and resulting in the state (S) of the environment changes. These changes then have impacts (I) on the ecosystems, human health and other materials. The impacts cause society to respond (R) to the driving forces, or directly to the pressure, state, or impacts through preventive, adaptive or curative solutions.

The DPSIR framework is applied here where inflow is the pressure, estuarine condition is the state, and change in marine living resources (MLR) is the biological response (Figure 2). This is a very powerful way to think about the effects of inflow on estuarine resources because it helps us to define the ecological health of estuaries and identify management actions. Assessing risk by defining health is often the first step in managing environmental resources. The major change in the current approach is that ecological responses are now called "impacts" rather than responses.

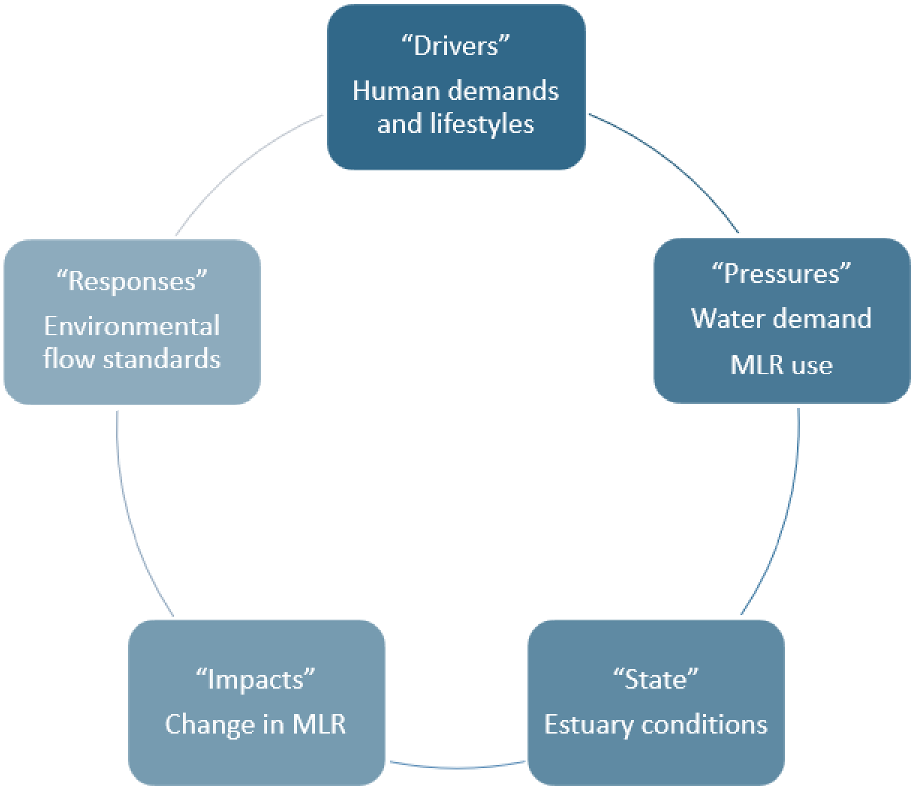

Figure 2. DPSIR framework applied to relationship between freshwater inflow and ecological health. MLR = marine living resources.

Implementing the five steps of the DIPSR framework for assessing ecological health is complex. But the key is to identify the pressure, state, and impacts. As mentioned above, it is necessary to identify the indicators of ecological health, particularly as they relate to pressure from altered freshwater inflow. Also, the acceptable spatial and temporal ranges for the indictors must be identified. In the end, the most important indicator is likely ecological sustainability. Sustainability is the ultimate definition of ecological health because an environment that is sustainable is healthy in the strict sense. This is why long-term data and time-series analysis is so important.

7.2 Study Area

Lavaca Bay is a secondary bay of the Lavaca-Colorado Estuary (LCE) (Figure 3). The estuary is composed of Matagorda Bay, which is a primary bay connected to the Gulf of Mexico; Lavaca Bay, which is a secondary bay that receives drainage from the Lavaca River; and the eastern arm of Matagorda Bay, which receives drainage from the Colorado River. Estuaries are named for their river sources, and the TWDB has adopted this convention for naming all Texas estuaries system (Longley 1994). Prior to 1994, the LCE had been named the Lavaca-Tres Palacios Estuary because the dominant river sources were the Lavaca and Tres Palacios Rivers (TDWR 19080, Bao et al. 1994). But in July 1992, the Colorado River was diverted so that flows drained into the eastern arm of Matagorda Bay, rather than emptying into the Gulf of Mexico (Wilber and Bass 1998). This diversion was constructed to increase flows to Matagorda Bay for environmental enhancement. Because the Colorado River flow is larger than the Tres Palacios River flow, the estuary was renamed to LCE (Longley 1994). However, there are different naming conventions. The Federal Government typically names estuaries for the primary bay, so the LCE is also called the Matagorda Bay System in some publications, especially those published by the National Oceanic and Atmospheric Administration (NOAA) (Orlando et al. 1993).

Lavaca Bay is shallow with an average depth of 1.2 m, except for ship channel, which has a depth of 10.5 m. The bay is also small (190 km^2) relative to other Texas bays. The Navidad River flows into the Lavaca River and the fresh water and sediment flows into the northeast corner of the bay. Minor freshwater inflows also come from Keller Bay, Cox Bay, Garcitas Delta and other small intermittent streams and creeks.

7.3 Data Sets

7.3.1 Hydrology Data (Inflow)

A daily time series of historical freshwater inflows into Lavaca Bay were assembled for the period from January 1, 1940 through December 31, 2017. The primary source for this data is the input file for the TWDB Matagorda Bay System TxBLEND salinity circulation model. This model includes daily inflows at fifteen locations (Figure 3).

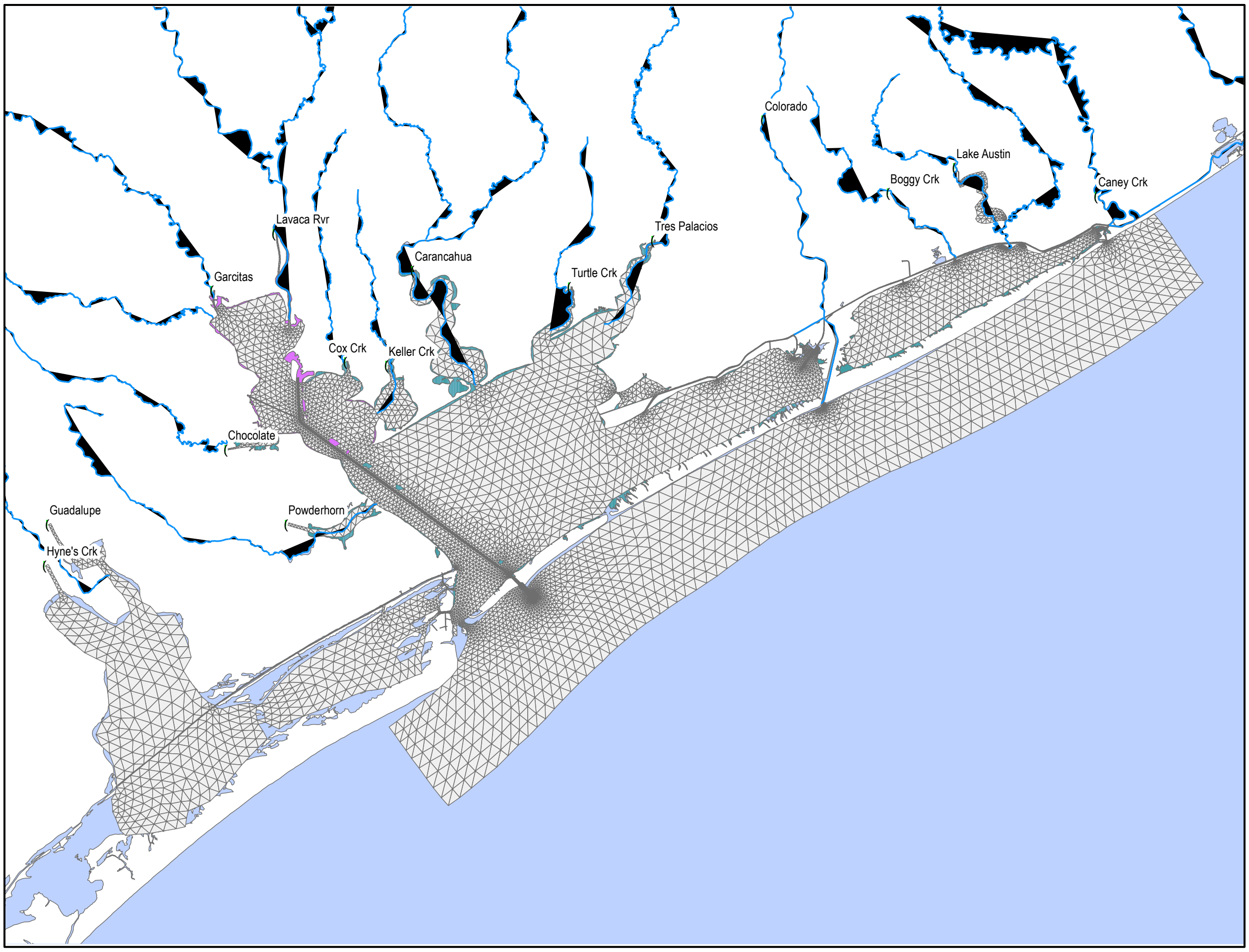

Figure 3. Lavaca-Colorado Estuary including the Lavaca River, Tres Palacios River, and Colorado River; and Lavaca Bay and Matagorda Bay.

The data used to develop these historical inflow sets are available on TWDB's Water Data for Texas webpage (https://waterdatafortexas.org/coastal/hydrology/matagorda) and includes gage flows, measured at USGS streamflow gage locations, ungaged flows, estimated from a rainfall runoff model (TxRR) and diversion and return flows downstream of USGS gage locations. Historical freshwater inflows are calculated as show in Figure 4 and described in Schoenbaechler et al. 2011.

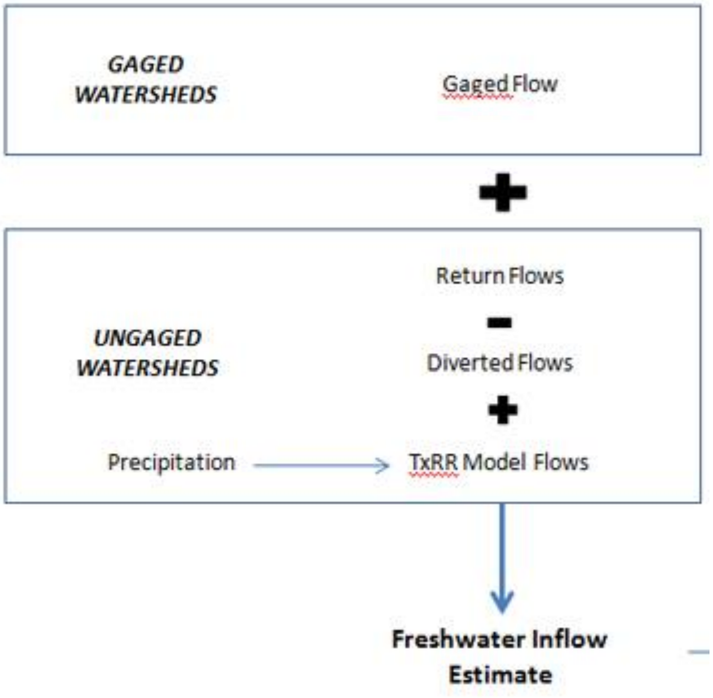

Figure 4. Conceptual model for estimating freshwater inflow rates.

The most recent set of daily inflows for the Matagorda TxBLEND model was provided by TWDB on December 20, 2018 and includes the period of record from January 1, 1977 through December 31, 2016. These input files were compared with the estimates of inflow derived from data on the Water Data for Texas website and with inflow sets provided in earlier versions of the TxBLEND model. Several discrepancies were identified and updated files were provided by TWDB.

Although the Matagorda Bay System model requires inputs from 15 locations, only two (Garcitas and Lavaca River) flow directly into Lavaca Bay while 3 others flow into secondary bays (Chocolate, Cox and Keller Creeks) before reaching Lavaca Bay (Figure 5). The Garcitas inflow represents inflow from both Garcitas and Placedo creeks, both of which are currently gaged though the cumulative inflow estimates also include ungaged runoff downstream of the gages and adjustments for diversions and returns in these ungaged areas. The Lavaca River inflow represents inflow from the Lavaca River and its tributaries including the Navidad River, which since 1980 has been regulated by Lake Texana, a 170,000 acre-feet storage reservoir.

Prior to 1977 (the earliest date for which Lavaca River inflow estimates has been provided by TWDB as part of the TxBLEND inputs) the estimate of historical inflows from the Lavaca river watershed is complicated somewhat by the construction of Lake Texana and the fact that several of the gages in the watershed have relatively short periods of record (Figure 6). For the period 1977-2016, TWDB had to carefully account for the dates when specific gages came on-line and then make estimates for ungaged inflow contributions based on the different drainage areas that were included within these gages. Prior to 1977, a reasonable estimate of historic inflows from the Lavaca watershed was calculated by the fairly straightforward approach of summing daily gaged stream flows from the Lavaca River Edna and the Navidad River at Ganado plus the ungaged contribution downstream of these two gages (primarily watershed area 16008 plus a small portion of watershed area 16014 downstream of the gage at Ganado – see Figure 6).

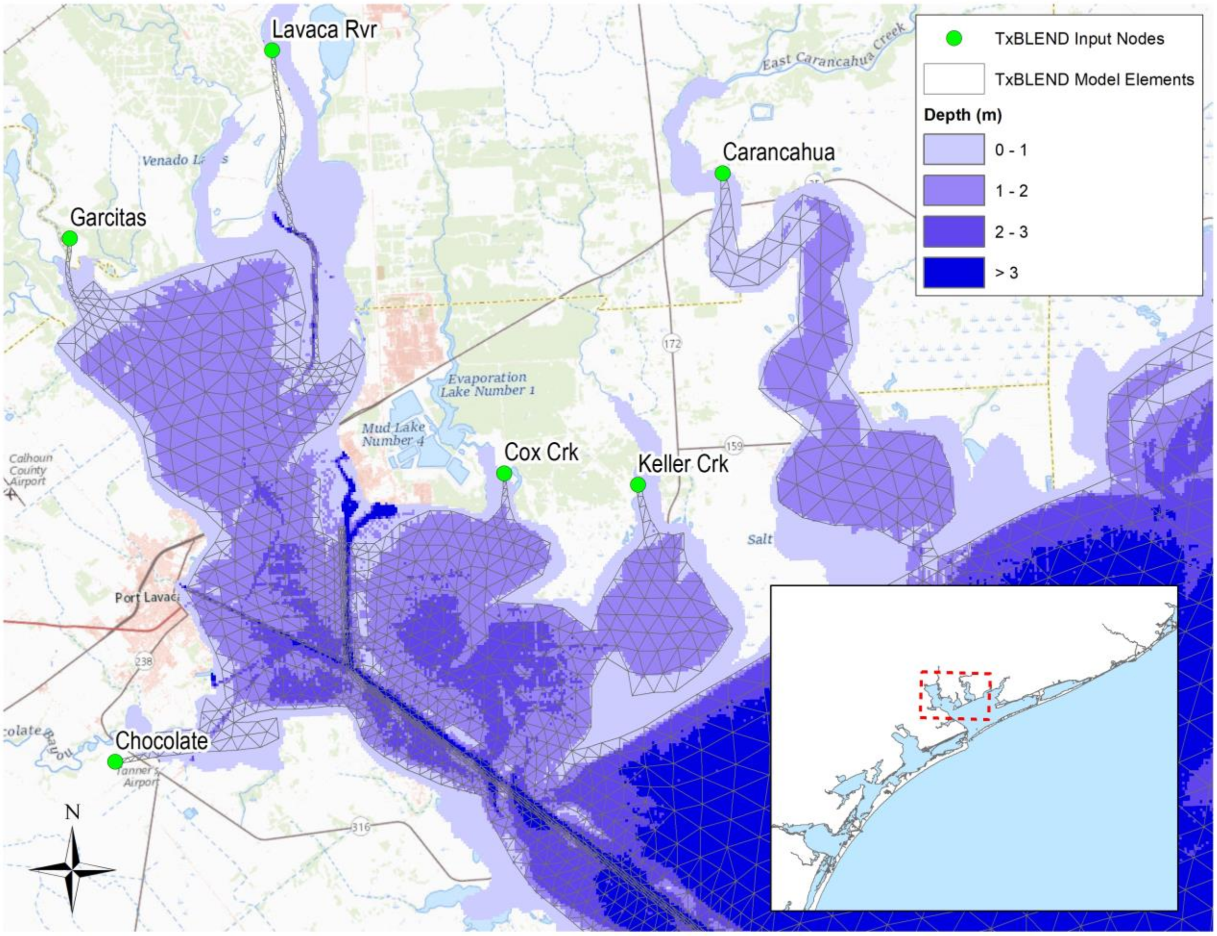

Figure 5. Lavaca Bay inflow locations and TxBLEND input nodes and model elements, overlayed on bathymetry.

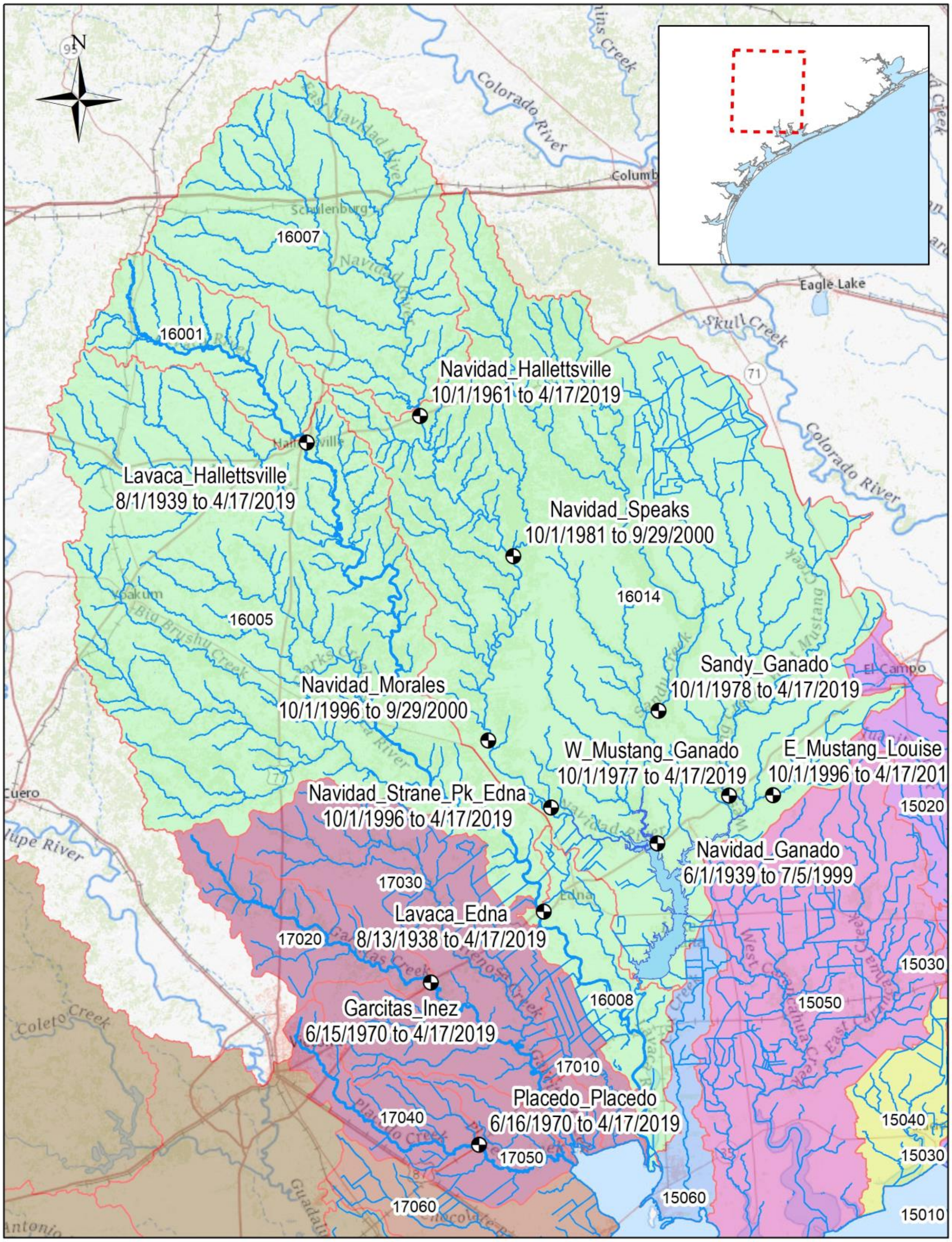

Figure 6. Watersheds contributing flow to the Lavaca River.

Fortunately, TWBD provided the ungaged flows for watershed 16008 for the period from 1940-2016. Thus, only a drainage area adjustment to the Ganado gage was needed to be able to construct a reasonable estimate of historic Lavaca watershed inflow for the entire 1940-2016 time period.

7.3.2 Climate Data (Conditions)

Data indicating long-term climate drivers was obtained from the National Oceanic and Atmospheric Administration (NOAA), Climate Prediction Center (CPC). This includes monthly Ocean Niño Index (ONI), North Atlantic Oscillation (NAO), and North Pacific Index (NPI), which are used to related inflow with global climatic conditions.

7.3.3 Physical and Chemical Data (Conditions)

Water quality data was obtained from the Texas Commission on Environmental Quality (TCEQ), Surface Water Quality Monitoring Program (SWQMP). This consists of regular water quality monitoring, as well as special studies. The data set contains mostly physical-chemical measurements such as salinity, temperature, nutrients, and some contaminants. While this data is from multiple sources and was collected by multiple programs, all the data would have been associated with a Quality Assurance Project Plan (QAPP), or it would not have been put in the database.

The Texas Parks and Wildlife Department (TPWD), Coastal Fisheries Program, collects biological samples monthly (see below) and measures salinity, temperature, dissolved oxygen, and turbidity at all sampling locations. The data series began in 1977. The methods are described in Martinez-Andrade et al. (2005).

Additional water quality data was provided by the PI Montagna at the Harte Research Institute (HRI). This data set goes back to 1984 and was collected specifically to identify freshwater inflow effects on water quality (salinity, temperature, dissolved oxygen, pH, turbidity, nutrients, and chlorophyll). The methods are described in many publications (Montagna 1989, 1999, 2000, 2013,2014), and a QAPP (Montagna 2003).

Additional water quality data was obtained from Freese and Nichols, Inc. (thanks to Lisa Vitale), which has been conducting quarterly monitoring of the Formosa Plastics Corporation discharge site into Lavaca Bay. This data set is very large and complex, and includes both conventional water quality indicators (such as salinity, temperature, dissolved oxygen, pH, and turbidity), but also potential pollutants such as trace metals, semivolatile organic compounds (SVOC includes hydrocarbons, aldehydes, ethers, esters, phenols, organic acids, ketones, amines, amides, nitroaromatics, polychlorinated biphenyls also known as Aroclors, polycyclic aromatic hydrocarbons, phthalate esters, nitrosamines, haloethers and trihalomethanes), and volatile organic compounds (VOC includes halogenated hydrocarbons, aromatics, ketones, nitriles, acrylates, acetates, ethers, and sulfides). These contaminant measurements were comprehensive being made in water, sediment, and tissues from oysters and hardhead catfish. The collection and analytical methods are described in Freese and Nichols (2019) where it is stated that the scope and methods have been approved by TCEQ and the monitoring meets the requirements of the National Pollutant Discharge Elimination System (NPDES) Sampling and Analysis Program.

7.3.4 Biological Data (Bioindicator Response)

Benthic infauna has been collected by P. Montagna (HRI) since 1984 specifically to identify inflow effects on bioindicators. Benthos are integrators of long-term effects in the overlying water column because they cannot move when conditions are poor. Benthos are also secondary consumers and thus linked to primary production more closely than tertiary consumers (such as fish). The infauna, meaning they live in the sediment, were collected using a 6.7 cm diameter (35 cm^2) core to a depth of 10 cm, preserved with 10% formalin, extracted on a #35 sieve (0.5 mm mesh), and identified to the lowest taxonomic level possible (Montagna and Kalke 1992). Abundance is scaled to the number of individuals per meter square (n/m^2) by multiplying by 283.64.

The TPWD, Coastal Fisheries program, has been running a fisheries-independent monitoring program designed to manage fisheries by estuary throughout Texas (Martinez-Andrade et al. 2005). Species surveys were completed using three gear types: bag seines (1977-present), trawls (1982-present), and gillnets (1975-present). Benthic epifauna (that live on the sediment) are collected by trawls in a stratified randomized sampling design. The trawls are 6.1 m wide at mouth, 3.8 cm mesh, doors 1.2 m long x 0.5 m tall; and towed in a circular pattern for 10 minutes. Juvenile fish and small invertebrates are collected using bag seines. The Bag seine is 18.3 m long x 1.8 m deep with 1.3 cm mesh, it is pulled parallel to the shore for 15.2 m, thus collects an area of about 0.01 ha. Large fish are collected using gill nets. The gill net is 183 m long, 1.2 m deep, four 45.7 sections of 7.6, 10.2, 12.7, and 15.1 cm mesh, is set perpendicular to the shoreline, and is set overnight. Oysters are collected by dredge. The dredge is a Louisiana style 9-tooth dredge that is 46 cm wide, 25 cm tall, and 36 cm deep bag.

The TPWD uses a random sampling method to monitor estuaries, i.e., whole bay systems. Only 10 stations out of hundreds from within a bay are sampled each month. A scheme was devised to aggregate stations within areas of similar salinity conditions within each bay, and referred to as segments (Kurr 2019). In addition to using salinity gradients and location of HRI stations, the general geography of the bays was considered to create the segments. Salinity gradients were by averaging each station by month, and then by year to balance seasonal and year-to-year variability. Once segments were created, all trawl samples were averaged by quarter for each segment. The TPWD quarterly segment data was merged with the quarterly HRI benthic core data, which was collected quarterly.

The Formosa Plastics dataset also contains infauna, epifauna, and fish (Freese and Nichols 2019). While the data is currently being collected by Freese and Nichols, it was formerly collected by Espey Associate, PBSJ, and Atkins.

7.3.5 Sampling Locations

Data was collected from the sources named above. The most extensive sampling is performed by TPWD and TCEQ (Figure 7). Long-term, fixed point, sampling was collected at two stations by HRI and 19 stations by Freese and Nichols (Figure 8).

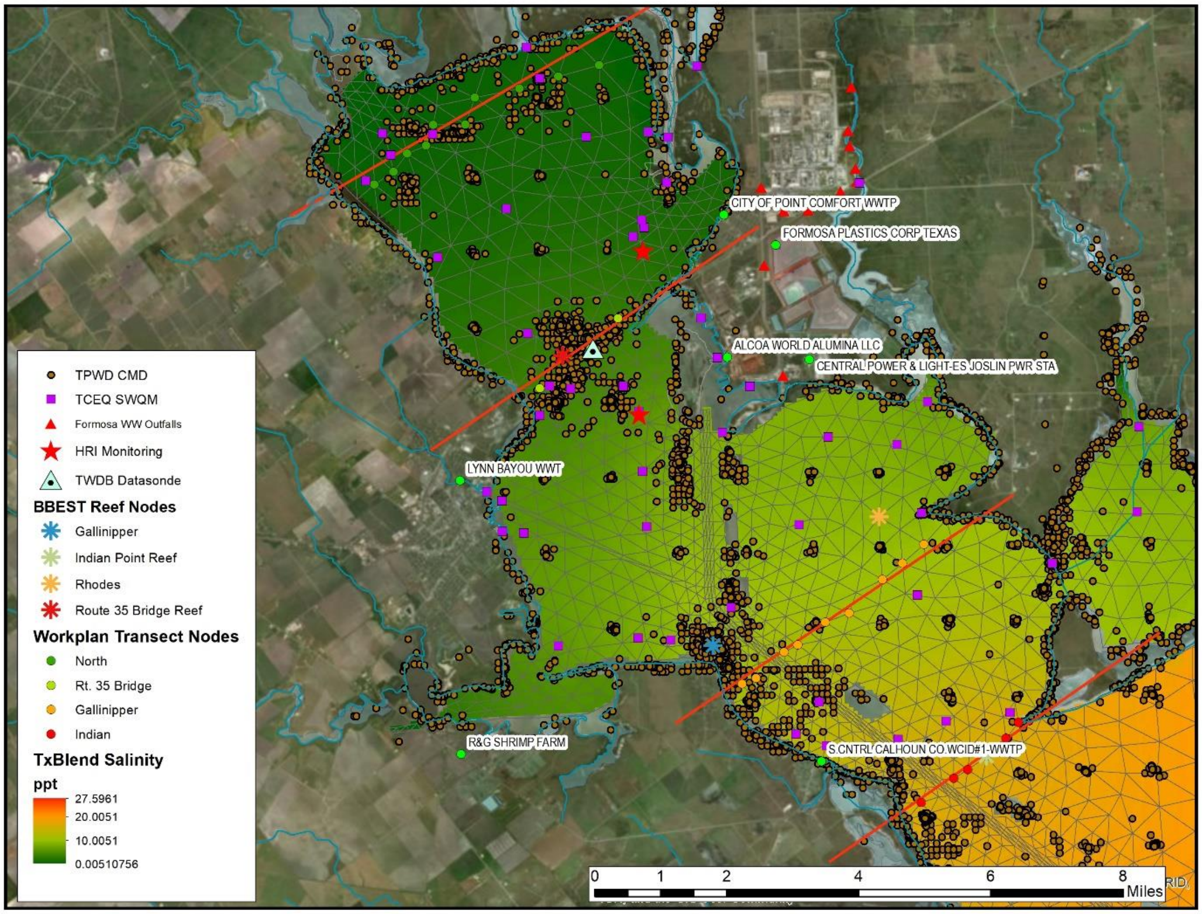

Figure 7. Locations of samples for five datasets, and the data used in the 2010 CL BBEST report (CL BBEST Reef Nodes) and the 2015 SB3 Workplan (Workplan Transect Nodes).

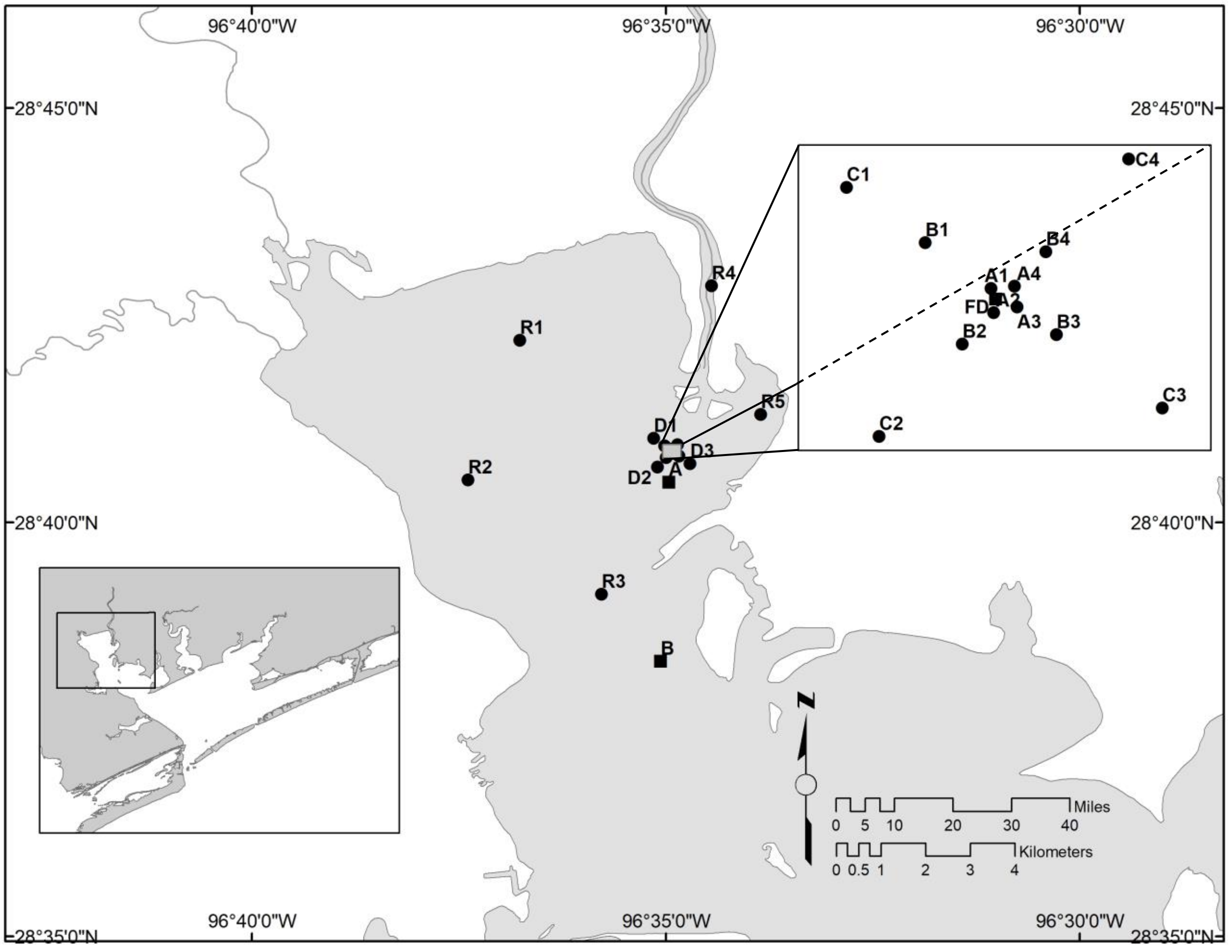

Figure 8. Sampling locations by HRI (squares; A, B, and FD) and Freese and Nichols (dots; A1-A4, B1-B4, C1-C4, D1-D). Inset zoomed to area surrounding the Formosa discharge location.

7.4 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.

7.4.1 Bioindicators

Analyses were performed on three levels of biological organization: 1) habitat (e.g., oyster reef, open bay bottom, and nekton), 2) community structure (e.g., infaunal benthos, epifaunal benthos, and nekton), and 3) key or indicator species. Key species are those deemed ecologically, commercially, or recreationally important (e.g., redfish, seatrout, flounder, blue crab, shrimp, etc.). Indicator species are those that are known to respond to inflow in their adult life stages, this includes primary suspension feeding benthos that are bivalve mollusks (e.g., eastern oyster *Crassostrea*, *Rangia*, *Mulinia*, etc.), but also some crustaceans and polychaete worms. Oysters are one of the few species that are both key and indicator species.

Previous work has identified those benthic species that are indicators of freshwater inflow (Montagna et al. 2008, Montagna and Kalke 1995, Palmer et al. 2015, Pollack et al. 2009) and these are primarily mollusk species (Table 1).

Table 1. Benthic Indicator species. Responses from multiple references separated by a semicolon. Abbreviations: Ph = Phylum, Cl = Class, Or = Order, and Fa = Family.

Ph	Cl	Or	Fa	Genus species	Salinity range (psu)	Reference(s)
Mollusca						
	Gastropoda					
		Heterostropha				
			Pyramidellidae			
				Eulimastoma sp.	2 to 29 (mean 21)	Montagna & Kalke (1995)
				Odostomia canaliculata	13	Montagna & Kalke (1995)
				Odostomia sp.	25	Montagna & Kalke (1995)
		Neotaenioglossa				
			Littorinidae			
				Littoraria irrorata	>2	Montagna et al. (2008)
			Hydrobiidae			
				Texadina sphinctostoma	1 to 33 (mean 13)	Montagna & Kalke (1995)
		Cephalaspidea				
			Cylichnidae			
				Acteocina canaliculata	2 to 41 (mean 24)	Current Study
		Cycloneritimorpha				
			Neritidae			
				Neritina usnea	<18	Montagna et al. (2008)
	Bivalvia					
		Pholadomyoida				
			Pandoridae			
				Pandora trilineata	2 to 31 (mean 23)	Montagna & Kalke (1995)
		Veneroida				
			Corbiculidae			
				Corbicula fluminea	<7 (most ≤2)	Montagna et al. (2008)
				Polymesoda caroliniana	1 to 20	Montagna et al. (2008)
			Mactridae			
				Mulinia lateralis	>2; 0 to 36 (mean 19)	Current Study; Montagna et al. (2008)
				Rangia cuneata	10; <16 (most ≤10)	Montagna & Kalke (1995); Montagna et al. (2008)
			Pharidae			
				Ensis minor	4 to 31 (mean 23)	Montagna & Kalke (1995)
			Solecurtidae			
				Tagelus plebeius	23; >2	Montagna & Kalke (1995); Montagna et al. (2008)
			Tellinidae			
				Macoma mitchelli	15.4; 0 to 33 (mean 16)	Pollack et al. (2009); Current Study
				Tellina versicolor	2 to 18	Montagna et al. (2008)
		Mytiloida				
			Mytilidae			

Amygdalum papyrium	2 to 20	Montagna et al. (2008)
Geukensia granosissima	10 to 24	Montagna et al. (2008)
Ischadium recurvum	>6	Montagna et al. (2008)
Ostreoida		
Ostreidae		
Crassostrea virginica	13; >7; 19	Montagna & Kalke (1995); Montagna et al. (2008); Current Study
Annelida		
Polychaeta		
Errantia		
Pilargidae		
Hermundura ocularis	15; 0 to 36 (mean 17)	Pollack et al. (2009); Current Study
Nereididae		
Alitta succinea	22 to 41 (mean 27)	Current Study
Canalipalpata		
Spionidae		
Diolydora socialis	1 to 32 (mean 20)	Current Study
Polydora cornuta	0 to 35 (mean 16)	Current Study
Streblospio benedicti	21.3; 0 to 41 (mean 18)	Pollack et al. (2009); Current Study
Order Not Assigned		
Capitellidae		
Capitella capitata	0 to 41 (mean 14)	Current Study
Heteromastus filiformis	1 to 33 (mean 18)	Current Study
Mediomastus californiensis	0 to 32 (mean 16)	Current Study
Crustacea		
Malacostraca		
Amphipoda		
Ampeliscidae		
Ampelisca abdita	0 to 40 (mean 22)	Current Study
Isopoda		
Idoteidae		
Edotia triloba	0 to 33 (mean 16)	Current Study
Insecta		
Pterygota		
Diptera		
Chironomidae		
Chironomidae (larvae)	0 to 20 (mean 4)	Current Study

7.4.1.1 Salinity Habitat

Habitats are defined here as zones with preferred salinity ranges. A mathematical modeling technique was used to identify preferred average salinity ranges (Montagna et al. 2002, 2008). This method was later refined and is now called the MaxBin regression method (Turner and Montagna 2016).

7.4.1.2 Diversity Indicators

Diversity indices are univariate metrics that summarize multivariate community characteristics in a single number. Diversity indices exist to identify the number of species relative to one another. 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 (R) is an index of the number of species present. The simplest richness index is the total number of all species (S) 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' (i.e., total species or richness:

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

7.4.1.3 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 $\log_{10}$ transformed. Log 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.

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 describes 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.

7.4.2 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).

7.4.3 Inflow Identification

After the conditions that support bioindicators is determined using the two steps above, it is possible to calculate the inflow levels needed to maintain the conditions in an acceptable range. This approach has been used by the Nueces BBEST (N-BBEST 2011), the Galveston-BBEST (T-BBEST 2009), and in Matagorda Bay (Anchor QEA et al. 2015) in their reports, and it has been used by the Montagna group to develop inflow criteria for the Caloosahatchee River estuary in Florida (Palmer et al. 2016). This analysis is based on non-linear regression, so it is also possible to calculate the bounds of error for the biological responses to inflow, as was done for the Caloosahatchee River.

The non-linear regression was used to determine the inflow volume necessary to achieve design salinity targets at specific locations within Lavaca Bay is based on salinities predicted by the TWDB TxBLEND model. This model simulates salinity throughout Lavaca Bay for the time period from November 1, 1986 through December 31, 2016. Although the TxBLEND model iterates at 120 second (2minute) timestep, outputs are produced as monthly average values, for all nodes in the model domain, and as daily average values for a subset of nodes (up to 100) defined in the model input file. Based on the monthly outputs it is possible to develop a time series of maps showing how monthly average isohalines change in response to historical inflows and meteorological conditions. A series of these maps is provided in Appendix A.

7.4.4 Time Series 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 used the multivariate autoregressive state space (MARSS) modeling framework (Holmes et al. 2012a, 2012b).

MARSS Model Framework:

$$\boldsymbol{x}_t = \boldsymbol{B}\boldsymbol{x}_{t-1} + \boldsymbol{C}\boldsymbol{c}_{t-1} + \boldsymbol{w}_t, \text{ where } \boldsymbol{w}_t \sim \text{MVN}(0,\boldsymbol{Q})$$

$$\boldsymbol{y}_t = \boldsymbol{Z}\boldsymbol{x}_t + \boldsymbol{v}_t, \text{ where } \boldsymbol{v}_t \sim \text{MVN}(0,\boldsymbol{R})$$

The observed abundance data is standardized by catch per unit effort (annual CPUE), log-transformed and enter the model as $\mathbf{y}_t$. Annual CPUE is then modeled as a linear function of the true state of abundance ($\mathbf{x}_t$) and observation error ($\mathbf{v}_t$). **B** is the interaction of the effects of abundances on each other, **C** is the effect of each hydrologic driver on abundances, and $\mathbf{w}_t$ is the process error.

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 will identify response complexities, inter-connectedness, and factors that could confound the relationship between inflow and biological responses.

7.4.5 Event Identification

The hydrology of estuaries is complex, but along the Texas central coast it is clearly driven by the periodic onset of large rain events associated by thunderstorms and seasonal disturbances (Montagna et al. 2011b). The timing of these larger rain events co-occur during El Niño periods (Tolan 2007) and this is particularly true in Lavaca Bay (Pollack et al. 2011). Therefore, we will assess biological responses by wet, average, and dry conditions. In the past, we have defined these by quartiles, i.e., wet <25%, average is between 25 and 75%, and dry is >75% (Palmer and Montagna 2015). For the current study we will use the definition in the RFQ and define low flow as <20%, high flow is >75%, and average flow is between 20% and 75%.

Daily river discharge data in cubic feet per second from the USGS (08164000) Lavaca River near Edna gage (1988-2012) was used to quantify hydrological change and variability following the methods described in Sabo and Post (2008) and Sabo et al. (2017). We used a bootstrapped 20-year window discrete fast Fourier transform (DFFT) to estimate the long-term detrended seasonal signal using the "discharge" R-package (Shah and Ruhi, 2019). Normalized discharge data was detrended prior to DFFT analysis and hydrologic variance was quantified using the detrended seasonal signal that was fit to the detrended river discharge time series. Detrending is necessary to remove a long-term effect using linear regression to emphasize a short-term effect. High and low flow events from the seasonal signal were used to identify nine hydrologic components that provide information about the timing, frequency, duration, and magnitude of the deviations of river discharge. The nine components of hydrologic variance that vary from year-to-year are:

1. LSAM = low spectral anomaly magnitude
2. HSAM = high spectral anomaly magnitude
3. Transition time between LSAM and HSAM
4. LSAF = low spectral anomaly frequency
5. HSAF = high spectral anomaly frequency
6. Timing for LSAM
7. Timing for HSAM
8. IFI =interflood interval
9. IDI = interdrought interval

7.4.6 Linking Inflow Events and Communities

Community metrics were linked with environmental variables using Spearman rank correlations between sample ordinations from all the environmental variables as calculated as new principal component variables and metrics of biotic variables. Spearman's is a nonparametric measure of rank correlation (statistical dependence between the rankings of two variables). The Spearman correlation between two variables is equal to the Pearson correlation between the rank values of those two variables; while Pearson's correlation assesses linear relationships, Spearman's correlation assesses monotonic relationships (whether linear or not).

8. Results

8.1 Bioindicator Identification

All seven Basin and Bay Expert Science Teams (BBESTs) identified species or taxa that are bioindicators of freshwater inflow effects (Table 2). Organisms are designated as bioindicators when they exhibit sensitivity or dependence on low salinity conditions. Five of the seven BBESTs, which were describing bay systems, identified benthic organisms as the most sensitive indicators of inflow effects; and all of these were shellfish, i.e., mollusks or crustaceans. The other two systems, Brazos River and Laguna Madre, were different. The Brazos River is a river that empties into the Gulf of Mexico and the BBEST identified only physical metrics (i.e., salinity, nutrients, sediment supply). Laguna Madre is hypersaline, has species that are adapted to high salinities, and seagrass was chosen as the bioindicator. Sabine Lake, where the 32-year salinity average only 7.1 (standard deviation 2.8) (Montagna et al. 2011a), also chose plant communities that are sensitive to salinity as bioindicators. However, it is not only oysters, *Rangia*, shrimp and crab that are benthic bioindicators, it is nearly all benthic species (Table 1). This is because benthos are fixed in place and must tolerate overlying water conditions or perish.

Table 2. Freshwater inflow bioindicators identified by BBEST groups. Listed northeast to southwest.

Bay System (Reference)	Indicator Species
Sabine Lake (SN-BBEST 2009)	Eastern oyster, Atlantic *Rangia*, blue crab juveniles, Olney bulrush, intermediate marsh, brackish marsh
Galveston Bay (TSJ-BBEST 2009)	Eastern oyster, Atlantic *Rangia*, dermo, oyster drill, wild celery, Gulf menhaden, blue catfish, mantis shrimp, pinfish
Brazos River (BR-BBEST 2012)	Salinity, nutrients, sediment supply
Lavaca and Matagorda Bays (CL-BBEST 2011)	Eastern oyster, dermo, oyster drill, brown shrimp, white shrimp, blue crab, Gulf menhaden and Atlantic croaker, Benthic infauna
Mission, Copano, Aransas, and San Antonio Bays (GSA-BBEST 2011)	Eastern oyster, Atlantic *Rangia*, brown *Rangia*, white shrimp, blue crab
Nueces, Corpus Christi, and Baffin Bays (N-BBEST 2011)	Eastern oyster, Atlantic *Rangia*, smooth cordgrass, benthic infauna, blue crab, Atlantic croaker, nutrient cycling, sediment loading
Lower Laguna Madre (RG-BBEST 2012)	Seagrasses

8.1.1 Benthic Groups Sensitive to Salinity

There are two approaches used here in which bioindicators based on salinity are being identified. One approach is to compare species presence or absence in Lavaca Bay where the average salinity is 50% lower than the average salinity in Matagorda Bay (Table 3). The second approach is to use the existing list in Table 1 and Table 2, and then subject those species to a MaxBin analysis to identify optimal salinities.

Table 3. Hydrographic parameters over 31.25 years (HRI data, April 1988 - July 2019).

	Lavaca Bay*		Matagorda Bay*	
Parameter	Mean	(STD)	Mean	(STD)
Salinity (psu)	17.4	(9.4)	26.1	(5.9)
Temperature (°C)	22.1	(6.7)	22.0	(6.5)
DO (mg/L)	8.0	(1.5)	7.4	(1.4)

*Lavaca Bay = Stations A and B, Matagorda Bay = Stations C and D.

Water and sediment quality sampling have occurred in the Lavaca-Colorado Estuary since 1988 (Figure 9). The average salinity at two Lavaca Bay (Stations A and B) over 31 years is 17.4, which is 50% lower than the average salinity in Matagorda Bay (Station C and D) of 26.1. Thus, different community structure between the bays is correlated to the different salinities in the two bays because temperature and dissolved oxygen is more similar in the two bays."

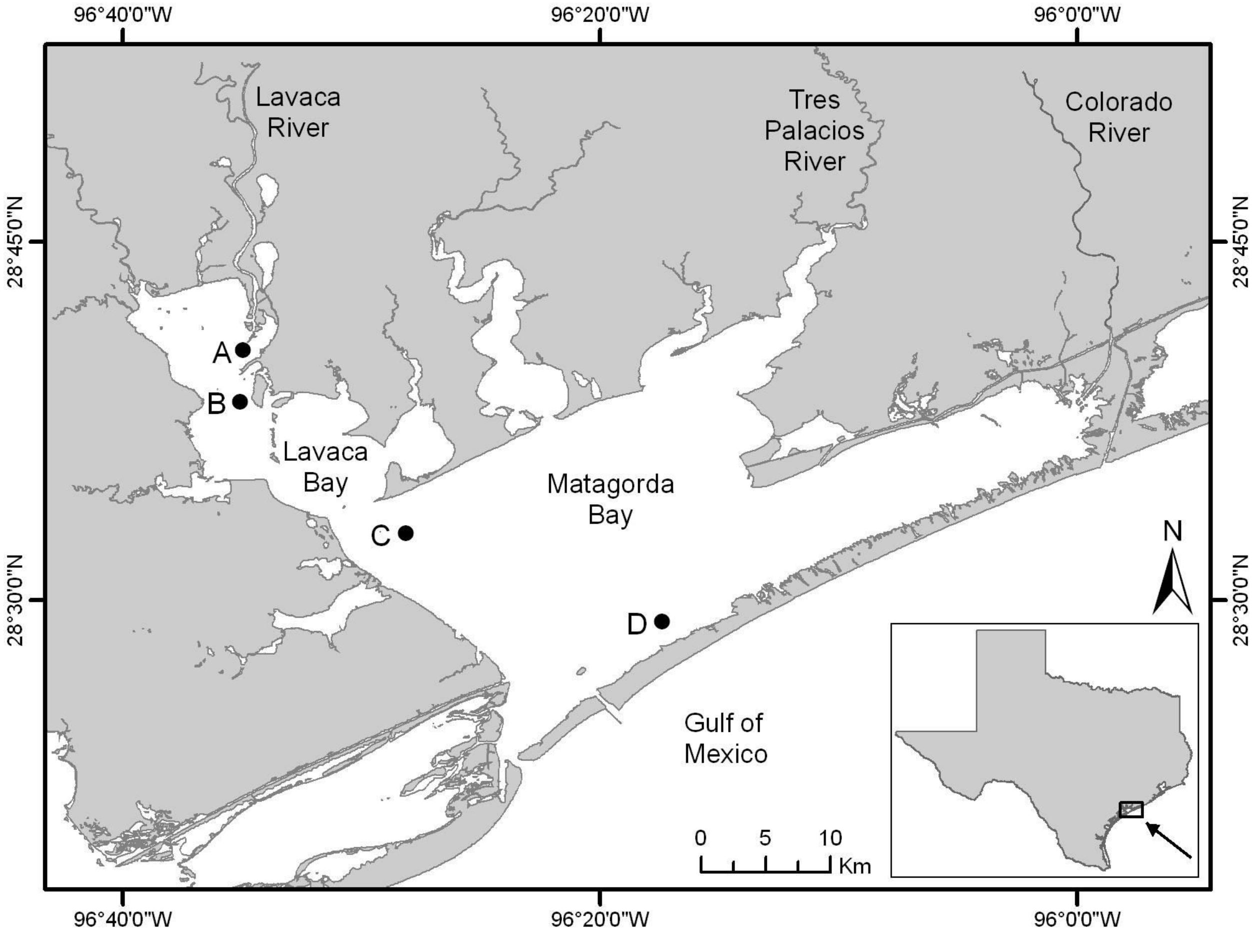

Figure 9 . Locations of HRI long-term stations in the Lavaca-Colorado Estuary.

A total of 255 species have been found in the Lavaca-Colorado Estuary (Figure 9) over the 32-year period (Appendix 1). However, only 133 occur in Lavaca Bay, and 217 occur in Matagorda Bay. A total of 47 species are more prevalent in Lavaca Bay than Matagorda Bay, and 208 species are more prevalent in Matagorda Bay than Lavaca Bay.

The species that are relatively exclusive to Lavaca Bay are freshwater inflow indicator species. When the number of species in Lavaca Bay is divided by the number in Matagorda Bay, there are 208 species with a ratio < 1, which means that they occur mostly in Matagorda Bay. A total of 47 species have a ratio > 1, meaning they occur mostly in Lavaca Bay. Three species (99th percentile) had ratios > 19.3, 10 species (95th percentile) had ratios between 18.8 and 7.0), and 13 species (90th percentile) had ratios between 6.7 and 3.0 (Appendix 1). So, a total of 26 species make up the top 90th percentile of species preferring Lavaca Bay and represent the freshwater inflow indicator species (Table 4).

Table 4. Species found in Lavaca Bay relative to Matagorda Bay (=LB/MB). Average abundance (n/m2) from 1988 – 2012. Subset of Appendix 1.

		Lavaca Bay			Matagorda Bay		
Phylum	**Species**	**A**	**B**	**FD**	**C**	**D**	**LB/MB**
Annelida	*Capitella capitata*	57.7	24.4	138.4	5.3	0.0	27.7
Insecta	Chironomidae (larvae)	12.3	3.2	47.3	0.0	0.0	20.9
Mollusca	*Texadina sphinctostoma*	46.9	4.2	6.8	0.0	0.0	19.3
Crustacea	*Edotia triloba*	13.0	0.0	16.9	1.1	0.0	18.8
Mollusca	*Macoma mitchelli*	158.2	87.1	111.4	8.5	5.3	17.2
Crustacea	*Corophium louisianae*	6.7	1.1	40.5	0.0	0.0	16.1
Crustacea	*Ampelisca abdita*	280.0	51.0	182.3	15.9	7.4	14.6
Annelida	*Laeonereis culveri*	7.0	1.1	30.4	0.0	0.0	12.8
Annelida	*Polydora cornuta*	8.9	1.1	10.1	1.1	0.0	12.6
Annelida	*Hermundura ocularis*	59.0	20.2	13.5	6.4	0.0	9.7
Crustacea	Ostracoda (unidentified)	4.0	21.2	0.0	0.0	0.0	8.4
Mollusca	*Ensis minor*	13.6	0.0	10.1	0.0	0.0	7.9
Crustacea	*Grandidierella bonnieroides*	0.8	0.0	20.3	0.0	0.0	7.0
Annelida	*Sabellastarte magnifica*	6.5	0.0	13.5	0.0	0.0	6.7
Annelida	*Heteromastus filiformis*	11.3	4.2	3.4	0.0	0.0	6.3
Annelida	*Alitta succinea*	2.4	3.2	13.5	2.1	0.0	6.0
Crustacea	*Cerapus tubularis*	0.0	0.0	16.9	0.0	0.0	5.6
Annelida	*Scolelepis texana*	2.3	2.1	10.1	0.0	0.0	4.8
Mollusca	*Tagelus plebeius*	11.1	0.0	0.0	0.0	0.0	3.7
Crustacea	*Leptochelia rapax*	0.8	0.0	10.1	0.0	0.0	3.6
Annelida	*Streblospio benedicti*	971.6	806.3	830.7	336.8	173.2	3.4
Annelida	*Microphthalmus aberrans*	0.0	0.0	10.1	0.0	0.0	3.4
Mollusca	*Amygdalum papyrium*	0.0	0.0	10.1	0.0	0.0	3.4
Mollusca	*Solen viridis*	0.0	0.0	10.1	0.0	0.0	3.4
Annelida	*Diolydora socialis*	13.2	0.0	121.6	22.3	7.4	3.0
Mollusca	*Rangia cuneata*	8.9	0.0	0.0	0.0	0.0	3.0

Several species in Table 4 are interesting because they occur in the list of previously identified species (Table 1) and they are relatively restricted to Lavaca Bay and are abundant. This includes *Capitella capitata*, *Macoma mitchelli*, *Ampelisca abdita*, *Hermundura ocularis*, and *Tagelus plebeius*. Three other species, *Edotia triloba, Eulimastoma* sp., and *Rangia cuneata* were identified as being typical of low salinity environments (Table 1). Six of these species were chosen to determine the optimal salinity range using the MaxBin analysis (Table 5).

The MaxBin analysis estimates three parameters: the maximum abundance (a), the initial rate of increase (b), and the salinity where the peak abundance occurs (c) (Table 5). Four of the species had salinity peaks between 8 and 13 psu. The detection limit is zero when there are no individuals found in three replicate cores, and 94.5 individuals/m^2 when there is one individual among the three cores (Figure 10 - Figure 16).

Table 5. Parameters from nonlinear regressions to predict abundance (n/m^2) from salinity. Number of occurrences (n), bins, and parameters for maximum biological value (a), rate of change (b), and salinity in which maximum abundance occurs (c) with standard errors of the estimates in parentheses.

Species	n	Bins	a (max Y)	b (rate)	c (Peak X)
Infauna					
Capitella capitata	60	9	893 (358)	0.907 (0.630)	8.2 (4.6)
Eulimastoma sp.	33	7	1712 (515)	1.131 (0.872)	9.0 (5.8)
Edotia triloba	20	9	219 (38)	-0.790 (0.186)	10.0 (1.8)
Macoma mitchelli	105	7	1712 (515)	0.452 (0.175)	13.0 (2.3)
Hermundura ocularis	54	8	2717 (377)	0.088 (0.016)	21.6 (0.8)
Ampelisca abdita	87	8	12400 (258)	-0.130 (0.003)	25.3 (0.1)
Epifauna					
Crassostrea virginica	729	15	2189 (408)	.372 (0.085)	19.5 (1.6)

Capitella capitata had the lowest peak salinity of 8.2 psu (Figure 10). The model was not significant (p = 0.1166) and R^2 was 74%. *Capitella* occurred over a large salinity range but was mostly abundant when salinities were below 15 psu. *Capitella* is a deposit feeding polychaete.

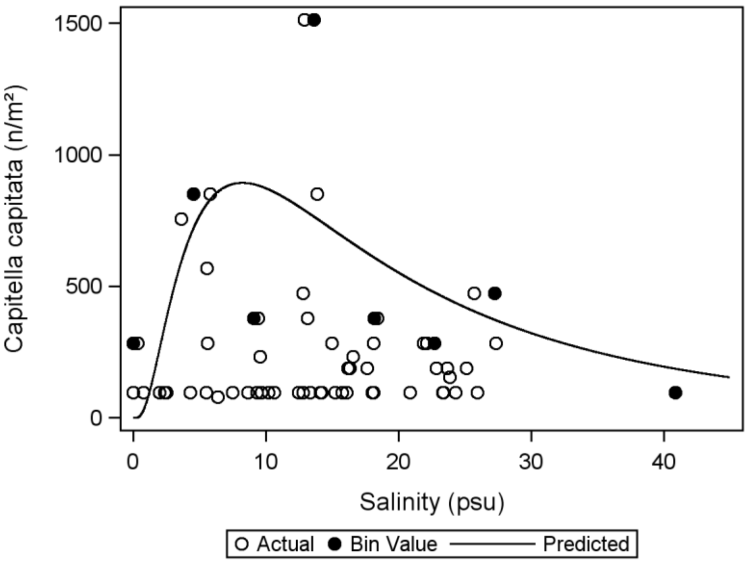

Figure 10. Capitella capitata abundance as a function salinity. Dots are the maximum values of bins, and line is the predicted values.

Eulimastoma sp. had the second lowest peak salinity of 9.0 psu (Figure 11). The model was significant (p = 0.0092) and R^2 was 93%. *Eulimastoma* occurred over a large salinity range, and most occurred in the middle to high salinity ranges. *Eulimastoma* is a surface feeding gastropod.

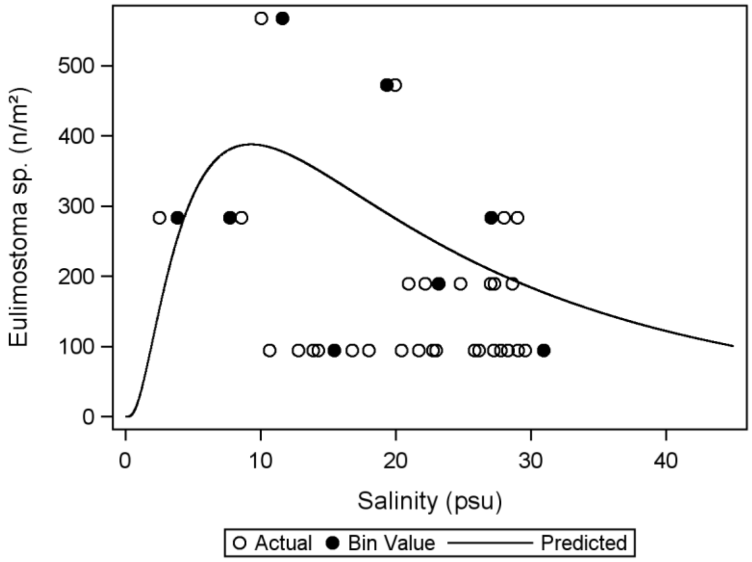

Figure 11. *Eulimastoma* abundance as a function of salinity. Dots are the maximum values of bins, and line is the predicted values.

Edotia triloba had the third lowest peak salinity of 10.0 psu (Figure 12). The model was significant (p = 0.0094) and R^2 was 92%. *Edotia* also occurred over a large salinity range, but abundance tapers off with higher salinities. *Edotia* a surface feeding gastropod (i.e., a snail).

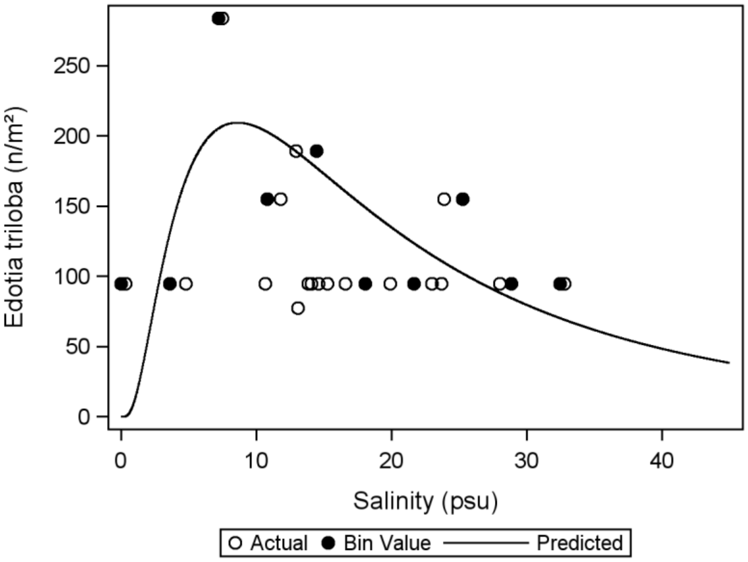

Figure 12. *Edotia triloba* abundance as a function of salinity. Dots are the maximum values of bins, and line is the predicted values.

Macoma mitchelli had a salinity peak of 13.0 psu (Figure 13). The model was barely not significant (p = 0.0615) and R^2 was 81%. *Macoma* also occurred over a large salinity range, but abundance is most common at lower salinities. *Macoma* is a deposit-feeding bivalve clam with split siphons. It was also the most common species among those chosen for analysis with 105 occurrences (Table 5).

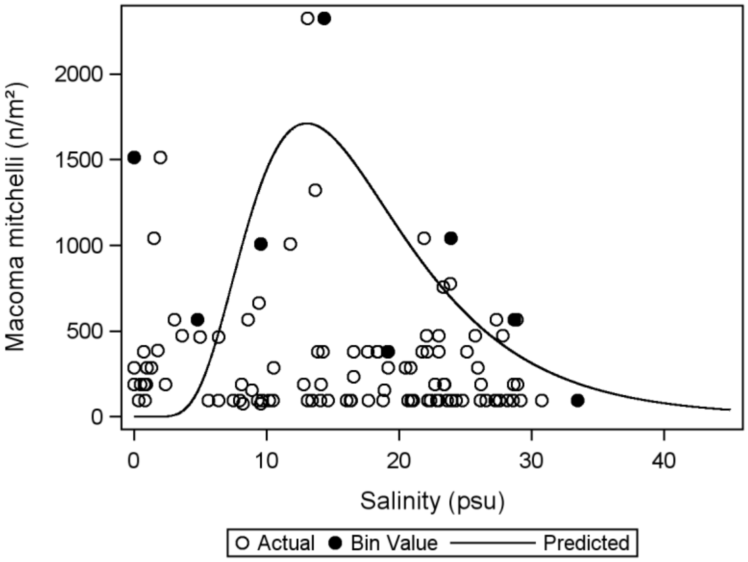

Figure 13. ***Macoma mitchelli*** **abundance as a function of salinity. Dots are the maximum values of bins, and line is the predicted values.**

Hermundura ocularis had a salinity peak at 21.6 psu (Figure 14). The model was significant ($p = 0.0009$) and R^2 was 95%. *Hermundura ocularis* occurred over a large salinity range but had a high abundance at one salinity only. *Hermundura ocularis* is a deposit feeding polychaete.

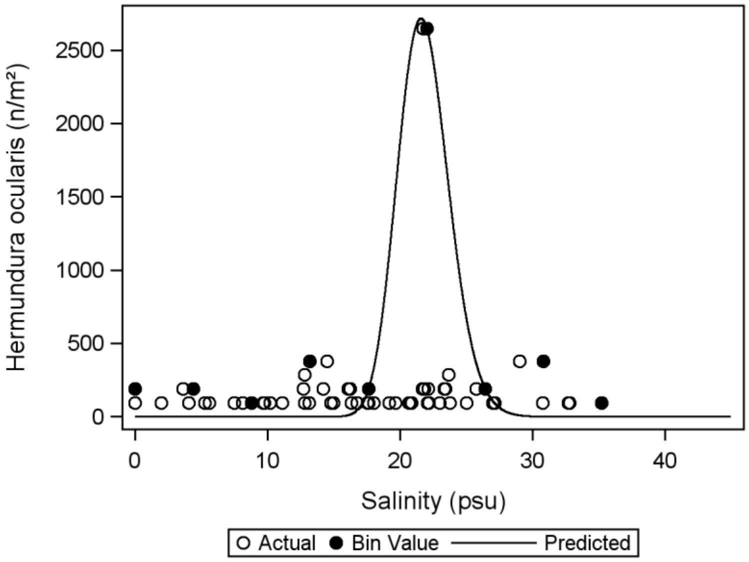

Figure 14. *Hermundura ocularis* abundance as a function of salinity. Dots are the maximum values of bins, and line is the predicted values.

Ampelisca abdita had a salinity peak at 25.3 psu (Figure 15). The model was significant ($p < 0.0001$) and R^2 was 99%. *Ampelisca abdita* occurred over a narow salinity range between 15 and 35 psu. It had a high abundance at center of that salinity range. *Ampelisca abdita* is an amphipod.

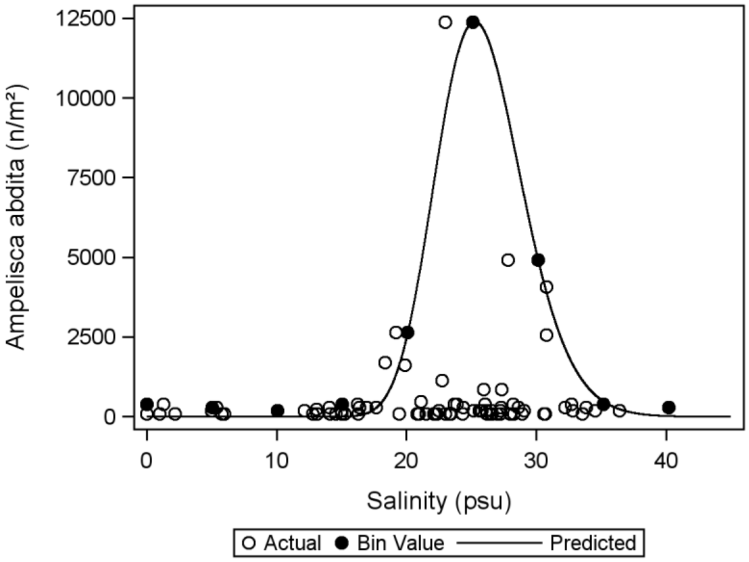

Figure 15. ***Ampelisca abdita*** **abundance as a function of salinity. Dots are the maximum values of bins, and line is the predicted values.**

The oyster *Crassostrea virginica* is a filter-feeding bivalve, but it is a large epifaunal organism, not small infaunal organism like the others in this group. This data is from TPWD oyster dredge sampling, whereas the other data is from the HRI benthic sampling. Oysters have economic value and form reefs, which are biogenic habitat. Oysters had a salinity peak at 19.5 psu (Figure 16). The model was significant ($p = 0.0003$) and R^2 was 80%. Oysters occurred over a large salinity range and had high abundances between 10 and 28 psu.

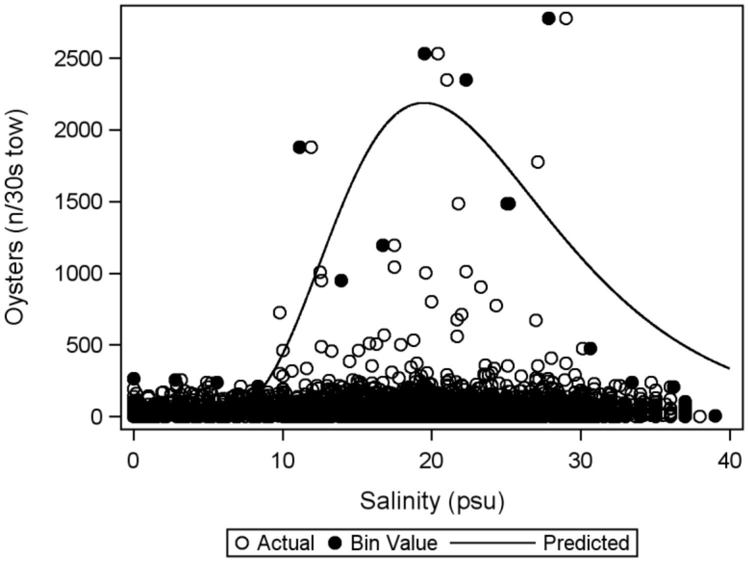

Figure 16. ***Crassostrea virginica*** **abundance (from TPWD data) as a function of salinity. Dots are the maximum values of bins, and line is the predicted values.**

8.2 Condition Identification

As freshwater enters Lavaca Bay several changes occur: salinity is diluted, and dissolved nutrients and particulate matter is increased. Thus, there is a multivariate relationship between freshwater and water quality constituents that define estuary conditions (Figure 1). HRI has collected these water quality metrics quarterly between 1988 and 2018, and this data set was analyzed using principal components analysis (PCA). While the focus of the present report is on Lavaca Bay, it is necessary to compare water quality data from Lavaca Bay to Matagorda Bay in order to have the full range of response from river to the sea. Water quality data from the four HRI long-term stations (Figure 9) and the HRI Formosa Discharge(FD) station (Figure 8) were used for this analysis.

The PC 1 and PC 2 loads for hydrographic variables explained 30% and 22% (total 53%) of the variation among all hydrographic data (Figure 17). The PC 1 loads for the hydrographic data had the highest positive values for nutrients (ammonium, nitrite+nitrate, and phosphate), and low negative values for salinity. The PC 1 axis clearly represents an inflow effect, where a decrease in salinity (or increase in freshwater inflow) is associated with an increase in nutrients. The PC 2 axis had low values for temperatures correlated with high dissolved oxygen, and pH increased with DO. The PC 2 axis represents a seasonal effect because it is well known that the solubility of oxygen increases with decreasing temperatures and it is cooler in winter than summer. The PC 3 axis had high positive loads for chlorophyll, silicate, and phosphate, which inversely correlated with low values of salinity and ammonia. Thus, PC 3 represents a primary production axis because high chlorophyll biomass is an indicator of productivity.

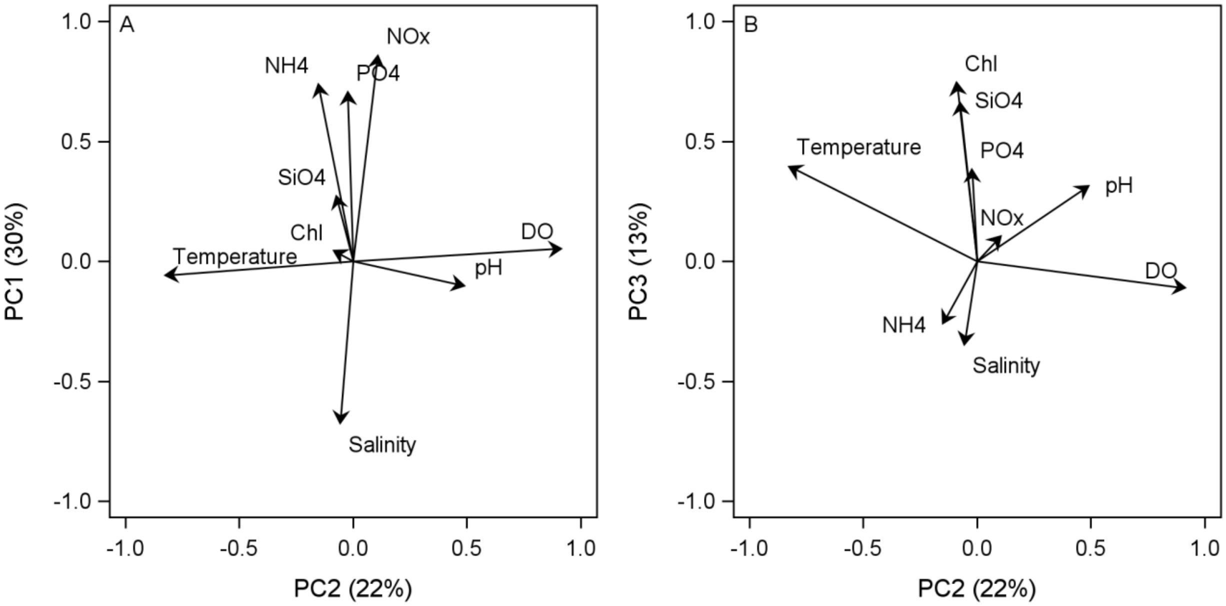

Figure 17. Variable loads from principal components (PC) analysis of water quality variables. A) PC1 versus PC2. B) PC2 vs PC3. Abbreviations: Chl = chlorophyll, DO = dissolved oxygen, NH4 = ammonium, NOx = nitrite+nitrate, PO4 = phosphate, SiO4 = silicate.

Station loading scores were distributed in a distinct spatial pattern along the inflow gradient (Figure 18Figure 18. Station scores. Stations A, B and FD are in Lavaca Bay, C and D are in Matagorda Bays.

). Stations A, B, and FD generally exhibited the most positive relationship with PC 1 and stations C and D the most negative relationships with PC 1.

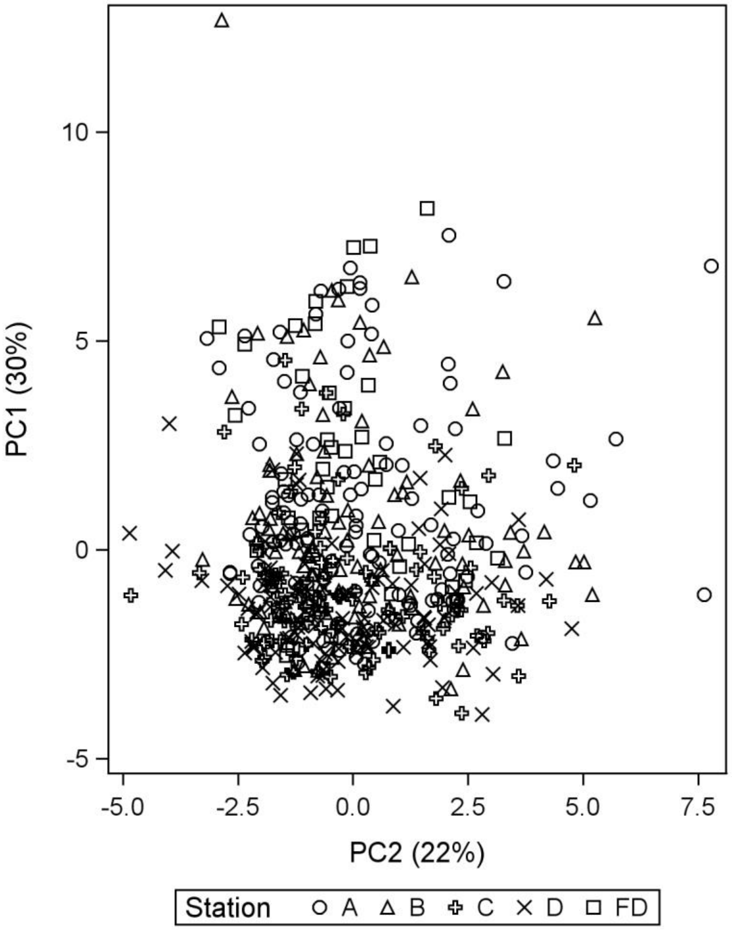

Figure 18. Station scores. Stations A, B and FD are in Lavaca Bay, C and D are in Matagorda Bays.

Station scores had a distinct seasonal distribution pattern (Figure 19). The highest PC 2 scores were for winter and the lowest scores were for summer, which correlates to high DO and low temperatures (Figure 17). Although freshwater inflow was highest in spring and fall, the variability was high enough such that inflow effects and seasonal effects were independent of one another.

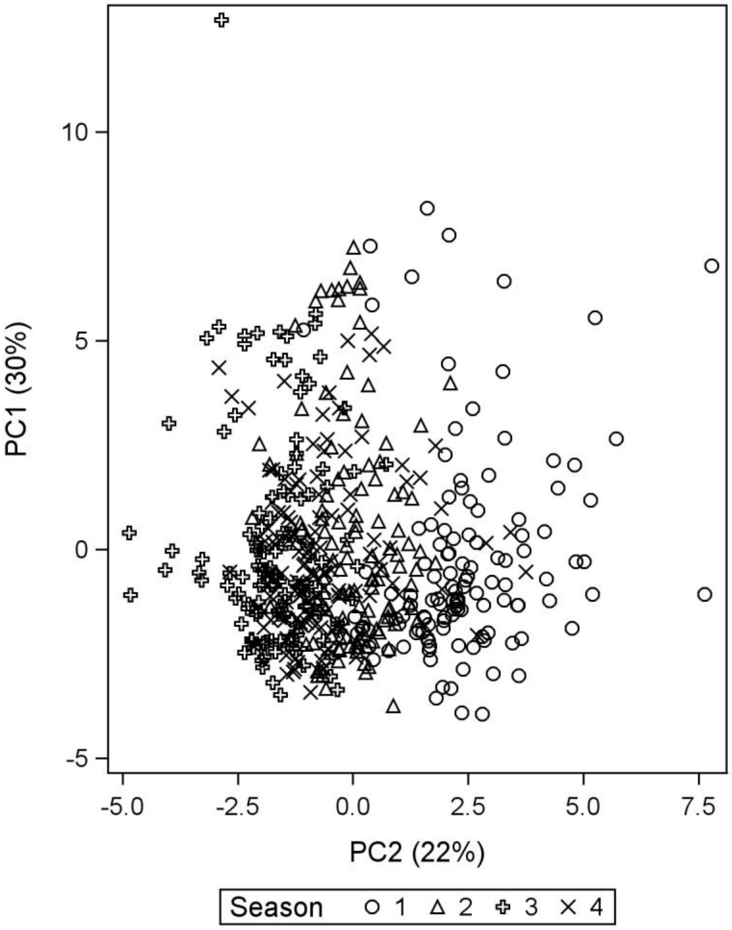

Figure 19. Season scores from the PCA. Abbreviations: 1 = winter, 2 = spring, 3 = summer, and 4 = fall.

8.3 Inflow Identification

8.3.1 Salinity zone areas

Figure 20 shows the percentage of the Lavaca Bay area (approximately 13,350 hectares) for which the modeled salinities were within 5 psu wide bins (0 - 5, 6 - 10, 11 - 15, 16 - 20, 21 - 25, 25 - 30, 30 - 35 and > 35). The bins are color-coded from green (0 – 5 psu) to red (30 – 35 psu), thus a long vertical bar of one color indicates a large area with that salinity. There is a clear relationship between large freshwater inflow events (bottom chart) and extended periods of low salinities (i.e., green colors) for significant portions of the bay. The converse is true for droughts.

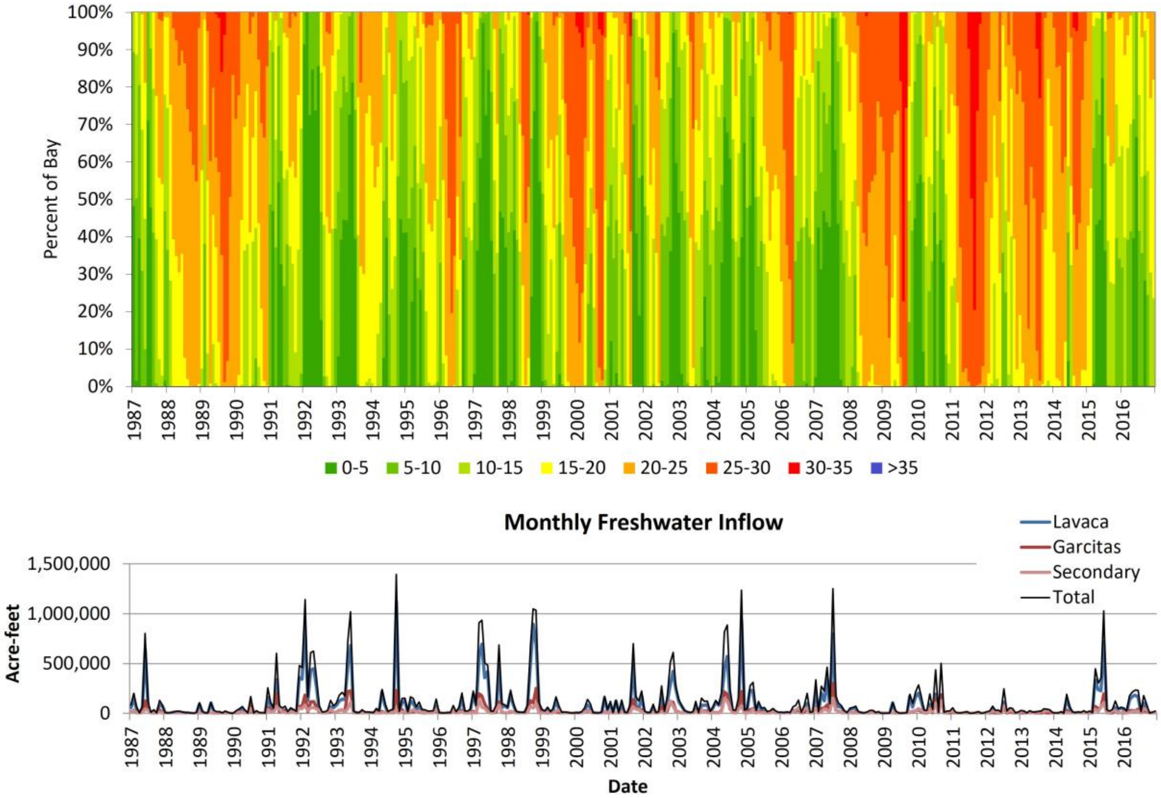

Figure 20. Percent of Lavaca Bay within 5 psu salinity bins and corresponding freshwater inflows.

Each of the monthly columns in Figure 20 were converted to 360 maps of the average monthly salinity conditions throughout Lavaca Bay over the 30-year period described above (Appendix 2). Nearly all the months had average salinity throughout Lavaca Bay in the range of 15 - 20 psu. Salinities reach closer to 25 psu in the lower 10% of the bay (near the connection with Matagorda Bay). Each of the 360 monthly average were averaged again to create a long-term average salinity (Figure 21). Over the long-term, salinity averaged about 12 psu near the river mouth, about 15 psu under the bridge, and about 23 psu at the intersection where Lavaca Bay meets Matagorda Bay. However, salinity variance is inversely correlated with mean salinity, and variance is highest (about 70 psu) at the river mouth, and lowest (about 50 psu) at the intersection between the two bays.

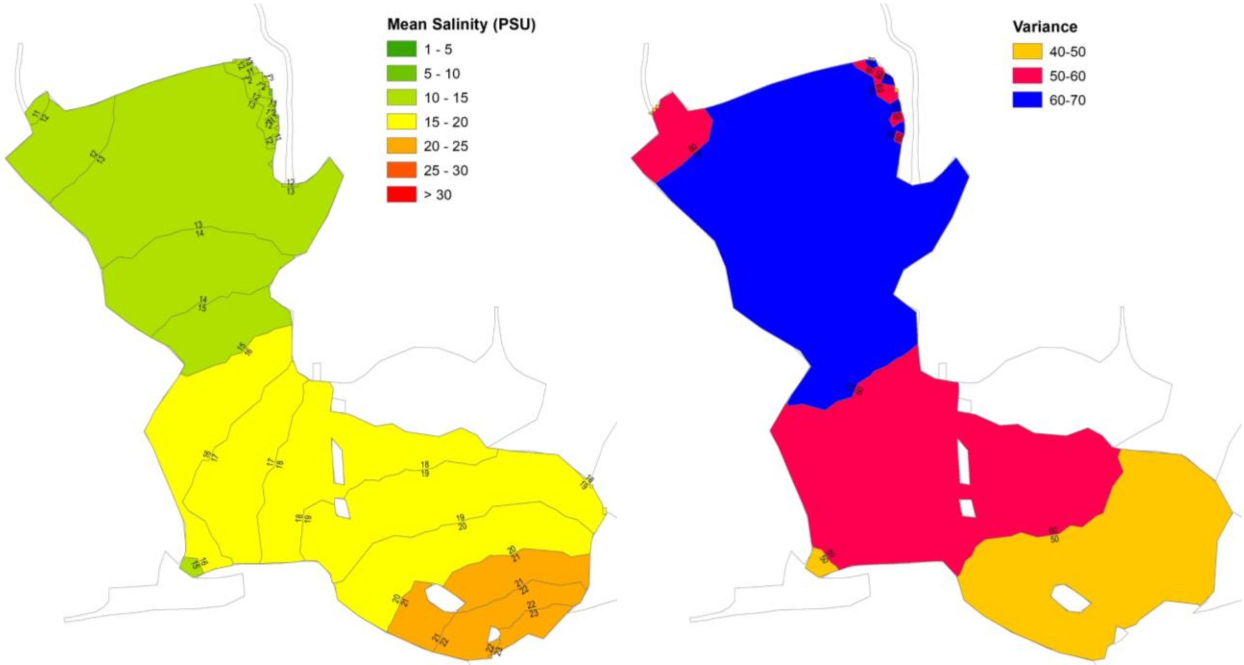

Figure 21. Long-term (1987 – 2016) mean and variance of salinity interpolated by inverse distance weighting between nodes. Numbers in maps are upper bounds of bins.

8.3.2 Salinity versus flow

The daily average salinities and antecedent inflows are available for approximately 100 locations within Lavaca Bay (Figure 22). A salinity-inflow relationship based on antecedent inflows and daily average salinity at node number 2, located near the midpoint of the Indian point transect (Figure 22), was used in the BBEST analysis and a subsequent SB3 workplan study to estimate the flow need to achieve design salinities (30, 25, 22 and 20 psu) which corresponded to subsistence, low, medium and high freshwater inflow recommendations for Lavaca Bay inflows (Lavaca, Garcitas and Placido combined) at this locations . A similar relationship based on the most updated TxBLEND model outputs is presented in Figure 23 to determine freshwater inflows needed to achieve design salinities. Revised or updated design salinities from this study could be used to determine updated flow targets.

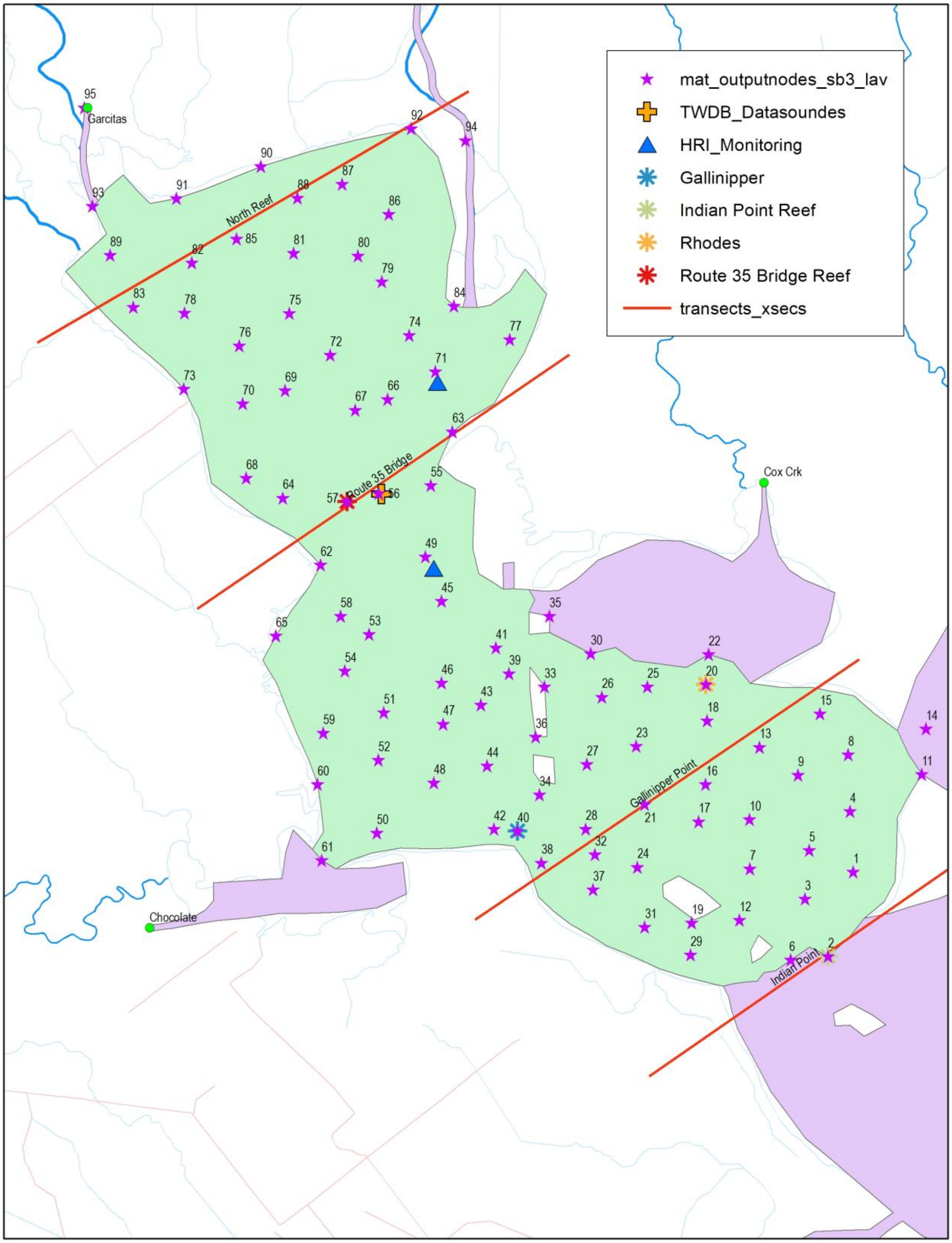

Figure 22. TxBLEND daily output nodes.

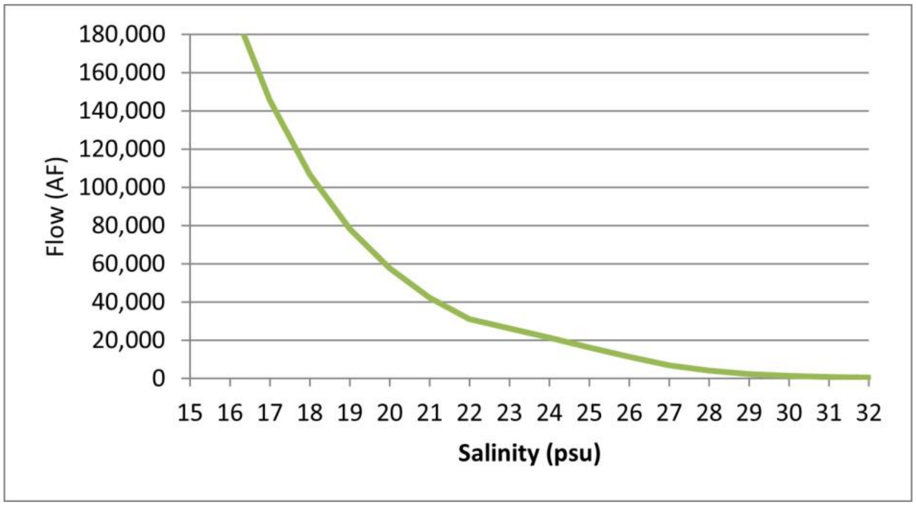

Figure 23. Salinity-flow relationships for Indian Point Reef (Node 2 in Figure 21).

Assuming the design salinities were to remain the same as the original BBEST analysis the freshwater inflow recommendations based on the updated TxBLEND model would be slightly higher. (Table 6)

Table 6. Freshwater inflows needed to achieve design salinity criteria targets.

Inflow Criteria	Indian Point Reef Salinity Criteria (psu)	BBEST Study (ac-ft/y)	Current Study (ac-ft/y)
High	20	41,400	57,500
Medium	22	23,700	31,000
Low	25	10,200	16,300
Subsistence	30	2,500	1,400

8.3.3 Analysis of historical flows

Average inflow to Lavaca Bay (for the period from 1977 to 2016) was approximately 1.3 million acre-feet per year, with about 65% coming from the Lavaca River, about 20% from Garcitas and Placido Creeks and about 15% from the Keller, Cox, and Chocolate Bayous (Figure 24).

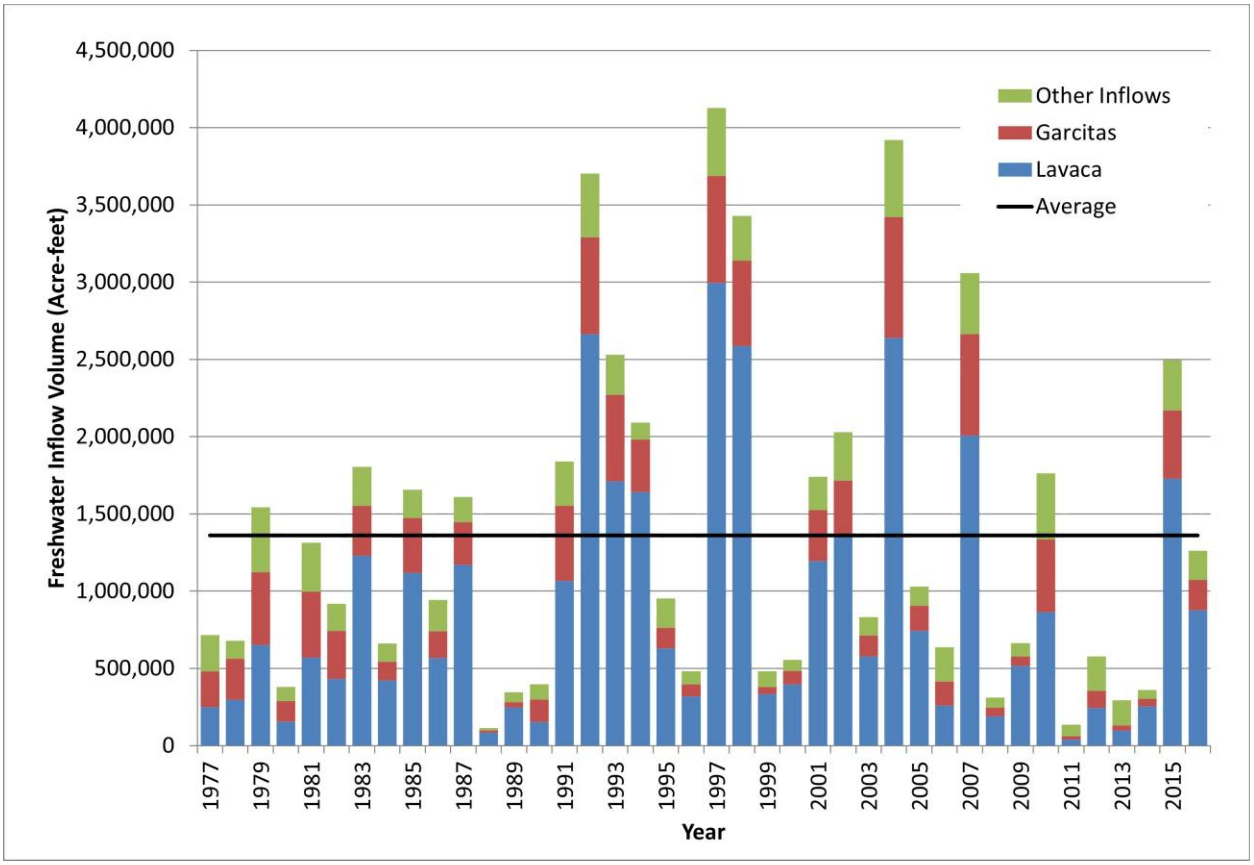

Figure 24. Inflows to Lavaca Bay since 1977 by source. Horizontal black line represents the average total freshwater inflow from the Lavaca River, Garcitas Creek and other inflows for the period from 1977 – 2016.

The water permit for Lake Texana includes special conditions which prescribe releases to protect the bay and estuary. Based on the 1940 to 2016 dataset described above, it is possible to analyze the potential change in inflows from the Navidad River due to outflows from Lake Texana (Figure 25). For the period from 1940-1980 approximately 28% of the inflow from the Lavaca-Navidad watershed came from the Lavaca river, 65% from the Navidad river and 7% from ungaged runoff downstream of gages on these two rivers. After the construction of Lake Texana these values changed only slightly to 32% came from the Lavaca, 61% from the Navidad and 7% from ungaged runoff downstream of gages. So, while there has been a reduction in the relative contribution of inflows from the Navidad River, from 65% to 61%, which might be attributed to Lake Texana it does not appear that the annual inflows have declined significantly since the construction of Lake Texana.

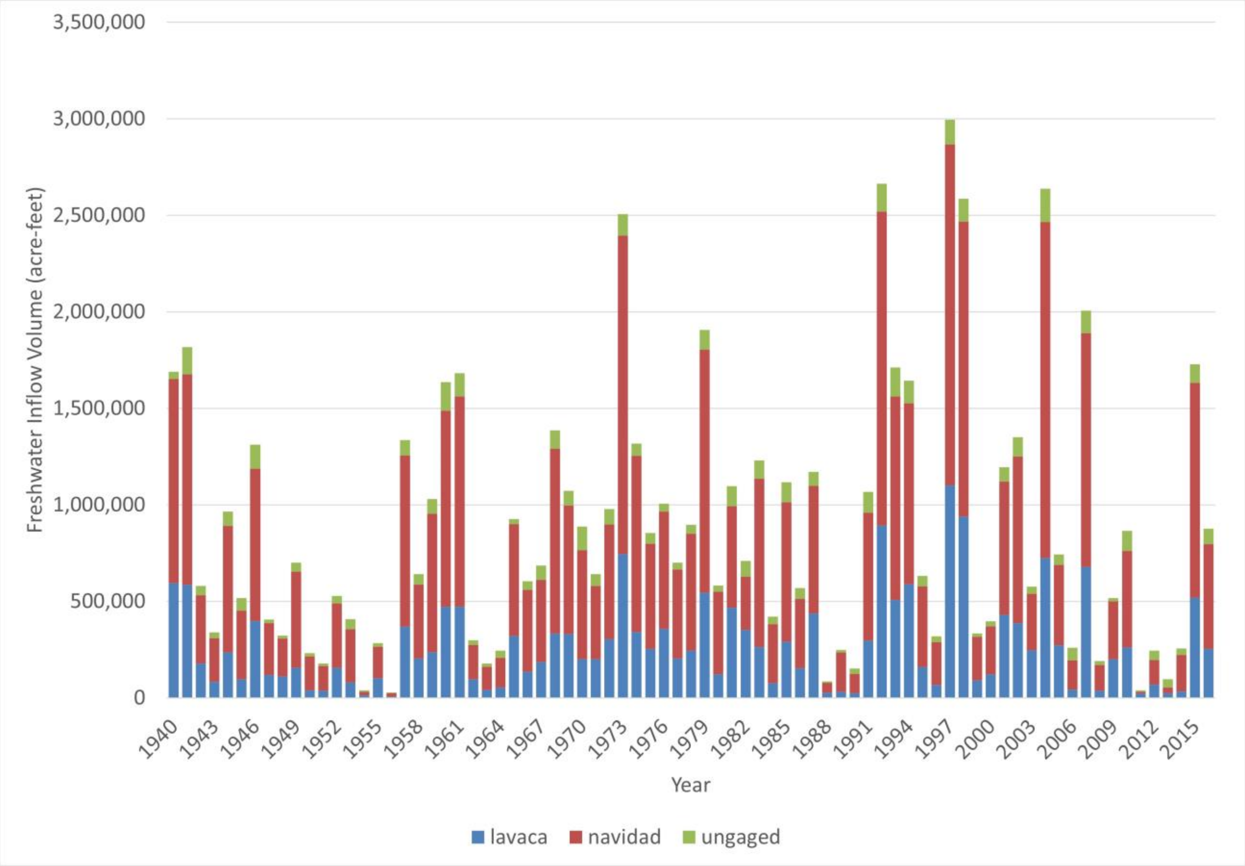

Figure 25. Inflows to Lavaca Bay since 1940 by source.

It is possible that the shift in the inter annual distribution of flows has been altered due to regulation from of flows from Lake Texana (Figure 26). The median monthly inflows from the Lavaca watershed for the period from 1940-1980 (green symbols and lines) are much higher than the period from 1981-2016 (red symbols). The green error bars indicate that current conditions for many months are outside the range (+/- 17%) of the median flows that occurred during pre-reservoir conditions.

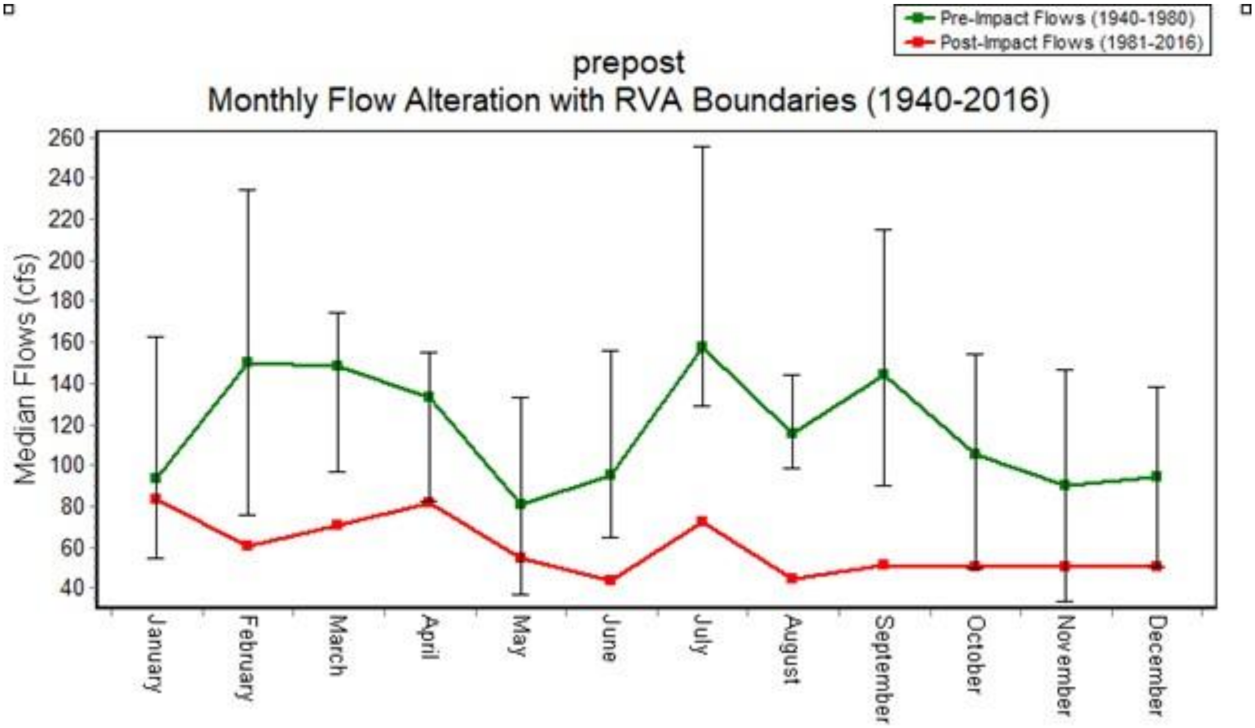

Figure 26. Median monthly inflows from the Lavaca River watersheds. Green is pre-impact flows and red is post-impact flows.

8.4 Time Series Identification

8.4.1 Hydrology

Results of discrete fast Fourier transform (DFFT) analysis of the Lavaca river discharge (USGS, gage: 08164000) from 1988 to 2012 and the seasonal signal were fit to the Lavaca river discharge series (Figure 27). There is a clear long-term seasonal signal with highest discharge rates in spring (March) and lowest discharge rates in fall (September).

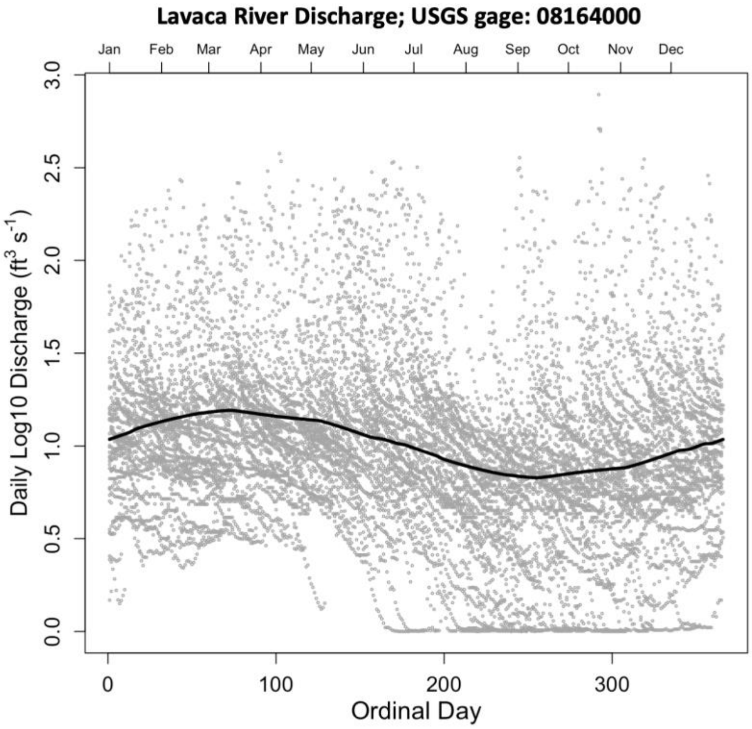

Figure 27. A hydrograph showing the extracted seasonal signal (black line) and normalized Lavaca River discharge (grey points) for one year. The x-axis are the ordinal days for the years 1988-2012.

The seasonal signal was extracted and the detrended signal was fit to a detrended normalized discharge to demonstrate years that were dry (red dots) and years that were wet (blue dots) (Figure 28). The period between 1988 and 1992 was an extended drought. The period between 1992 and 2008 was an extended wet period. Then drought returned during the period between 2008 and 2013.

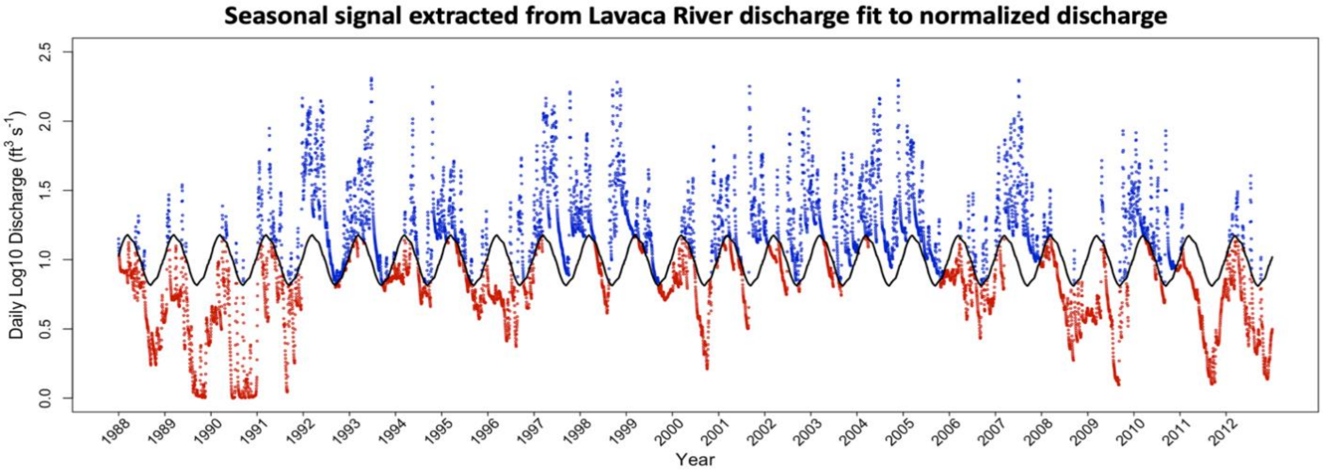

Figure 28. The detrended seasonal signal (black line) fit to the detrended normalized river discharge in cubic feet per second. Red points are low flow deviations from the expected seasonal trend; blue points are high flow deviations from the expected seasonal trend.

Hydrologic variance was quantified from the seasonal signal fit to Lavaca river discharge for the years 1988 to 2012. Nine shape components of hydrologic variance or hydrologic drivers were quantified: 1) Low Spectral Anomaly Magnitude (LSAM), 2) High Spectral Anomaly Magnitude (HSAM), 3) Transition Time between LSAM and HSAM, 4) Low Spectral Anomaly Frequency (LSAF), 5) High Spectral Anomaly Frequency, 6) Timing of LSAM, 7) Timing of HSAM, 8) Interflood Interval (IFI), and the 9) Interdrought Interval (IDI). Because some shape components are highly correlated, HSAF was eliminated as a covariate in the final MARSS model after testing for collinearity, i.e., variance inflation factor (VIF < 5). After culling for collinearity, the eight hydrologic shape components used in the final MARSS model shown below reveal variation of drivers from year-to-year (Figure 29).

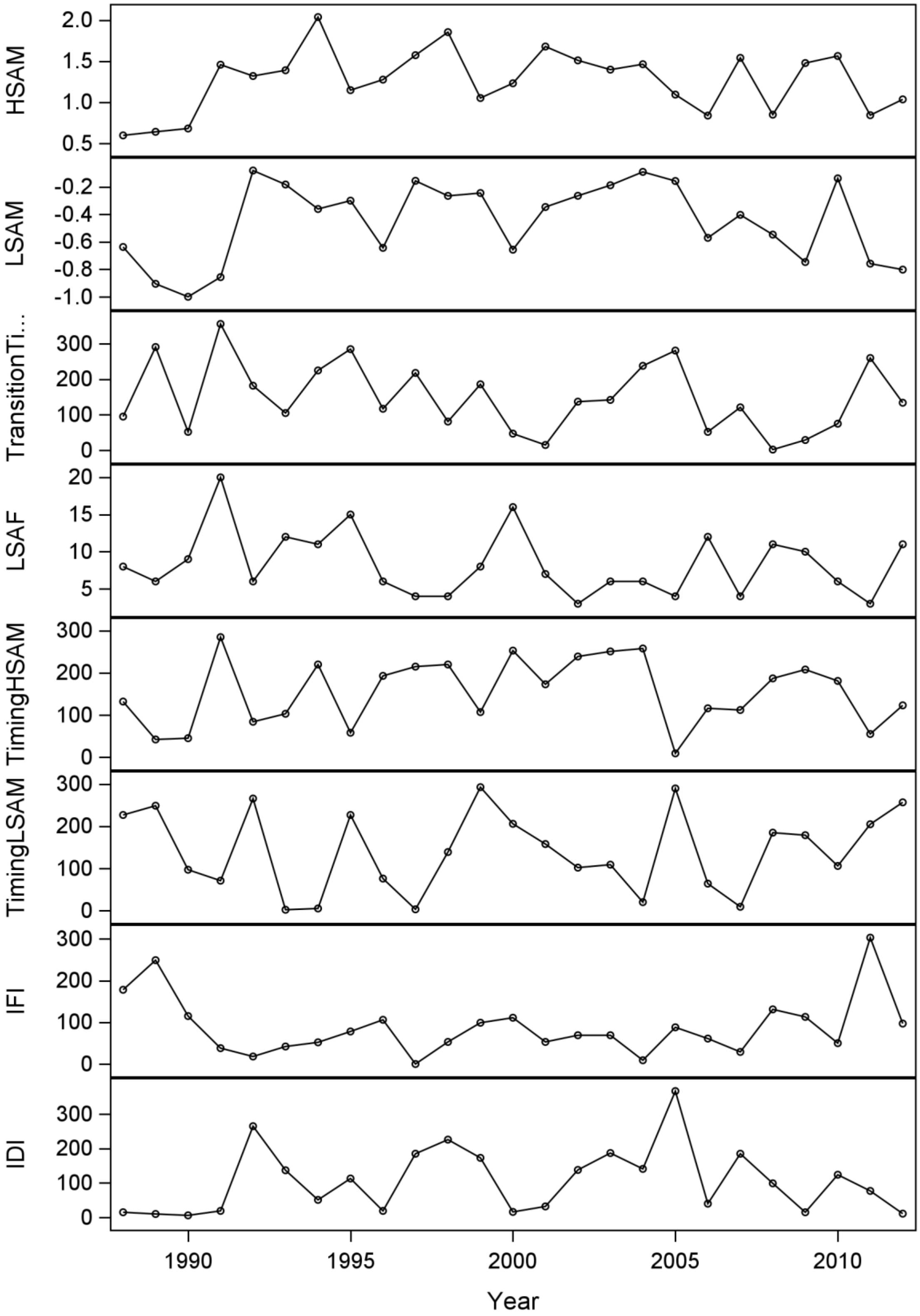

Figure 29. Annual variability in the hydrological components

Below is an example of an 18-month long season window that visually describes six of the eight shape components quantified for the year 1982; although the year 1982 was not used in this analysis, this year was chosen because it is representative of a year without extreme drought or flooding which makes the hydrograph with labeled shape components more comprehensible [figure format is adapted from Sabo et al. (2007)] (Figure 30). The LSAM and HSAM components quantify the magnitude of the largest negative and positive spectral anomalies within an 18-month hydrologic window respectively. The timing of HSAM and LSAM measure the number of days between each of the largest spectral anomalies (HSAM and LSAM) and the long-term mean peak flood. The IFI measures the number of days of the most extensive continuous dry periods of negative deviations from the expected seasonal baseline within the 18-month window. The IDI measures the number of days of the most extensive continuous wet periods of positive deviations from the expected seasonal baseline within the 18-month window. Although not shown below, LSAF and HSAF were quantified and measure the number of independent observations that are greater or less than the expected discharge values.

The sum of positive and negative anomalies across the entire timeseries is 0, but the interannual variation of anomalies do not sum to 0 within a year. This is the Net Annual Anomaly (NAA). If there are more negative anomalies in a year, NAA will be a negative number (atypical dryness) and if there are more positive anomalies in a year then NAA will be a positive number (atypical wetness).

The Flood Pulse Extent (FPExt) is the average deviation between stage and baseflow multiplied by the number of days in which flow exceeds baseflow (i.e., average magnitude × duration).

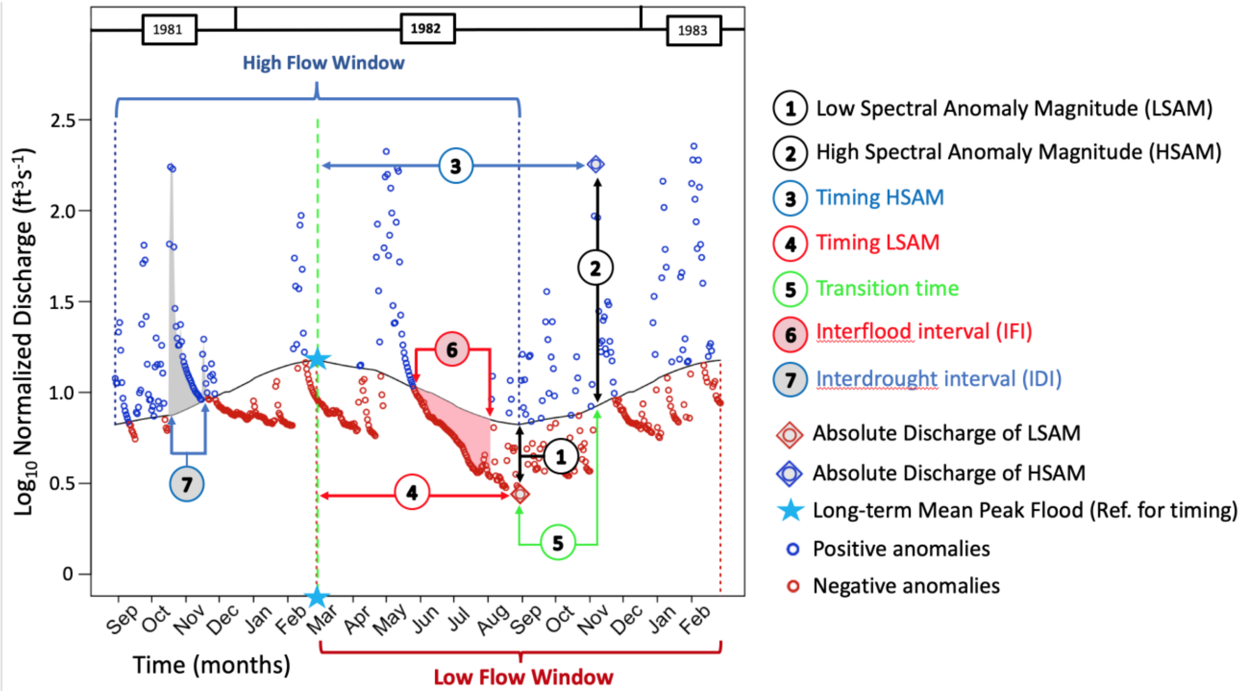

Figure 30. Shape components for the hydrologic variance for Lavaca River discharge for the period 1982 - 2012. The blue star is a reference point representing the highest expected discharge value for each seasonal window for the year 1982. Numbers 1 & 2 (LSAM and HSAM respectively) are the magnitude of the low and high flow spectral anomalies quantified for only days within 1982. Numbers 3 & 4 (Timing of HSAM and LSAM respectively) measure the number of days between the occurence of HSAM and LSAM and the expected long-term mean peak flood (blue star). Number 5 (Transition Time) measures the number of days between LSAM and HSAM). Numbers 6 & 7 (IFI and IDI) respectively measure the most extensive continuous periods of positive and negative deviations of discharge with respect to the predicted seasonal baseline (black line)

8.4.2 Biological Responses

The unobserved or "true" abundances of eight estuarine dependent species and two benthic infauna metrics were modeled using the MARRS approach (Figure 31). Eight hydrologic drivers (HSAM, LSAM, Timing of HSAM, Timing of LSAM, Transition Time, IFI, and IDI) were included in the MARSS model as covariates. Our model assumes that each biological component is a subpopulation within Lavaca bay (i.e., each component has different biological responses to hydrologic drivers and population densities). Species and metrics within each taxa group (crustaceans, mollusks, fish, benthic infauna metrics) are assumed to have independent temporally correlated process error variance (i.e., good and bad years are correlated within each group). Site and method specific observation error variance is assumed to be shared (i.e., sampling conducted at the same sites that used gill nets, trawls, dredges, or benthic cores each share observation error variance). The density dependence of each biological component was estimated from the MARSS model, however, we were most interested in the effects of hydrologic drivers on abundance of species. Several species do not appear to be changing over time including white shrimp, brown shrimp, red drum, and spotted seatrout. Two species appear to be increasing over time including eastern oyster and black drum. Two species and all benthic metrics are decreasing over time including blue crab, southern flounder, and benthos.

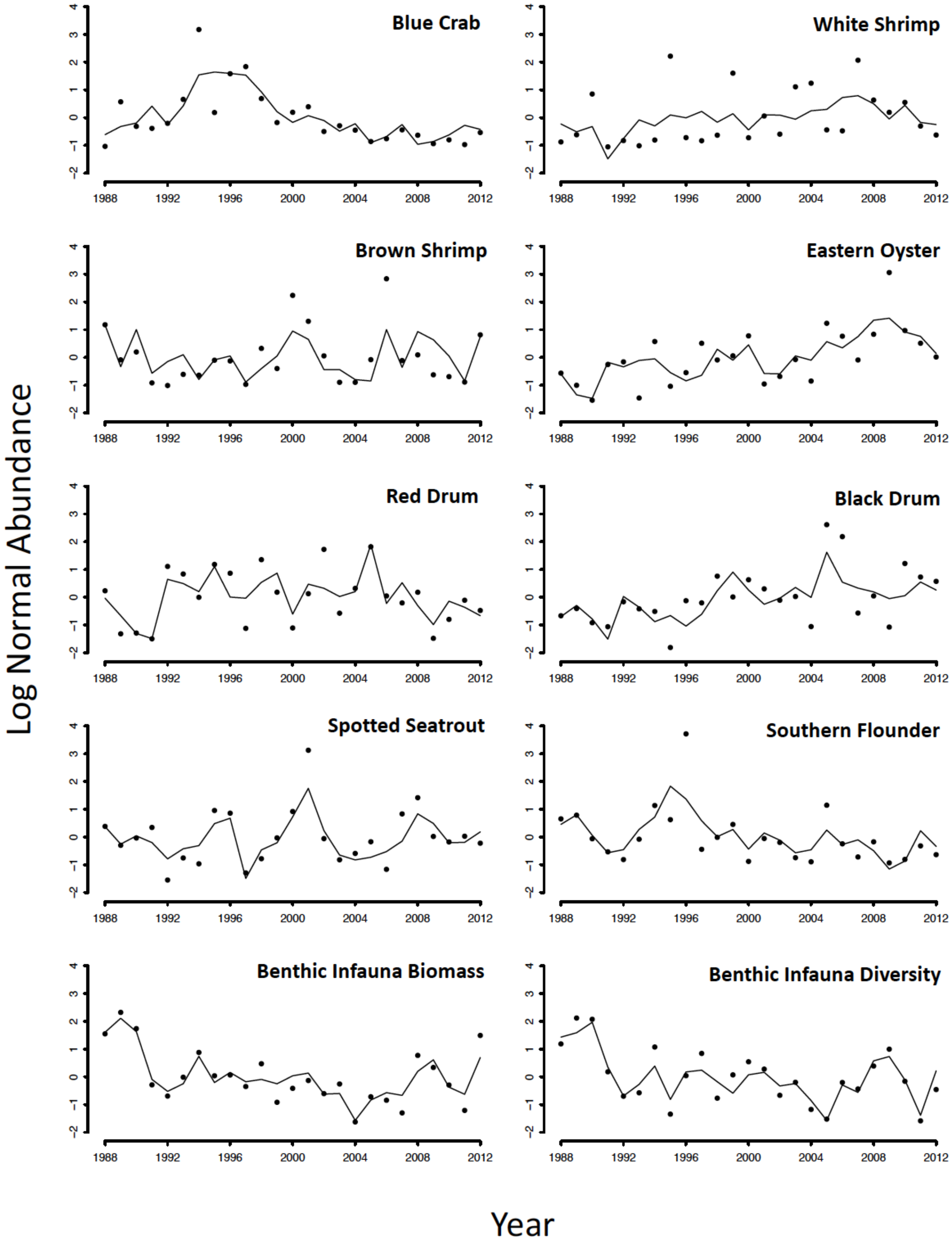

Figure 31. Time series for recreationally and commercially important species, and benthic infauna biomass and diversity between 1988 and 2012 (black dots). Black line is the true unobserved abundance of each group predicted by the MARSS model.

8.5 Linking Inflow Events and Communities

8.5.1 Time Series Approach

Results of the MARSS model show the covariate coefficients or effect size (effect size because the hydrologic drivers are standardized with z-scoring) of hydrologic drivers on the

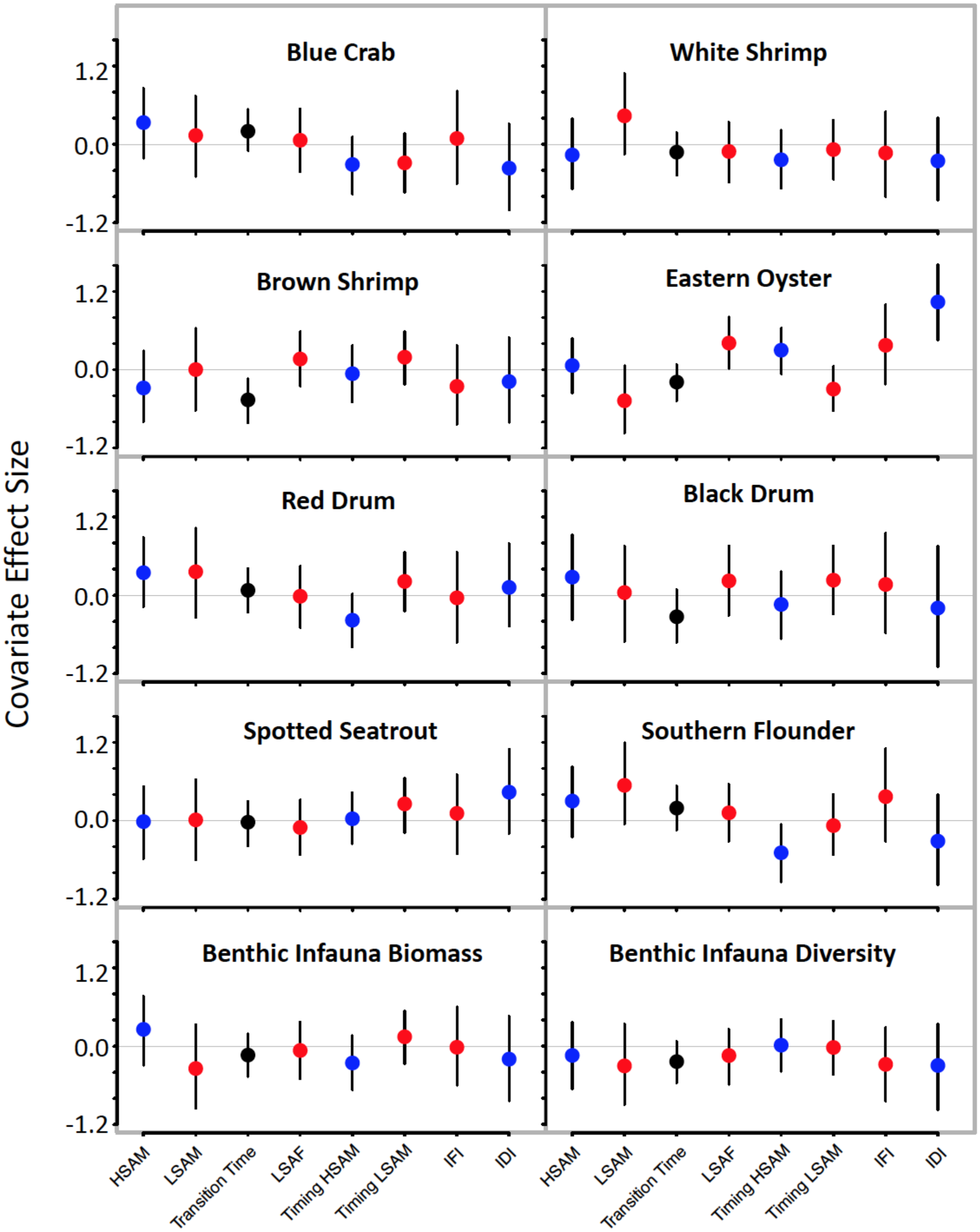

Figure 32. Covariance effect size between hydrological components and taxa.

abundance of each species or benthic infauna metric is shown in Figure 32. Effect sizes greater than zero represent positive effects on the biological components and effect sizes less than zero represent negative effects on the biological components (e.g., IDI had a positive effect on the abundance of oysters; therefore, we expect an increase in abundance of oysters following a year with longer continuous wet periods). The 95% confidence intervals were calculated by performing 1000 parametric bootstraps on the hydrologic driver effect for each biological component of the model, and the 95% confidence intervals that do not overlap with zero are statistically significant. The conclusion is that hydrological components effects are consistent over time.

There was a strong correlation between some of the hydrological components shown in Figure 29, but most were weak (Figure 33). For example, the correlation between HSAF and LSAF was 0.98, in contrast the correlation between LSAM and HASM was 0.56. There was a strong relationship between infauna biomass and diversity (0.70), but only weak relationships with the Oceanic Niño Index (ONI) and North Atlantic Oscillation (NAO) climatic indices. There were moderately strong correlations between biomass and diversity and certain hydrological components such as IFI, but inverse correlations between biomass and diversity and IDI, NAA and FPE.

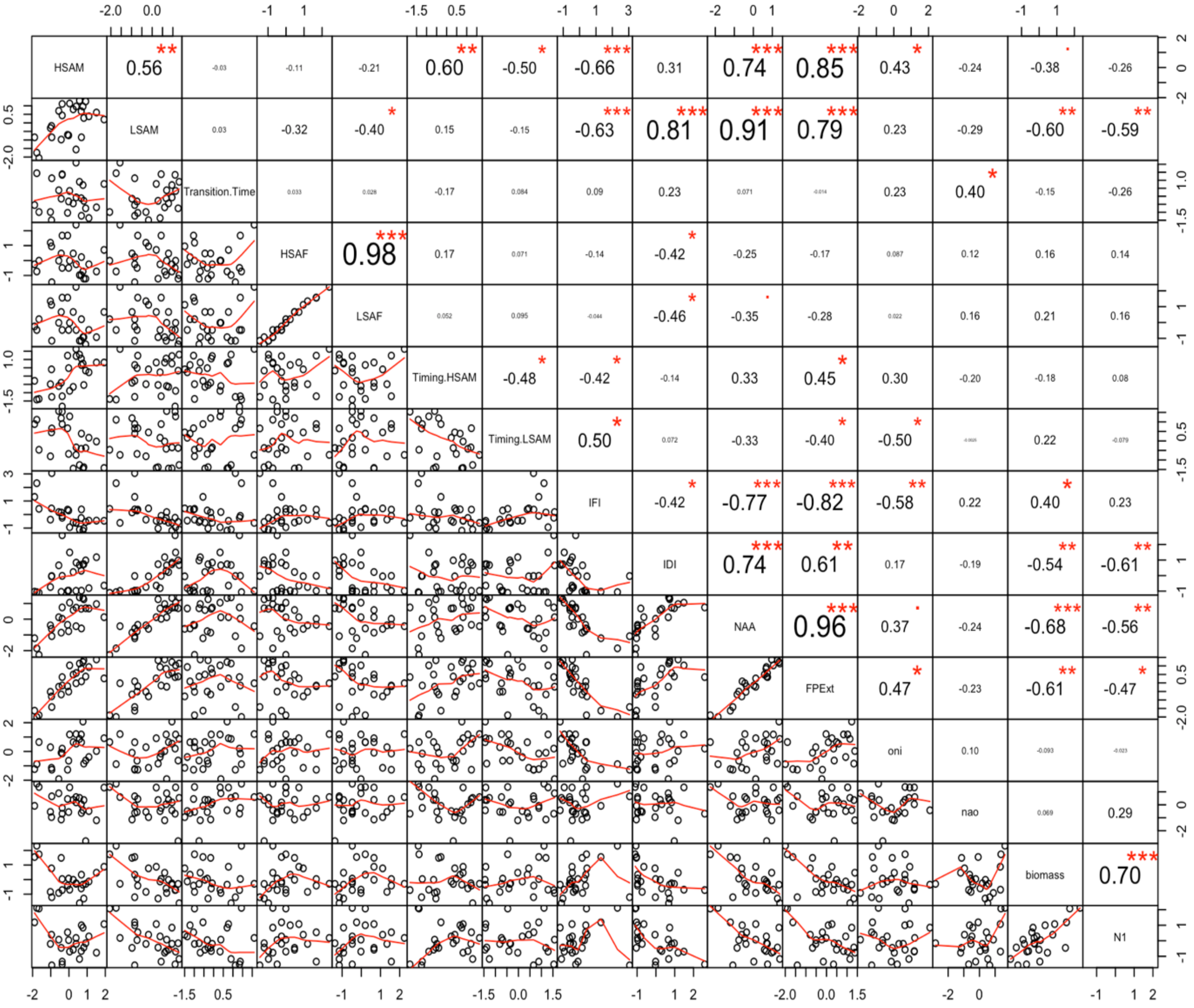

Figure 33. Person correlation coefficients between hydrological components, climatic variables, and infauna.

8.5.2 Water Quality Approach

Another approach to link physical drivers to biological responses is to correlate the water column conditions (Section 7.2) with biological metrics (Section 7.1). This is easily done using simple non-parametric correlations (Table 7). There were 367 samples where there were station-date combinations that had both water column and benthic measurements. Correlation coefficients range from 1 to -1 and the statistical test is for r = 0. Statistical significance (i.e., probability, P) with this large number of samples must be applied with caution because P is a function of sample size. All of the abundance and diversity metrics were inversely correlated to PC1, which means as the freshwater inflow index increases (i.e., more nutrients and less salinity) then macrofauna count and diversity decreases. Only abundance was positively correlated with PC2, which means as the season index increases (i.e., higher dissolved oxygen and lower temperatures) the abundance increases. All of the abundance and diversity metrics were inversely correlated to PC2, which means as the productivity index increases (i.e., more chlorophyll) then macrofauna count and diversity decreases. Evenness indices did not have strong correlations with any of the PC scores.

Table 7. Relationship (Spearman correlation coefficients and probability that r = 0) between Principal Component (PC) scores and benthic metrics for date-station combinations (n = 367).

	Spearman Correlation Coefficients (r), P | r = 0		
Benthic Metric	**PC1**	**PC2**	**PC3**
Abundance(n/m^2)	-0.22, <0.0001	0.17, 0.0015	-0.31, <0.0001
Diversity(S/105 cm^2)	-0.38, <0.0001	0.11, 0.0406	-0.41, <0.0001
Diversity(H′/105 cm^2)	-0.34, <.0001	0.06, 0.2521	-0.35, <0.0001
Diversity(Hill's N1/105 cm^2)	-0.34, <0.0001	0.06, 0.2521	-0.35, <0.0001
Evenness(J′/105 cm^2)	-0.08, 0.1089	-0.05, 0.3489	-0.025, 0.6361
Evenness(Hill's E5/105 cm^2)	0.13, 0.0142	-0.10, 0.0463	0.16, 0.0019

8.5.3 Mapping Approach

To analyze the TPWD data over the long-term, the random stations were converted to segments within the bay based on long-term average salinity (Figure 34). The estuary has lower salinities in segments near the Lavaca River (LC-1, LC-2) and Colorado River (LC-9). Segments LC-4 and LC-6 both have lower salinities from freshwater contribution from Carancahua Creek and Tres Palacios River, respectively. LC-7 has the highest salinity where the Gulf of Mexico inlet is located.

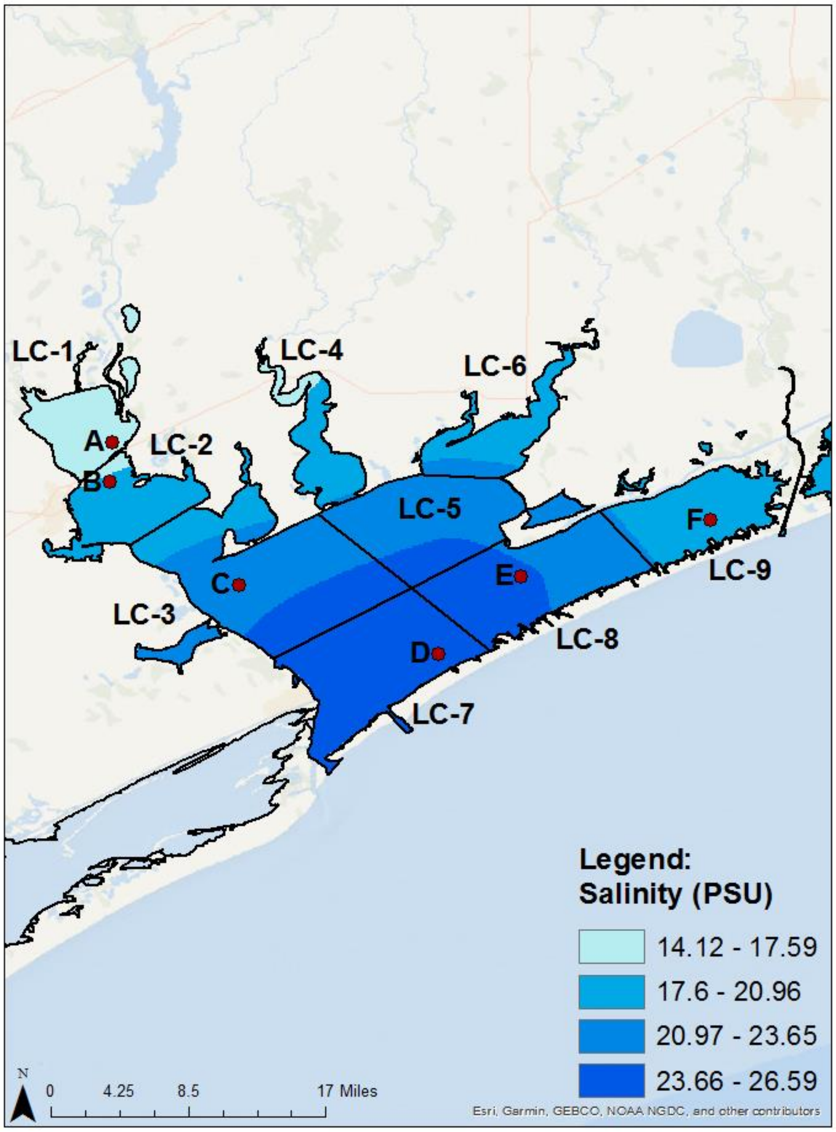

Figure 34. Location of TPWD segments and sampling stations. Red dots are HRI stations, and black lines separate segments within bays. Blue colors are long-term average salinity gradients.

The mean epifauna abundance in segments located near freshwater inflow sources had significantly less epifauna than those close to Gulf inlets and further from freshwater inflow (Table 8). LC-6, encompassing the Tres Palacios Bay region, had the lowest mean epifauna (mean 75.6). LC-1 and LC-2 in Lavaca Bay (LC-1 mean 88.9, LC-2 mean 101.7), and LC-4 in Carancahua Bay (LC-4 mean 123.4) closely followed the lowest mean. The fourth source of freshwater inflow comes from the Colorado River inlet and LC-9 includes this area. LC-9 had the fourth highest mean epifauna (mean 140.2). LC-7 and LC-8 had the highest mean epifauna abundance (LC-7 mean 160.9; LC-8 mean 157.9). Both segments LC-7 and LC-8 are located near the gulf inlet. Epifauna richness was significantly greater in segments further from freshwater inflow. LC-7 had the most species (10) and was significantly different from all other segments. Epifauna richness in LC-1, LC-4, and LC-6 had the lowest means, while LC-7, LC-3, LC-8, and LC-5 had the greatest means.

Table 8. Mean (+ standard deviation) of salinity, infauna and epifauna abundance and richness for each segment in the estuary.

Segment	**Salinity (PSU)**	**Infauna**		**Epifauna**	
		Abundance (n/m^2)	**Richness**	**Abundance (n/10min trawl)**	**Richness**
LC-1	15.9 (8.7)	20939 (15359)	14.1 (8.8)	88.9 (105.1)	5.9 (3.1)
LC-2	20.5 (7.7)	16046 (10865)	13.9 (7.6)	101.7 (168.0)	6.9 (3.7)
LC-3	24.1 (5.7)	29760 (21707)	30.6 (14.5)	131.2 (131.1)	8.6 (3.2)
LC-4	20.7 (7.5)	.	.	123.4 (202.7)	6.7 (3.6)
LC-5	23.9 (5.5)	.	.	143.1 (155.6)	8.5 (3.6)
LC-6	20.8 (6.9)	.	.	75.6 (96.7)	5.9 (3.4)
LC-7	26.8 (4.6)	48356 (48300)	34.8 (15.2)	160.9 (199.3)	10.0 (3.4)
LC-8	24.2 (5.1)	30618 (25028)	25.7 (10.6)	157.9 (154.3)	9.1 (3.0)
LC-9	20.9 (7.1)	29197 (25390)	18.9 (7.8)	140.2 (186.3)	7.7 (2.8)

Principal component analysis (PCA) for the combined TPWD-HRI samples had three factors that described 72% of variation in the data (Figure 35). PC1 described 28% and was positively associated with temperature, epifauna abundance and richness and negatively associated with dissolved oxygen. PC2 described 22% and was positively associated with salinity, lag salinity and infauna richness and slightly positively associated with infauna abundance and epifauna richness. PC3 described 14% and was positively associated with infauna abundance and richness and negatively associated with lag temperature. PC1 clearly displays seasonal differences. Summer falls to the far right where temperature is high and dissolved oxygen is low. Additionally, PC1 describes summer as having increase epifauna abundance and richness. Winter falls to the far left where temperature is low and dissolved oxygen is high. Spring and fall in between. PC2 describes salinity conditions. Segments closer to freshwater inflow (LC-1, LC-2 and LC-9) are lower on the PC2 axis while segments further from freshwater inflow have higher salinities and higher PC2 values. Dry conditions have higher PC2 values, with higher salinity, increased epifauna and infauna abundance and richness.

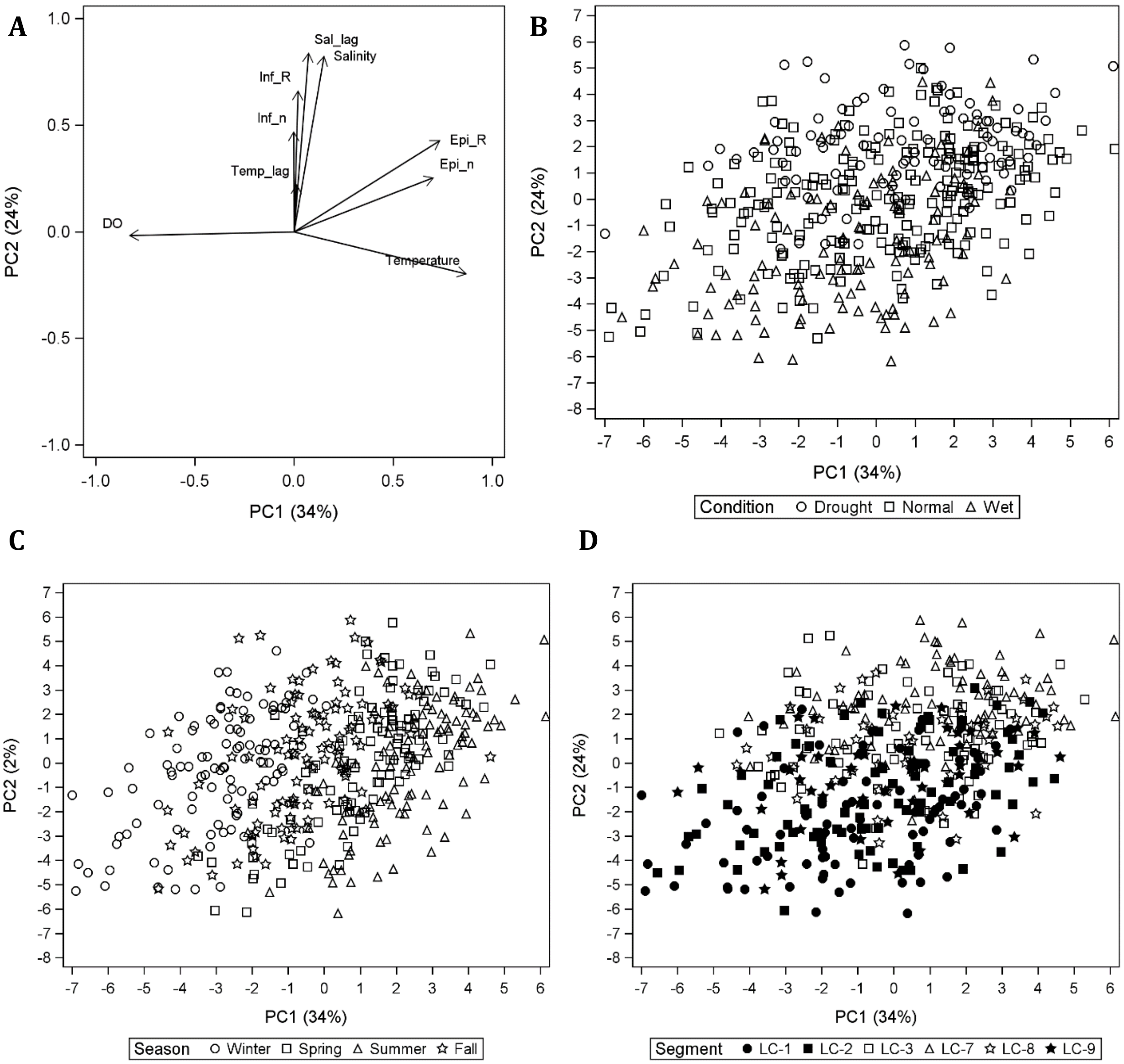

Figure 35. Principal component analysis (PC) for epifauna and infauna communities (abundance and richness) and environmental variables (salinity, temperature, DO). A) Variable loads. B) Scores for conditions. C) Scores for seasons. D) Scores for segments.

Spatial distributions of several target species were examined (Figure 36). Atlantic Croaker had higher abundance and smaller average length in the LC segments closer to the gulf inlet and barrier island (Figure 36A). LC-1 and LC-2 had the lowest average catch but some of the largest average lengths. LC-5 had the greatest average abundance and the smallest average length. Blue Crab had lower average abundance across the whole bay area (Figure 36C). While there were more Blue Crabs caught on average in segments close to freshwater inflow sources, the total range of average catch was 2-5. Gulf Menhaden had the highest abundance in LC-1 and LC-9 and were the smallest in these segments (Figure 36B). Larger and fewer individuals were caught in segments closer to the gulf inlet. Both brown and white shrimp have the same pattern of being smaller and more abundant in segments closer to freshwater inflow (Figure 36C and Figure 36D). As the distance from freshwater inflow increases, larger and fewer individuals are caught.

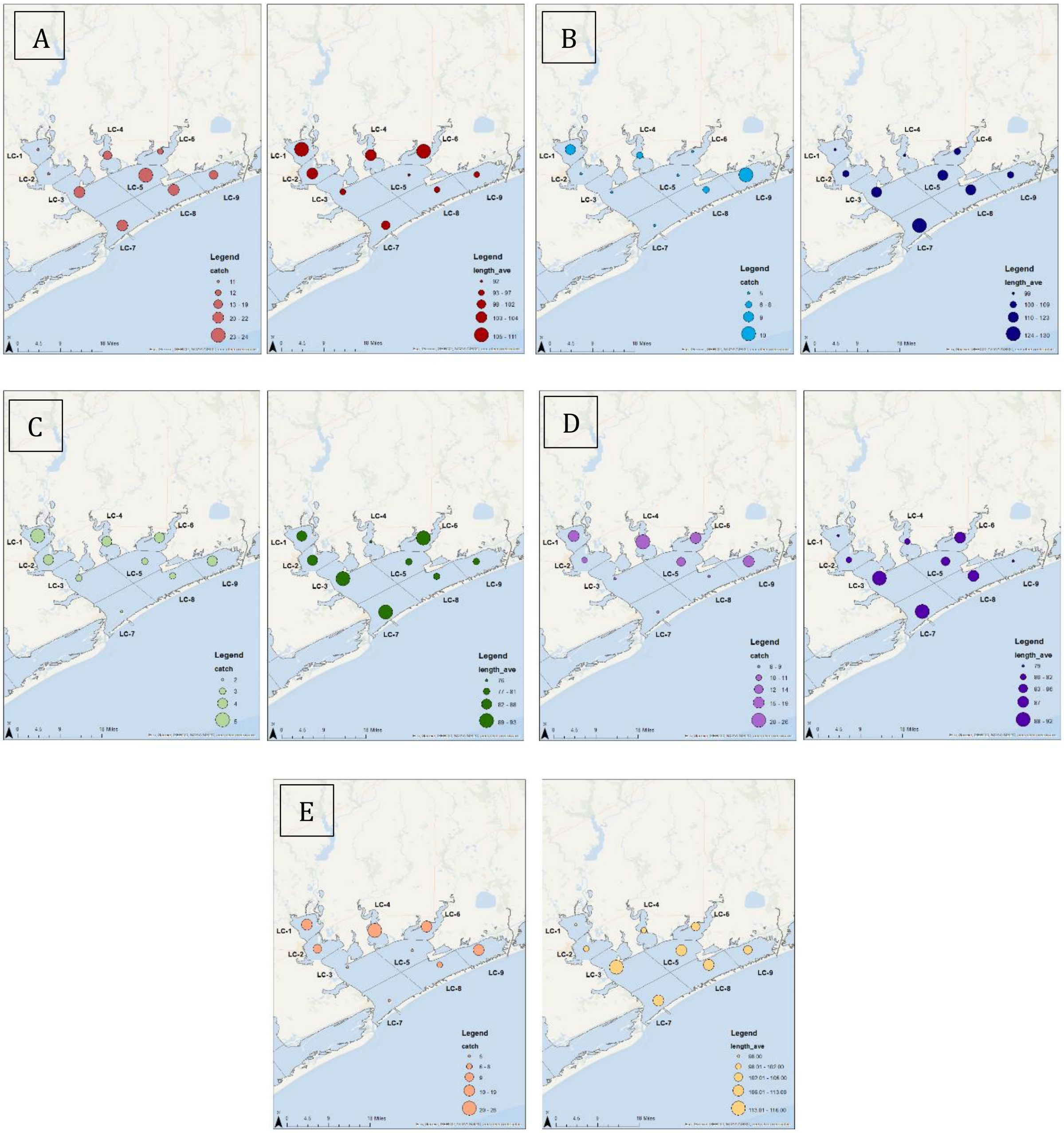

Figure 36. Target species average total abundance (n/10 min trawl) and average length (mm) in each segment for five species. A. Atlantic roaker. B. Gulf Menhaden. C. Blue Crab. D. Brown Shrimp. E. White Shrimp.

8.5.4 Response to Events

The salinity distribution of each segment was calculated using all trawl samples to determine salinity ranges for each condition (i.e., dry, normal, and wet). Dry conditions were salinities above the third quartile. Normal conditions were salinities within or equal to the interquartile range. Wet conditions were salinities below the first quartile. Each segment had unique salinity values to determine conditions (Table 9).

Table 9 . Salinity distribution for trawl samples over the entire sampling period in LC Estuary by segments. Abbreviations: STD = standard deviation, Q1 = 1st quartile, Q3 = 3rd quartile.

Segments	Mean	STD	Minimum	Q1	Median	Q3	Maximum
LC-1	15.68	8.77	0	9.10	15.33	22.5	40.2
LC-2	20.35	7.71	1.25	15.53	20.55	26.25	39.26
LC-3	24.05	5.76	6.70	20.46	24.46	28.10	35.67
LC-4	20.68	7.45	3.28	15.55	20.58	26.3	37.00
LC-5	23.93	5.51	8.82	20.34	23.91	28.41	36.13
LC-6	20.81	6.90	5.00	16.33	20.80	26.00	35.58
LC-7	26.81	4.62	10.83	24.00	27.5	30.08	35.03
LC-8	24.23	5.15	9.58	21.19	24.86	28.00	36.35
LC-9	20.93	7.18	3.29	15.45	21.87	25.76	36.82
Whole Bay	21.95	7.32	0	17.45	22.88	27.55	40.20

Infauna and epifauna response was different during events (Table 10). One-way ANOVAs were used to determine effects of wet-dry conditions within each individual segment. In LC-1 and LC-2, epifauna abundance and richness was greater during dry conditions than in wet conditions. LC-9 also had greater epifauna richness during dry than wet conditions. Infauna abundance and richness was greater in dry conditions than in wet conditions in LC-2, but not LC-1. LC-3 also has greater infauna richness in dry conditions. LC-7 has greater infauna abundance and richness in dry and wet conditions than in normal conditions.

Table 10 . Mean (+ standard deviation) of infauna and epifauna abundance and richness during different salinity conditions for each segment.

Segment	Condition	Salinity (PSU)	Infauna		Epifauna	
			Abundance (n/m^2)	Richness	Abundance (n/ 10 min trawl)	Richness
LC-1	Dry	26.9 (3.9)	21083 (8314)	17.6 (8.6)	125.2 (133.0)	7.0 (3.3)
	Normal	15.5 (3.4)	20903 (18121)	13.5 (9.4)	85.2 (101.9)	6.0 (3.1)
	Wet	4.7 (3.0)	20887 (14390)	12.3 (5.1)	54.4 (51.2)	4.7 (2.7)
LC-2	Dry	29.8 (2.8)	20889 (12325)	19.4 (9.0)	150.1 (191.2)	8.5 (3.9)
	Normal	20.9 (2.9)	13719 (9189)	12.6 (7.0)	94.9 (180.4)	6.5 (3.7)
	Wet	10.0 (3.8)	15694 (11178)	11.3 (4.4)	58.8 (74.8)	5.7 (2.5)
LC-3	Dry	30.8 (1.8)	37812 (30017)	37.5 (14.5)	161.6 (170.5)	8.7 (2.8)
	Normal	24.6 (2.1)	30315 (19582)	30.9 (14.9)	120.5 (124.6)	8.5 (3.7)
	Wet	16.5 (4.0)	20918 (12634)	23.2 (10.1)	117.7 (75.5)	8.8 (2.4)
LC-4	Dry	30.1 (2.8)			133.4 (233.8)	6.8 (3.0)
	Normal	21.0 (2.9)			141.2 (228.9)	6.8 (4.0)
	Wet	11.0 (3.5)			79.7 (72.5)	6.3 (3.6)
LC-5	Dry	30.5 (1.7)			171.2 (216.1)	8.6 (3.0)
	Normal	24.3 (2.3)			137.1 (131.6)	8.5 (3.8)
	Wet	16.6 (3.2)			123.8 (114.0)	8.3 (4.0)
LC-6	Dry	29.4 (2.7)			103.3 (124.4)	6.2 (3.2)
	Normal	20.8 (2.8)			67.8 (89.2)	5.5 (3.5)
	Wet	11.7 (3.4)			58.6 (64.1)	6.3 (3.2)
LC-7	Dry	32.0 (1.5)	62115 (39954	41.8 (15.0)	203.9 (299.8)	9.8 (3.5)
	Normal	27.5 (1.8)	44299 (56232)	31.4 (14.1)	156.7 (166.1)	9.8 (3.5)
	Wet	20.7 (3.7)	44005 (34598)	35.4 (16.0)	120.5 (100.8)	10.6 (3.4)
LC-8	Dry	30.1 (1.8)	40959 (27680)	29.4 (9.2)	159.4 (125.6)	9.7 (3.0)
	Normal	24.6 (2.0)	24318 (18973)	24.4 (9.8)	157.0 (178.9)	8.9 (3.1)
	Wet	17.3 (3.2)	32693 (29678)	25.1 (12.7)	158.0 (130.7)	8.5 (2.8)
LC-9	Dry	30.0 (2.6)	26679 (20761)	23.1 (8.9)	159.5 (195.5)	8.8 (2.9)
	Normal	21.5 (2.8)	31977 (28549)	18.7 (5.9)	136.8 (153.6)	7.6 (2.5)
	Wet	11.6 (3.9)	26112 (23049)	17.0 (9.5)	125.2 (236.1)	6.5 (2.6)

8.6 Potential Confounding Factors

While this report focuses on biological responses to salinity, there is also concern that pollution factors could confound salinity effects. In particular, there is an industrial discharge into Lavaca Bay by the Formosa Plastics Corporation(FPC) facility in Point Comfort, Texas (Figure 8).

8.6.1 Formosa Monitoring Program

FPC began discharging on September 22, 1993 and long-term monitoring has occurred at the discharge site and reference sites in Lavaca Bay since May 1993 (Freese and Nichols

2019). It is possible that contamination effects from the discharge are confounded with inflow effects from the river, so the monitoring data for the potentially toxic compounds, known as priority pollutants, are compared with known standards of biological effects. The priority pollutants include heavy metals, volatile organics, polycyclic aromatic hydrocarbons (PAH), pesticides, and polychlorinated biphenyls (PCB).

The FPC monitoring results for sediment contaminant concentrations were compared to existing sediment quality guideline values (Long et al. 1995, MacDonald et al. 1996) (Table 11). None of the PAHs or pesticides were within a detectable range. PCBs were detected in 20% of samples, but the highest value was 4 µg/kg, which is far below the effects levels of 180 – 189 µg/kg.

Potentially toxic trace metals were detected in most samples. The average concentration over all the trips was much lower than the effects levels (Table 11). However, there were some instances where the concentrations were higher than the ERM or PEL guidelines. This occurred only once for chromium, copper, and nickel; three times for lead; and 31 times for mercury (Table 12). The exceedance for mercury occurred in station A1, closest to the discharge outfall, eight times, but the highest value was 1.19 mg/kg. High mercury values occurred 12 times in reference stations.

Table 11. Comparison between effects range median (ERM) and probable effects levels (PELs) guidelines for sediments with data from the FPC study.

	Guidelines[1]		Monitoring Data				Non-Detects	
Substance	**ERM**	**PEL**	**n**	**Mean**	**Min**	**Max**	**n**	**Percent**
Polycyclic aromatic hydrocarbons (µg/kg)								
Acenaphthene	500	88.9	2061	17	1	155	2061	100%
Acenaphthylene	640	128	2059	17	1	155	2059	100%
Anthracene	1100	245	2061	17	1	155	2061	100%
Fluorene	540	144	2063	17	1	155	2063	100%
Naphthalene	2100	391	2061	17	1	155	2061	100%
Phenanthrene	1500	544	2061	17	1	155	2061	100%
Benzo(a)anthracene	1600	690	2061	17	1	155	2061	100%
Benzo(a)pyrene	1600	762	2059	17	1	155	2058	100%
Chrysene	2800	846	2060	17	1	155	2060	100%
Dibenz(a,h)anthracene	260	135	132	26	1	155	132	100%
Fluoranthene	5100	1494	2063	17	1	155	2063	100%
Pyrene	2600	1398	2057	17	1	155	2057	100%
Pesticides and polychlorinated biphenyls (µg/kg)								
Chlordane	6	4.79	126	6.63	2.4	25.6	126	100%
Dieldrin	8	4.3	134	4.11	0.04	17	134	100%
4,4 DDD	20	7.81	134	5.09	0.2	17	134	100%
4,4 DDE	27	3.74	134	4.32	0.04	17	134	100%
4,4 DDT	7	4.77	134	4.83	0.2	17	134	100%
Total PCBs	180	189	5	0.02	0.004	0.04	4	80%
Trace metals (mg/kg)								
Arsenic	70	41.6	2277	9.1	0.07	8840	79	3%
Cadmium	9.6	4.21	145	0.22	0.056	2.2	29	20%
Chromium	370	160	2266	11	1	540	22	1%
Copper	270	108	2270	9	0.5	4500	24	1%
Lead	218	112	2262	15	0.5	8014	12	1%
Mercury	0.71	0.7	2188	0.1	0.004	6.64	737	34%
Nickel	51.6	42.8	2284	8.3	0.734	51.8	18	1%
Silver	3.7	1.77	145	0.8	0.04	20.54	62	43%
Zinc	410	271	2300	24.8	0.5	147.8	4	0%

[1] Effects levels derived from Long et al. 1995, MacDonald et al. 1996

Table 12. Exceedance of sediment metal concentrations in the FPC data set.

Variable	Station	Date	Concentration (µg/kg)
Arsenic	A4	7/26/2004	3921
Arsenic	B2	7/26/2004	2029
Arsenic	R4	1/15/2008	8840
Chromium	A3	4/1/2014	540
Copper	A3	1/15/2008	4500
Lead	A2	4/3/2012	6386
Lead	B3	7/27/2005	8014
Lead	C4	4/5/2011	606
Mercury	A1	7/28/1993	0.88
Mercury	A1	7/28/1993	0.93
Mercury	A1	9/21/1993	1.06
Mercury	A1	9/21/1993	1.17
Mercury	A1	10/13/1993	1.19
Mercury	A1	10/13/1993	1.19
Mercury	A1	12/7/1993	0.71
Mercury	A1	12/7/1993	0.74
Mercury	A3	10/13/1993	0.74
Mercury	A4	1/19/1999	3.9
Mercury	B2	1/21/2014	1.57
Mercury	C1	12/6/1993	0.88
Mercury	C2	12/6/1993	0.82
Mercury	C2	4/18/1994	1.5
Mercury	C3	12/6/1993	0.81
Mercury	C3	12/6/1993	0.82
Mercury	D3	7/28/1993	0.81
Mercury	D3	10/11/1993	0.76
Mercury	D3	1/19/2011	6.64
Mercury	R1	7/26/1993	1.7
Mercury	R1	7/25/2001	0.78
Mercury	R1	7/25/2001	1.04
Mercury	R1	7/27/2004	0.93
Mercury	R1	7/27/2004	0.93
Mercury	R1	1/25/2005	0.96
Mercury	R2	7/27/1993	0.73
Mercury	R2	7/27/1993	1.06
Mercury	R2	9/22/1993	1.19
Mercury	R2	9/22/1993	1.19
Mercury	R3	7/26/1993	0.85
Mercury	R3	4/3/2018	0.96
Nickel	A4	1/19/1999	51.8

8.6.2 HRI Monitoring Study

Benthic abundance, biomass, and diversity was sampled by HRI at the Formosa Discharge point (Station FD) quarterly from April 2007 to October 2012 and from October 2012 to January 2019. Thus, it is possible to compare this station to Stations A and B to determine if there are differences that might be ascribed to the discharge (Figure 37). Except for a few instances, all three stations appear to track one another over time.

A two-way ANOVA was performed and a linear contrast was used to test the hypothesis that abundance, biomass, and diversity at the FD station was different from the A and B stations (Table 13). There appears to be differences only with abundance, and the FD stations has lower benthic abundance than stations A and B. Biomass and richness (i.e., the number of species present) was not different among the stations. The abundance at FD was about 9% less than the average of Stations A and B.

Table 13. ANOVA at reference and discharge stations.

A. ANOVA		**P-Values**		
Source	**DF**	**Log Abundance**	**Log Biomass**	**Richness**
Station	2	<.0001	0.2025	0.4214
Date	30	<.0001	<.0001	<.0001
Date*Station	60	<.0001	<.0001	<.0001
Error	186			
B. Contrast				
FD vs AB	1	<.0001	0.5441	0.2884
C. Means				
Log Abundance		8.137	7.768	7.214
		A	B	FD
Log Biomass		0.6589	0.5747	0.5552
		A	FD	B
Richness		4.59	4.47	4.30
		FD	A	B

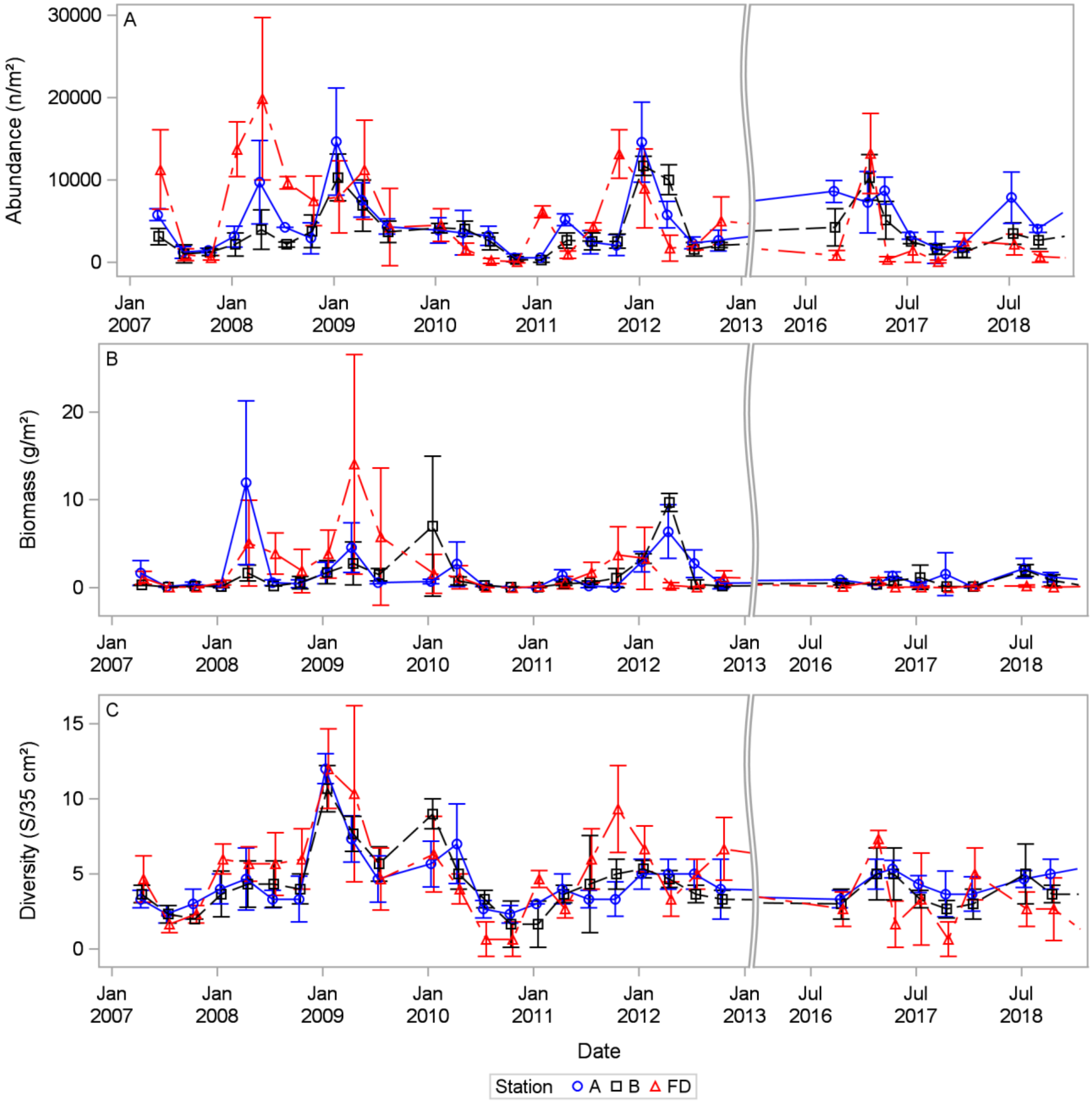

Figure 37. Benthic metrics at the long-term stations A and B, and the Formosa discharge (FD). A) Abundance, B) Biomass, and C) Diversity.

Another interesting finding is the occurrences of plastic spheres at Station FD (Figure 38). There have been no chemical analyses of these spheres, but it is thought they may be catalyst materials. The spheres have not been seen in other samples and are not always present. The average number of pellets per core (35 cm2) is mean 58 ± standard deviation 88 in the top 0-3 cm of sediment, and a mean of 116 ± standard deviation 221 in the bottom 3-10 cm of sediment.

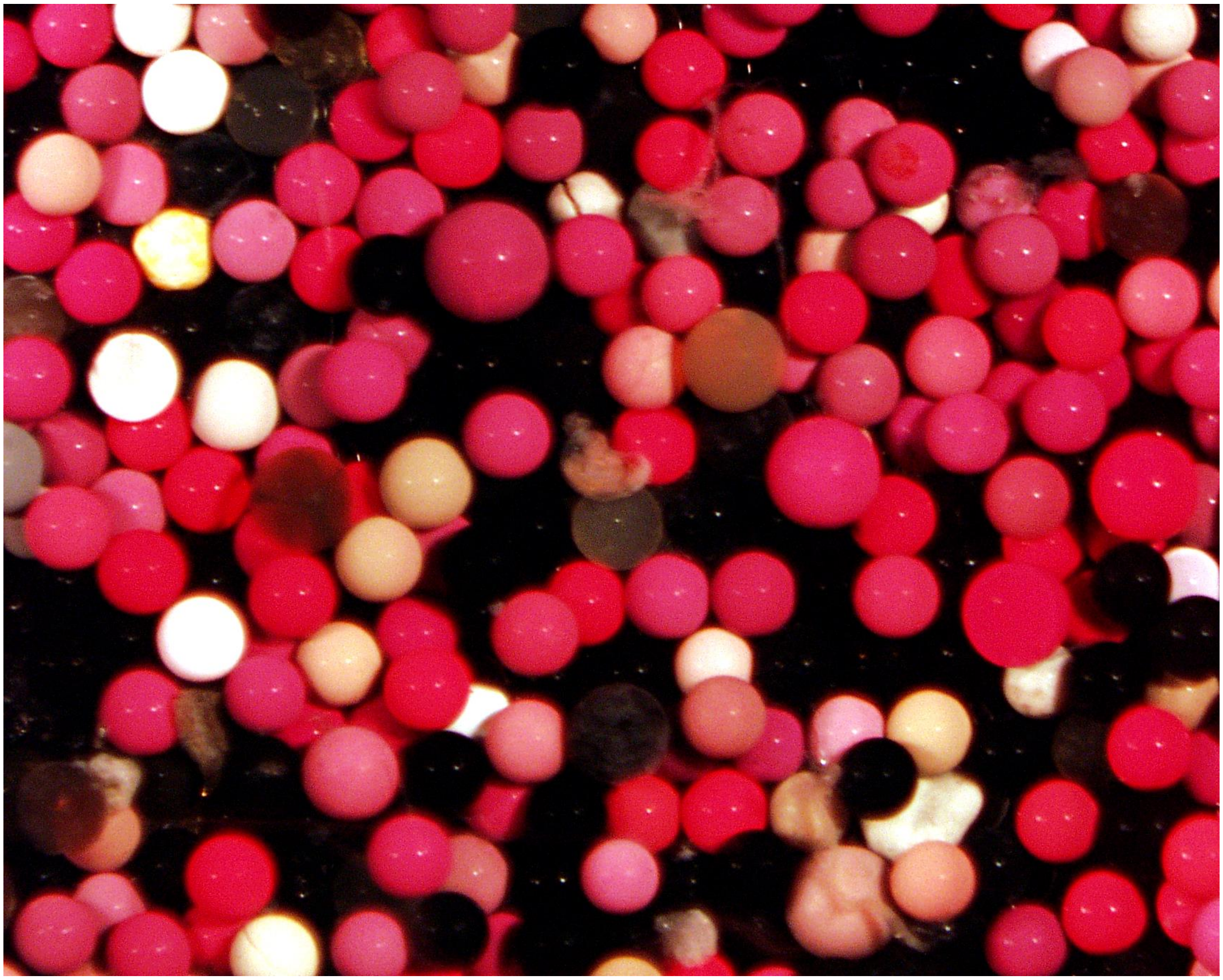

Figure 38. Plastic spheres found at the Formosa Discharge station FD in the HRI study. Spheres are about 0.5 mm in diameter.

9. Discussion

This project was performed to support environmental flow studies identified by the Colorado and Lavaca Rivers and Matagorda and Lavaca Bays Basin and Bay Area Stakeholder Committee (CL-BBASC) as part of the adaptive management phase of the Senate Bill 3 (SB3) process (80th Texas Legislature) for establishing environmental flow standards for Texas river basins and estuaries. Funding for this project was made available through funds appropriated to the TWDB during the 85th Texas Legislature.

The goal of the project is to provide an understanding of the relationships between freshwater inflow and habitat in Lavaca Bay based on long-term monitoring data. This information is critical for consideration by the CL-BBASC for recommending future rulemaking related to environmental flow standards for Lavaca Bay. Existing flow standards are based on CL-BBASC (2011a) and Colorado and Lavaca Rivers and Matagorda and Lavaca Bays Basin and Bay Area Expert Science Team (CL-BBEST 2011) recommendations for Lavaca Bay inflows, which were extrapolated using data from Matagorda Bay. Thus, it is necessary to obtain information specific to Lavaca Bay.

This project fulfills the Colorado and Lavaca Rivers and Matagorda and Lavaca Bays Basin and Bay Area Stakeholder Committee Work Plan (CL-BBASC 2011b) Task 12 priority project, which seeks to describe the relationship between freshwater inflow to bays and the physical, chemical, and biological structure and function of the estuaries and how these relationships support ecological health

9.1 Habitat

Lavaca Bay is shallow, the shoreline is lined with patchy *Spartina alternifora*, and the surrounding low salinity marshes adjacent to the river are vegetated mainly with *Juncus roemerianus* and *Phragmites communis*. The majority of freshwater inflow into upper Lavaca Bay comes from the Lavaca and Navidad Rivers, while lesser contributions come from Venado, Garcitas and Placedo Creeks. The Palmetto Bend Project, a dam, was constructed on the Navidad River in May 1980 to form Lake Texana. This reservoir was constructed to supply water for industrial and municipal use and was not intended for flood control. Major floods are allowed to pass through the flood gates and inundate the marsh system associated with the Lavaca-Navidad River delta. Circulation between the upper and lower bay is modified by the presence of State Highway 35 Causeway and the Causeway oyster reef, which extends across the mouth of the upper bay. The Causeway Reef is a combination of Lap, Hole in the Wall, and Chicken Reefs (Munro 1961). Sedimentation from the Lavaca River occurs in upper Lavaca Bay at a rate of 200,000 tons of silt annually. Only minimal amount of fill has occurred at the mouth of the Lavaca River with no appreciable extension of the river delta since 1870 (Shepard 1953).

9.1.1 Salinity Zone Habitats

It is well established that salinity forms habitat with estuaries. Salinity also drives water quality because salinity is inversely correlated with nutrients, meaning when there is a great amount of freshwater inflow the salinity is low and the nutrients are high (Figure 17). While there is a great range of salinity in Lavaca Bay, from 0 psu to 35 psu, and variability over time (Figure 20), the three HRI water quality stations are relatively homogeneous at any given time (Figure 18). This appears to indicate that Lavaca Bay is essentially one habitat. The idea that salinity zones are more variable over time than space is supported by the maps of monthly salinity structure within Lavaca Bay over time (Appendix 2). It is rare when salinity ranges more than 20 psu from the Lavaca River to Matagorda Bay, for example July 1996 and May 1998 when both green and red colors occur (Appendix 2).

Infaunal benthic organisms (e.g., polychaetes, amphipod crustaceans, and mollusks) are good indicators of salinity effects because they are relatively immobile compared to epibenthos (e.g., large mobile crustacean like shrimp and crabs, and demersal fish), plankton, and nekton (e.g., fish). The immobility means that benthos must adapt or survive to changing conditions in their habitat because they cannot move. The importance of benthic indicators was recognized by the BBESTs (Table 2). Five of the seven BBEST used oysters, *Rangia*, or benthos to derive inflow standards. Benthos are also at the base of food webs, and are thus important forage for higher trophic levels, i.e., crab, shrimp, and fish.

There are many species among the infauna that are found only in, or predominantly within, Lavaca Bay (Table 4). For example, nine species were at least 10 times more abundant in Lavaca Bay than Matagorda Bay, and three of them were found exclusively in Lavaca Bay but they were relatively rare in occurrence. Of the more dominant species, *Macoma mitchelli* (bivalve mollusk), and *Ampelisca abdita* (amphipod crustacean) were more than 10 times more common in Lavaca Bay. *Macoma* had an optimal salinity of 13 psu and *Ampelisca* had an optimal salinity of 25 psu (Table 5). This relationship means *Macoma* was common in wet conditions and *Ampelisca* was common in dry conditions.

In the Lavaca-Colorado (LC) estuary, epifauna (i.e., animals caught in the Texas Parks and Wildlife Trawls) abundance and richness is greater in segments with higher salinity and closer proximity to Gulf inlets (Figure 36, Table 9). Segments LC-7 and LC-8 had the greatest abundance and richness. LC-9 had greater abundance and richness then the other segments with freshwater inflow (LC-1 and LC-2). LC-2 had significantly lower abundance than LC-9 despite having similar salinities. The Lavaca-Colorado estuary has decreasing epifauna richness, primarily in the mid-bay area. Additionally, infauna abundance and richness has decreased in the lower bay, especially in LC-7 (Table 10). Spatial analysis showed that juveniles are using the upper reaches, closer to freshwater, for most target species (Figure 36). Atlantic Croaker was more abundant in the lower estuary. Brown Shrimp, White Shrimp, and Gulf Menhaden utilize segments in the upper reaches, while Blue

Crab have higher abundance in the mid-bay area. Each of these species has a similar life history of spawning offshore near tidal inlets and dispersion of eggs, larvae, and juveniles into estuaries (Beck et al. 2001, Reese et al. 2008). While having similar life cycles, the seasonal timing is different. Juveniles of each species have increased abundance in different seasons when juveniles move into the upper reaches (Pulich et al. 1998, Pulich et al. 2002, LCRA 2006). Atlantic Croaker has been previously observed to have decreased abundance with increased distance from the Gulf inlets, whereas penaeid shrimp species and Blue Crab have been seen to recruit in similar abundances regardless of distance from Gulf inlet (Reese et al. 2008). Shrimp species and Blue Crab have greater dispersion from the Gulf inlets and thus can be seen in greater abundance using lower salinity habitats in the estuary. Specific habitat types such as seagrass or sand bottom was not considered in the distribution of epifauna. While previous studies have shown that some species, such as Atlantic Croaker, are habitat generalist and appear to have no preference when settling, the effect of habitat in distribution of juveniles may have some impacts on location preference (Petrik et al. 1999). The preference for habitat type may also influence distribution into the upper reaches of estuaries where a specific habitat maybe more or less abundant.

9.1.2 Droughts and Floods

Previous studies have shown that low flows and droughts have different effects in the estuaries of the Texas Coastal Bend (Palmer and Montagna 2015). In Lavaca and Matagorda Bays, dry conditions increased epifauna abundance and richness in the upper reaches of Lavaca Bay. The increase in epifauna coincides with the results of higher salinity segments having increased epifauna abundance and richness. Infauna abundance and richness also follow the same pattern in some segments, mainly segments in the upper reaches. Droughts increase infauna abundance, diversity, and alter community structure (Palmer and Montagna 2015). The intrusion of marine benthic fauna species into areas with previous lower salinities has been observed when freshwater inflow decreases. Additionally, this increase in epifauna and infauna may be individuals seeking refuge in areas of lower salinity (Little et al. 2016). As dry conditions continue, the upper reaches become areas of optimal salinity while freshwater inflow is decreased and salinity gradients in the bay proper are not maintained. The upper reaches can become sanctuary habitats for species that cannot tolerant the rising salinities in segments closer to the gulf inlets and when normal inflows return, estuarine organisms can return to the lower estuary areas. Macroinvertebrates have been seen to repopulate areas after droughts through downstream drift with river discharge (Little et al. 2016).

Wet conditions reduced epifauna and infauna richness and abundance. The decrease in epifauna can be the result of salinity lower than species tolerance, flushing from high flow periods, or high turbidity resulting in difficulty in finding food (Yagi et al. 2011, Strydom et al. 2002). These factors can cause nursery grounds in the upper reaches to be suboptimal for many juveniles. For example, segment LC-7 had conflicting results with greater infauna abundance and richness in dry and wet periods than in normal periods. Typical salinity values in LC-7 may not favor marine or estuarine infauna species. When salinities increase, marine species presence may increase. But in wet periods, estuarine species presence may increase.

The effects of both dry and wet conditions are impactful for estuarine inhabitants. The resilience of a community is valuable when combating the effects of environmental change. The estuarine nekton community is able to recover quickly after flood events (Gonzáles-Ortegón and Drake 2012, Gonzáles-Ortegón et al. 2012). Benthic communities recovering from eutrophication effects had less resilience to flooding and slower to recover from both stressors (Cardoso et al. 2008). Emphasis on timing of freshwater inflow is as important as maintaining necessary quantity. Freshwater inflow is important for the occurrence of larval dispersion and juvenile settlement to allow organisms to enter the estuary and prevent drastic flushing events (James et al. 2018). Environmental flows require attention to timing, duration, quantity, and quality. All these freshwater inflow variables affect estuarine conditions and resources (Montagna et al. 2013, Dittmann et al. 2015).

9.2 Other Stressors

Inflow into Lavaca Bay is fed by a relatively rural watershed, but there are two major industrial plants in Point Comfort on the northeast shore of the bay. So, it is possible that inflow effects could be confounded by multiple stressor effects, such as contaminant exposure.

The Alcoa facility in Point Comfort operated for about 70 years, curtailed production in 2016, and closed permanently in 2020 (Venable 2019). Although the main product of the plant was alumina from bauxite, a Chlor-alkali facility at the plant discharged mercury into the bay from 1965 to 1981, and Lavaca Bay was listed as a Superfund Site in 1988. There are still high levels of mercury in fish in Lavaca Bay, and the area near the plant is still closed to fishing (Texas Department of State Health Service 2013, Priest 2020). Not surprisingly, the FPC monitoring did find some instances of high levels of mercury in sediments (Table 12).

The Formosa facility in Point Comfort has been in operation since 1983. The plant went online in 1983. The plant produces Vinyl Chloride Monomer (VCM) to manufacture Polyvinyl Chloride (PVC), Olefins, Linear Low-Density Polyethylene (LLDPE), High Density Poly Ethylene (HDPE), Polypropylene, Ethylene Dichloride, and Chlor-alkali. Plant waste is discharged into Lavaca Bay using a diffuser (Figure 8). Since plant expansion in 1993, a monitoring program has been required by TCEQ to evaluate compliance with the Texas Surface Water Quality Standards (TAC Chapter 307). Annual monitoring reports are produced (Freese and Nichols 2019). The reports generally assert that "there is no adverse impact to the health or structure of the biological community in Lavaca Bay" nor any "uptake of harmful constituents have been detected by the Monitoring Program" (Freese and Nichols

2019). The TCEQ defines level of concern as "Moderate" when measurements are higher than the 85th percentile of all measurements made State-wide. Some measurements of some metals in sediments have exceeded this standard as shown in Table 14, which is reproduced from the 26th Annual Report (Freese and Nichols 2019), and few of the values exceeded recognized sediment quality guidelines (Table 12).

Table 14. Texas 85th percentile values and FPC monitoring range (Table 5.1.3.2, Freese and Nichols 2019).

Metal	Texas 85th Percentile (mg/kg)	Monitoring Program Range (mg/kg)
Arsenic	9.08	<0.02–44.82 [1]
Cadmium	0.663	<0.05–0.75
Chromium	36.9	<1.0–48.0
Copper	19.9	<1.0–109.0 [2]
Lead	21.9	<0.50–58.0
Mercury	0.55	<0.004–3.90 [3]
Nickel	24.2	<1.0–51.8
Silver	0.6	<0.2–1.7 [4]
Zinc	62.2	<0.50–191.9 [5]

[1] Station C4, Trip 9; the next highest value was 10.9 mg/kg, Station A2, Trip 7.

[2] Station A2, Trip 7; the next highest values were 103.2 mg/kg, Station A2, Trip 6; 102.8 mg/kg, Station R3, Trip 2A; 93.0 mg/kg, Station A2, Trip 6.

[3] Station A4, Trip 26; the next highest values were 2.46 mg/kg, Station A3, Trip 11; 1.7 mg/kg, Station R1, Trip 2A.

[4] Only 3 detected values all from Station R1, Trip 21; 0.52, 0.65, and 1.7 mg/kg.

[5] Station A2, Trip 7; the next highest value was 141 mg/kg, Station R3, Trip 2B.

None of the hydrocarbon measurements were above detection limits required by the scope of the FPC study (Freese and Nichols 2019). However, polycyclic aromatic hydrocarbons (PAHs) have been found in sediment of Lavaca Bay in March 1995 (Carr et al. 1996). The difference is due to different study locations and to differences in the detection limits of the methods used in the two studies. The detection limits for PAH compounds in the FPC monitoring study is 150 µg/kg, whereas the detection limit for PAH in the Carr study is 5 µg/kg (Wade et al. 1988 cited in Brooks et al. 1989). Carr et al. (1996) found total PAHs in seven of 24 stations exceeded either the ERM or PEL, and these stations were all adjacent to the Alcoa facility. Carr et al. sampled the Formosa discharge site, labeled it Station 18, and found concentrations of total PCB 3.87 µg/kg, total DDT 0.47 µg/kg, and total PAH 65.9 µg/kg. Whereas the concentrations of toxic chemicals were low at this site, Carr et al. (1996) stated that the "most toxic station overall in this survey was station 18 at the Formosa Plastics Co. outfall. It is apparently receiving contaminates from a different source [other than the mercury contamination from the ALCOA plant]". The FPC study (Freese and Nichols 2019) states the Formosa's outfall has no adverse impacts to the health or biological community structure in Lavaca Bay. PAHs were the primary contributor to toxicity detected within Lavaca Bay, but the PAH levels were low in both the FPC and Carr et al. (1996) studies. Overall, the Freese and Nichols (2019) study states contaminates are detected within the sediment and water samples collected from Lavaca Bay but are not to be of any concern. The abundance of benthic fauna was 9% lower at the Formosa discharge site that references stations in the HRI Study (Table 13). Plastic pellets were found in the HRI samples at the discharge site (Figure 38), but these are not reported in the FPC monitoring program. Again, this is likely due to different methods, because HRI uses a 0.5 mm sieve and the FPC study uses a 1 mm sieve.

9.3 Management Implications

Texas law requires that environmental flow regimes reflect seasonal and yearly flow quantities specific to the bays' geographic characteristics to provide a "sound ecological environment" (House Bill 3 and Senate Bill 3, 80th Texas Legislature, 2007). The law required stakeholders and scientists to recommend individualized flow regimes for rivers, basins, and bays in Texas. The different regimes for each system reflect the climatic gradient along the coast. To develop the initial environmental flow standards in the 1990's, recreationally and commercially important species were used to simulate optimal harvest as a function of salinity patterns (Longley 1994, Powell et al. 2002). These flow rates focus on maintaining the salinity of the entire bay, a task that could require more water than available during droughts when both ecological and human needs are greatest. Focus on the upper reaches of estuaries, rather than the whole estuary, can protect areas of the bay more susceptible to drought impacts and create a sanctuary area for juveniles and species that have lower salinity requirements. The focus on upper reaches, rather than falling short of maintaining whole-bay salinity conditions, creates a smaller area to maintain and less freshwater inflow to keep salinity gradients. The TPWD currently has established areas of sanctuary in the Lavaca Colorado Estuary in the same area as segments LC-1 and LC-9 of the present study. These regions are maintained at a salinity of 25 psu in times of low flow or critical flow to protect important habitats and oyster beds (LCRA 2006). The present study has shown that LC-9 has a 3rd quartile value of 25.8 PSU (Table 9). However, LC-1 has a lower 3rd quartile salinity of 22.5 PSU. While this difference is not large, it may be beneficial to create critical flows that more closely reflect the typical salinity range of these different areas. Additionally, establishing environmental flow criteria for other segments in the estuary is important, such as those in Carancahua Bay (LC-4) and Tres Palacios Bay (LC-6). The importance of choosing restrictions that benefit the more sensitive habitat has been used in other environmental flow regulations (Mattson 2002). Using this information to establish beneficial environmental flow regulations is vital to the maintenance of estuaries health and integrity. Additionally, these flow regimes are important for developing and planning purchasing water rights, through which environmental flows can be managed or protected in times of drought. Currently, organizations seek to purchase water rights to establish a reserve of freshwater for ecological needs (Duval at al. 2017). Less water would be needed in reserve if focused flows are applied to the needs of upper reaches rather than the immense needs of the entire bay area.

Understanding how changes in freshwater inflow affect estuaries and associated living marine resources, especially those relying on the nursery function provided in the upper reaches of estuaries, is important for future management and planning. Changes in climate are predicted to increase temperature and decrease precipitation, but also increase storms. Projected population increase, especially in coastal areas will decrease freshwater availability and increase anthropogenic impacts on estuaries (Wetz and Yoskowitz 2013). Impacts from the human population along with increasing high flow and low flow events can affect the resilience and health of organisms utilizing estuaries for nursery habitat. Establishing environmental flows that meet freshwater quality, quantity, and timing will preserve the nursery function in upper reaches, which will ensure the protection of estuarine resources for years to come.

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11. Appendix

Contents

Appendix 1. Average species abundance over 20 years (1988 to 2008) listed in order of dominance. Stations A, B, and FD in Lavaca Bay (LB); and stations C and D in Matagorda Bay (MB). Average abundance (n/m2) from 1988 – 2012.

Appendix 2. Salinity distribution maps for the period 1987 to 2016. Average salinity at each node over each month.

Appendix 1. Average species abundance over 20 years (1988 to 2008) listed in order of dominance. Stations A, B, and FD in Lavaca Bay (LB); and stations C and D in Matagorda Bay (MB). Average abundance (n/m2) from 1988 – 2012.

Phylum	Class	Order	Family	Species	A	FD	B	C	D	Mean	Pct	CumPct	LB>MB
Annelida	Polychaeta	Order Not Assigned	Capitellidae	Mediomastus ambiseta	3,254.9	2,454.8	3,081.8	3,976.2	4,655.0	3,484.6	40.38%	40.38%	0.68
Annelida	Polychaeta	Canalipalpata	Spionidae	Streblospio benedicti	971.6	830.7	806.3	336.8	173.2	623.7	7.23%	47.60%	3.41
Mollusca	Bivalvia	Veneroida	Mactridae	Mulinia lateralis	596.9	803.6	360.1	423.9	21.2	441.2	5.11%	52.72%	2.64
Annelida	Polychaeta	Order Not Assigned	Capitellidae	Mediomastus californiensis	526.7	0.0	0.0	59.5	71.2	131.5	1.52%	54.24%	2.69
Crustacea	Malacostraca	Amphipoda	Ampeliscidae	Ampelisca abdita	280.0	182.3	51.0	15.9	7.4	107.4	1.24%	55.48%	14.64
Mollusca	Bivalvia	Veneroida	Tellinidae	Macoma mitchelli	158.2	111.4	87.1	8.5	5.3	74.1	0.86%	56.34%	17.22
Nemertea	Nemertea	Nemertea	Nemertea	Nemertea (unidentified)	82.6	47.3	91.4	264.5	464.2	190.0	2.20%	58.54%	0.20
Annelida	Polychaeta	Errantia	Goniadidae	Glycinde solitaria	71.5	50.7	59.5	165.7	59.5	81.4	0.94%	59.49%	0.54
Annelida	Polychaeta	Order Not Assigned	Cossuridae	Cossura delta	59.8	57.4	281.5	521.6	474.9	279.0	3.23%	62.72%	0.27
Annelida	Polychaeta	Errantia	Pilargidae	Hermundura ocularis	59.0	13.5	20.2	6.4	0.0	19.8	0.23%	62.95%	9.69
Annelida	Polychaeta	Order Not Assigned	Capitellidae	Capitella capitata	57.7	138.4	24.4	5.3	0.0	45.2	0.52%	63.47%	27.68
Mollusca	Gastropoda	Neotaeniogloassa	Hydrobiidae	Texadina sphinctostoma	46.9	6.8	4.2	0.0	0.0	11.6	0.13%	63.61%	19.29
Mollusca	Gastropoda	Cephalaspidea	Cylichnidae	Acteocina canaliculata	33.9	54.0	44.6	40.4	2.1	35.0	0.41%	64.01%	2.08
Annelida	Oligochaeta	Oligochaeta	Oligochaeta	Oligochaeta (unidentified)	25.7	101.3	10.6	32.9	1,332.1	300.5	3.48%	67.50%	0.07
Crustacea	Malacostraca	Cumacea	Bodotriidae	Cyclaspis varians	23.0	27.0	14.9	15.9	3.2	16.8	0.19%	67.69%	2.26
Annelida	Polychaeta	Order Not Assigned	Orbiniidae	Haploscoloplos foliosus	22.5	23.6	46.7	55.2	22.3	34.1	0.39%	68.09%	0.80
Mollusca	Bivalvia	Veneroida	Pharidae	Ensis minor	13.6	10.1	0.0	0.0	0.0	4.7	0.05%	68.14%	7.91
Annelida	Polychaeta	Canalipalpata	Spionidae	Diolydora socialis	13.2	121.6	0.0	22.3	7.4	32.9	0.38%	68.52%	3.02
Annelida	Polychaeta	Canalipalpata	Ampharetidae	Hobsonia florida	13.1	0.0	1.1	2.1	9.6	5.2	0.06%	68.58%	0.81
Crustacea	Malacostraca	Isopoda	Idoteidae	Edotia triloba	13.0	16.9	0.0	1.1	0.0	6.2	0.07%	68.65%	18.76
Insecta	Pterygota	Diptera	Chironomidae	Chironomidae (larvae)	12.3	47.3	3.2	0.0	0.0	12.6	0.15%	68.80%	20.94
Annelida	Polychaeta	Order Not Assigned	Orbiniidae	Haploscoloplos fragilis	11.3	0.0	15.9	14.9	8.5	10.1	0.12%	68.92%	0.78
Annelida	Polychaeta	Order Not Assigned	Capitellidae	Heteromastus filiformis	11.3	3.4	4.2	0.0	0.0	3.8	0.04%	68.96%	6.31
Mollusca	Bivalvia	Veneroida	Solecurtidae	Tagelus plebeius	11.1	0.0	0.0	0.0	0.0	2.2	0.03%	68.99%	3.70
Crustacea	Malacostraca	Amphipoda	Corophiidae	Microprotopus sp.	10.5	3.4	3.2	8.5	9.6	7.0	0.08%	69.07%	0.63
Annelida	Polychaeta	Canalipalpata	Spionidae	Paraprionospio pinnata	10.5	0.0	59.5	172.1	145.5	77.5	0.90%	69.97%	0.15
Crustacea	Malacostraca	Cumacea	Leuconidae	Leucon sp.	9.7	0.0	27.6	22.3	6.4	13.2	0.15%	70.12%	0.87
Mollusca	Bivalvia	Veneroida	Mactridae	Rangia cuneata	8.9	0.0	0.0	0.0	0.0	1.8	0.02%	70.14%	2.96
Annelida	Polychaeta	Canalipalpata	Spionidae	Polydora cornuta	8.9	10.1	1.1	1.1	0.0	4.2	0.05%	70.19%	12.60
Crustacea	Copepoda	Cyclopoida	Cyclopoida	Cyclopoida (commensal)	8.9	3.4	3.2	20.2	0.0	7.1	0.08%	70.27%	0.51

Phylum	Class	Order	Family	Species	A	FD	B	C	D	Mean	Pct	CumPct	LB>MB
Crustacea	Malacostraca	Cumacea	Diastylidae	Oxyurostylis smithi	8.1	0.0	2.1	5.3	1.1	3.3	0.04%	70.31%	1.07
Annelida	Polychaeta	Errantia	Hesionidae	Gyptis brevipalpa	7.3	3.4	12.7	192.3	140.2	71.2	0.82%	71.13%	0.05
Annelida	Polychaeta	Errantia	Nereididae	Laeonereis culveri	7.0	30.4	1.1	0.0	0.0	7.7	0.09%	71.22%	12.81
Crustacea	Malacostraca	Amphipoda	Corophiidae	Corophium louisianae	6.7	40.5	1.1	0.0	0.0	9.7	0.11%	71.33%	16.09
Mollusca	Bivalvia	Veneroida	Tellinidae	Tellina sp.	6.5	6.8	6.4	2.1	3.2	5.0	0.06%	71.39%	2.46
Annelida	Polychaeta	Canalipalpata	Sabellidae	Sabellastarte magnifica	6.5	13.5	0.0	0.0	0.0	4.0	0.05%	71.44%	6.66
Mollusca	Gastropoda	Heterostropha	Pyramidellidae	Eulimastoma sp.	6.5	0.0	26.6	21.2	0.0	10.9	0.13%	71.56%	1.04
Annelida	Polychaeta	Errantia	Onuphidae	Diopatra cuprea	6.5	20.3	10.6	12.7	27.6	15.5	0.18%	71.74%	0.62
Mollusca	Gastropoda	Neogastropoda	Nassariidae	Nassarius acutus	5.7	3.4	6.4	10.6	12.7	7.8	0.09%	71.83%	0.44
Annelida	Polychaeta	Errantia	Phyllodocidae	Hypereteone heteropoda	5.4	13.5	1.1	1.1	4.2	5.1	0.06%	71.89%	2.50
Crustacea	Malacostraca	Amphipoda	Oedicerotidae	Monoculodes sp.	5.2	3.4	3.2	10.6	0.0	4.5	0.05%	71.94%	0.74
Annelida	Polychaeta	Order Not Assigned	Maldanidae	Clymenella mucosa	4.8	0.0	8.5	46.7	2.1	12.4	0.14%	72.09%	0.18
Crustacea	Ostracoda	Ostracoda	Ostracoda	Ostracoda (unidentified)	4.0	0.0	21.2	0.0	0.0	5.1	0.06%	72.15%	8.43
Annelida	Polychaeta	Order Not Assigned	Maldanidae	Clymenella torquata	4.0	0.0	0.0	49.9	7.4	12.3	0.14%	72.29%	0.05
Annelida	Polychaeta	Canalipalpata	Chaetopteridae	Spiochaetopterus costarum	4.0	0.0	4.2	83.9	17.0	21.8	0.25%	72.54%	0.05
Mollusca	Bivalvia	Bivalvia	Bivalvia	Bivalvia (unidentified)	4.0	3.4	1.1	3.2	4.2	3.2	0.04%	72.58%	0.76
Annelida	Polychaeta	Errantia	Nereididae	Nereididae (unidentified)	4.0	0.0	1.1	7.4	13.8	5.3	0.06%	72.64%	0.16
Annelida	Polychaeta	Errantia	Glyceridae	Glyceridae (unidentified)	4.0	0.0	1.1	0.0	0.0	1.0	0.01%	72.65%	1.70
Crustacea	Malacostraca	Mysida	Mysida	Americamysis almyra	3.2	0.0	1.1	2.1	1.1	1.5	0.02%	72.67%	0.90
Annelida	Polychaeta	Errantia	Syllidae	Sphaerosyllis sp. A	3.2	0.0	2.1	18.1	21.2	8.9	0.10%	72.77%	0.09
Crustacea	Copepoda	Poecilostomatoida	Clausidiidae	Hemicyclops sp.	3.2	3.4	0.0	0.0	7.4	2.8	0.03%	72.81%	0.59
Mollusca	Bivalvia	Veneroida	Lasaeidae	Mysella planulata	3.2	0.0	5.3	11.7	53.1	14.7	0.17%	72.98%	0.09
Crustacea	Malacostraca	Mysida	Mysida	Mysidopsis sp.	3.1	0.0	3.2	3.2	2.1	2.3	0.03%	73.00%	0.79
Mollusca	Gastropoda	Heterostropha	Pyramidellidae	Odostomia canaliculata	2.4	0.0	0.0	0.0	0.0	0.5	0.01%	73.01%	0.81
Annelida	Polychaeta	Errantia	Pilargidae	Sigambra bassi	2.4	0.0	1.1	24.4	19.1	9.4	0.11%	73.12%	0.05
Mollusca	Bivalvia	Nuculoida	Nuculanidae	Nuculana acuta	2.4	0.0	1.1	65.9	26.6	19.2	0.22%	73.34%	0.03
Mollusca	Bivalvia	Nuculoida	Nuculanidae	Nuculana concentrica	2.4	0.0	6.4	18.1	9.6	7.3	0.08%	73.42%	0.21
Annelida	Polychaeta	Canalipalpata	Pectinariidae	Pectinaria gouldii	2.4	3.4	0.0	5.3	9.6	4.1	0.05%	73.47%	0.26
Cnidaria	Anthozoa	Anthozoa	Anthozoa	Anthozoa (unidentified)	2.4	3.4	5.3	19.1	77.5	21.6	0.25%	73.72%	0.08
Annelida	Polychaeta	Errantia	Nereididae	Alitta succinea	2.4	13.5	3.2	2.1	0.0	4.3	0.05%	73.77%	6.00
Crustacea	Malacostraca	Mysida	Mysida	Americamysis bahia	2.4	0.0	1.1	6.4	4.2	2.8	0.03%	73.80%	0.22
Mollusca	Gastropoda	Heterostropha	Pyramidellidae	Odostomia sp.	2.4	0.0	2.1	0.0	0.0	0.9	0.01%	73.81%	1.52
Annelida	Polychaeta	Canalipalpata	Spionidae	Scolelepis texana	2.3	10.1	2.1	0.0	0.0	2.9	0.03%	73.85%	4.84

Phylum	Class	Order	Family	Species	A	FD	B	C	D	Mean	Pct	CumPct	LB>MB
Annelida	Polychaeta	Errantia	Pilargidae	Sigambra tentaculata	2.0	0.0	0.0	15.9	102.0	24.0	0.28%	74.13%	0.01
Annelida	Polychaeta	Canalipalpata	Spionidae	Polydora websteri	1.6	0.0	0.0	0.0	0.0	0.3	0.00%	74.13%	0.54
Annelida	Polychaeta	Order Not Assigned	Capitellidae	Capitellides jonesi	1.6	0.0	0.0	0.0	0.0	0.3	0.00%	74.13%	0.54
Crustacea	Malacostraca	Amphipoda	Bateidae	Batea catharinensis	1.6	0.0	0.0	0.0	0.0	0.3	0.00%	74.14%	0.54
Mollusca	Bivalvia	Mytiloida	Mytilidae	Ischadium recurvum	1.6	0.0	0.0	0.0	0.0	0.3	0.00%	74.14%	0.54
Annelida	Polychaeta	Order Not Assigned	Capitellidae	Notomastus latericeus	1.6	0.0	0.0	3.2	15.9	4.2	0.05%	74.19%	0.06
Crustacea	Ostracoda	Myodocopida	Sarsiellidae	Eusarsiella texana	1.6	0.0	0.0	7.4	1.1	2.0	0.02%	74.21%	0.13
Mollusca	Gastropoda	Heterostropha	Acteonidae	Rictaxis punctostriatus	1.6	0.0	1.1	1.1	0.0	0.8	0.01%	74.22%	1.68
Annelida	Polychaeta	Order Not Assigned	Orbiniidae	Haploscoloplos sp.	1.6	0.0	1.1	2.1	0.0	1.0	0.01%	74.23%	0.84
Crustacea	Copepoda	Calanoida	Diaptomidae	Pseudodiaptomus pelagicus	1.6	0.0	5.3	9.6	10.6	5.4	0.06%	74.29%	0.23
Annelida	Polychaeta	Errantia	Goniadidae	Glycinde nordmanni	1.6	0.0	8.5	3.2	0.0	2.7	0.03%	74.33%	2.12
Mollusca	Bivalvia	Veneroida	Lasaeidae	Aligena texasiana	1.6	6.8	0.0	42.5	3.2	10.8	0.13%	74.45%	0.12
Annelida	Polychaeta	Canalipalpata	Cirratulidae	Tharyx setigera	1.6	10.1	2.1	283.6	17.0	62.9	0.73%	75.18%	0.03
Mollusca	Bivalvia	Pholadomyoida	Lyonsiidae	Lyonsia hyalina floridana	1.6	13.5	1.1	3.2	1.1	4.1	0.05%	75.23%	2.54
Annelida	Polychaeta	Canalipalpata	Ampharetidae	Melinna maculata	1.6	3.4	4.2	17.0	7.4	6.7	0.08%	75.31%	0.25
Platyhelminthes	Turbellaria	Turbellaria	Turbellaria	Turbellaria (unidentified)	1.6	3.4	6.4	27.6	29.7	13.8	0.16%	75.46%	0.13
Annelida	Polychaeta	Canalipalpata	Spionidae	Scolelepis squamata	1.6	0.0	0.0	0.0	0.0	0.3	0.00%	75.47%	0.54
Crustacea	Malacostraca	Decapoda (Reptantia)	Callianassidae	Callianassa sp.	1.5	0.0	0.0	0.0	1.1	0.5	0.01%	75.47%	0.92
Mollusca	Gastropoda	Heterostropha	Pyramidellidae	Fargoa cf. gibbosa	1.3	0.0	0.0	0.0	0.0	0.3	0.00%	75.48%	0.44
Annelida	Polychaeta	Errantia	Pilargidae	Ancistrosyllis jonesi	1.3	0.0	0.0	1.1	17.0	3.9	0.04%	75.52%	0.05
Crustacea	Malacostraca	Isopoda	Anthuridae	Xenanthura brevitelson	0.8	0.0	0.0	0.0	0.0	0.2	0.00%	75.52%	0.27
Mollusca	Gastropoda	Neotaeniogloassa	Assimineidae	Assiminea succinea	0.8	0.0	0.0	0.0	0.0	0.2	0.00%	75.53%	0.27
Insecta	Pterygota	Ephemeroptera	Potamanthidae	Potamanthidae (unidentified)	0.8	0.0	0.0	0.0	0.0	0.2	0.00%	75.53%	0.27
Insecta	Pterygota	Diptera	Diptera	Diptera (unidentified)	0.8	0.0	0.0	0.0	0.0	0.2	0.00%	75.53%	0.27
Mollusca	Gastropoda	Neogastropoda	Columbellidae	Mitrella lunata	0.8	0.0	0.0	1.1	0.0	0.4	0.00%	75.53%	0.51
Annelida	Polychaeta	Errantia	Dorvilleidae	Schistomeringos rudolphi	0.8	0.0	0.0	1.1	10.6	2.5	0.03%	75.56%	0.05
Mollusca	Gastropoda	Neotaeniogloassa	Caecidae	Caecum johnsoni	0.8	0.0	0.0	14.9	5.3	4.2	0.05%	75.61%	0.03
Annelida	Polychaeta	Order Not Assigned	Maldanidae	Axiothella sp. A	0.8	0.0	0.0	32.9	2.1	7.2	0.08%	75.69%	0.02
Annelida	Polychaeta	Order Not Assigned	Maldanidae	Asychis sp.	0.8	0.0	0.0	34.0	0.0	7.0	0.08%	75.78%	0.02
Mollusca	Bivalvia	Mytiloida	Mytilidae	Brachidontes exustus	0.8	0.0	1.1	0.0	0.0	0.4	0.00%	75.78%	0.62
Crustacea	Malacostraca	Decapoda (Reptantia)		Megalopa larvae	0.8	0.0	1.1	1.1	4.2	1.4	0.02%	75.80%	0.23
Annelida	Polychaeta	Order Not Assigned	Maldanidae	Sabaco elongatus	0.8	0.0	2.1	80.7	15.9	19.9	0.23%	76.03%	0.02

Phylum	Class	Order	Family	Species	A	FD	B	C	D	Mean	Pct	CumPct	LB>MB
Crustacea	Malacostraca	Amphipoda	Liljeborgiidae	Listriella barnardi	0.8	3.4	1.1	13.8	56.3	15.1	0.17%	76.20%	0.05
Mollusca	Bivalvia	Pholadomyoida	Pandoridae	Pandora trilineata	0.8	3.4	3.2	10.6	2.1	4.0	0.05%	76.25%	0.39
Crustacea	Malacostraca	Tanaidacea	Tanaidae	Leptochelia rapax	0.8	10.1	0.0	0.0	0.0	2.2	0.03%	76.27%	3.65
Crustacea	Malacostraca	Amphipoda	Corophiidae	Grandidierella bonnieroides	0.8	20.3	0.0	0.0	0.0	4.2	0.05%	76.32%	7.02
Crustacea	Malacostraca	Decapoda (Natantia)	Ogyrididae	Ogyrides alphaerostris	0.8	0.0	5.3	3.2	6.4	3.1	0.04%	76.36%	0.43
Crustacea	Malacostraca	Amphipoda	Gammaridae	Gammarus mucronatus	0.8	0.0	0.0	0.0	0.0	0.2	0.00%	76.36%	0.27
Annelida	Polychaeta	Errantia	Phyllodocidae	Phyllodocidae (unidentified)	0.8	0.0	0.0	0.0	0.0	0.2	0.00%	76.36%	0.27
Annelida	Polychaeta	Errantia	Phyllodocidae	Phyllodoce erythrophyllus	0.8	0.0	0.0	4.2	2.1	1.4	0.02%	76.38%	0.08
Mollusca	Gastropoda	Gastropoda	Gastropoda	Gastropoda (unidentified)	0.8	0.0	1.1	2.1	0.0	0.8	0.01%	76.39%	0.59
Mollusca	Bivalvia	Veneroida	Lasaeidae	Lepton sp.	0.8	0.0	2.1	10.6	410.0	84.7	0.98%	77.37%	0.00
Crustacea	Malacostraca	Amphipoda	Caprellidae	Caprellidae (unidentified)	0.8	6.8	0.0	3.2	6.4	3.4	0.04%	77.41%	0.53
Mollusca	Bivalvia	Veneroida	Tellinidae	Tellina texana	0.0	0.0	0.0	0.0	1.1	0.2	0.00%	77.41%	0.00
Mollusca	Bivalvia	Veneroida	Veneridae	Mercenaria campechiensis	0.0	0.0	0.0	0.0	1.1	0.2	0.00%	77.41%	0.00
Mollusca	Bivalvia	Arcoida	Arcidae	Anadara ovalis	0.0	0.0	0.0	0.0	1.1	0.2	0.00%	77.42%	0.00
Sipuncula	Sipuncula	Sipuncula	Sipuncula	Sipuncula (unidentified)	0.0	0.0	0.0	0.0	1.1	0.2	0.00%	77.42%	0.00
Annelida	Polychaeta	Canalipalpata	Flabelligeridae	Brada cf. villosa capensis	0.0	0.0	0.0	0.0	1.1	0.2	0.00%	77.42%	0.00
Annelida	Polychaeta	Errantia	Pilargidae	Ancistrosyllis cf. falcata	0.0	0.0	0.0	0.0	1.1	0.2	0.00%	77.42%	0.00
Annelida	Polychaeta	Errantia	Nephtyidae	Nephtys picta	0.0	0.0	0.0	0.0	1.1	0.2	0.00%	77.43%	0.00
Annelida	Polychaeta	Errantia	Onuphidae	Onuphis sp.	0.0	0.0	0.0	0.0	1.1	0.2	0.00%	77.43%	0.00
Annelida	Polychaeta	Canalipalpata	Ampharetidae	Isolda pulchella	0.0	0.0	0.0	0.0	1.1	0.2	0.00%	77.43%	0.00
Mollusca	Bivalvia	Myoida	Pholadidae	Cyrtopleura costata	0.0	0.0	0.0	0.0	1.1	0.2	0.00%	77.43%	0.00
Mollusca	Bivalvia	Myoida	Pholadidae	Martesia sp.	0.0	0.0	0.0	0.0	1.1	0.2	0.00%	77.44%	0.00
Crustacea	Malacostraca	Decapoda (Natantia)	Alpheidae	Alpheus heterochaelis	0.0	0.0	0.0	0.0	1.1	0.2	0.00%	77.44%	0.00
Echiuridea	Echiuridea	Echiuridea	Echiuridea	Echiuridae (unidentified)	0.0	0.0	0.0	0.0	1.1	0.2	0.00%	77.44%	0.00
Annelida	Polychaeta	Errantia	Lumbrineridae	Scoletoma tenuis	0.0	0.0	0.0	0.0	1.1	0.2	0.00%	77.44%	0.00
Annelida	Polychaeta	Errantia	Glyceridae	Glycera capitata	0.0	0.0	0.0	0.0	1.1	0.2	0.00%	77.45%	0.00
Annelida	Polychaeta	Errantia	Lumbrineridae	Lumbrineridae (unidentified)	0.0	0.0	0.0	0.0	1.1	0.2	0.00%	77.45%	0.00

Phylum	Class	Order	Family	Species	A	FD	B	C	D	Mean	Pct	CumPct	LB>MB
Crustacea	Malacostraca	Amphipoda	Corophiidae	Monocorophium acherusicum	0.0	0.0	0.0	0.0	1.1	0.2	0.00%	77.45%	0.00
Crustacea	Malacostraca	Isopoda	Munnidae	Uromunna hayesi	0.0	0.0	0.0	0.0	1.1	0.2	0.00%	77.45%	0.00
Annelida	Polychaeta	Errantia	Syllidae	Syllis cornuta	0.0	0.0	0.0	0.0	1.1	0.2	0.00%	77.46%	0.00
Annelida	Polychaeta	Canalipalpata	Terebellidae	Loimia medusa	0.0	0.0	0.0	0.0	1.1	0.2	0.00%	77.46%	0.00
Annelida	Polychaeta	Errantia	Hesionidae	Hesione picta	0.0	0.0	0.0	0.0	1.1	0.2	0.00%	77.46%	0.00
Crustacea	Malacostraca	Isopoda	Munnidae	Munnidae (unidentified)	0.0	0.0	0.0	0.0	1.1	0.2	0.00%	77.46%	0.00
Annelida	Polychaeta	Errantia	Amphinomidae	Eurythoe sp.	0.0	0.0	0.0	0.0	1.1	0.2	0.00%	77.47%	0.00
Mollusca	Bivalvia	Veneroida	Veneridae	Agriopoma texasianum	0.0	0.0	0.0	0.0	1.1	0.2	0.00%	77.47%	0.00
Annelida	Polychaeta	Errantia	Polynoidae	Malmgreniella sp.	0.0	0.0	0.0	0.0	1.1	0.2	0.00%	77.47%	0.00
Annelida	Polychaeta	Errantia	Nephtyidae	Aglaophamus verrilli	0.0	0.0	0.0	0.0	2.1	0.4	0.00%	77.48%	0.00
Annelida	Polychaeta	Errantia	Polynoidae	Polynoidae (unidentified)	0.0	0.0	0.0	0.0	2.1	0.4	0.00%	77.48%	0.00
Echinodermata	Holothuroidea	Holothuroidea	Holothuroidea	Holothuroidea (unidentified)	0.0	0.0	0.0	0.0	2.1	0.4	0.00%	77.49%	0.00
Annelida	Polychaeta	Errantia	Sigalionidae	Sthenelais sp.	0.0	0.0	0.0	0.0	2.1	0.4	0.00%	77.49%	0.00
Mollusca	Bivalvia	Veneroida	Tellinidae	Macoma sp.	0.0	0.0	0.0	0.0	2.1	0.4	0.00%	77.49%	0.00
Mollusca	Bivalvia	Veneroida	Veneridae	Cyclinella tenuis	0.0	0.0	0.0	0.0	2.1	0.4	0.00%	77.50%	0.00
Echinodermata	Holothuroidea	Dendrochirotida	Phyllophoridae	Allothyone mexicana	0.0	0.0	0.0	0.0	2.1	0.4	0.00%	77.50%	0.00
Annelida	Polychaeta	Canalipalpata	Spionidae	Polydora sp.	0.0	0.0	0.0	0.0	3.2	0.6	0.01%	77.51%	0.00
Mollusca	Gastropoda	Neotaeniogloassa	Calyptraeidae	Crepidula fornicata	0.0	0.0	0.0	0.0	3.2	0.6	0.01%	77.52%	0.00
Crustacea	Malacostraca	Amphipoda	Corophiidae	Corophium sp.	0.0	0.0	0.0	0.0	3.2	0.6	0.01%	77.53%	0.00
Annelida	Polychaeta	Errantia	Amphinomidae	Linopherus sp.	0.0	0.0	0.0	0.0	3.2	0.6	0.01%	77.53%	0.00
Annelida	Polychaeta	Errantia	Sigalionidae	Sthenelais boa	0.0	0.0	0.0	0.0	4.2	0.9	0.01%	77.54%	0.00
Annelida	Polychaeta	Errantia	Lumbrineridae	Lumbrineris latreilli	0.0	0.0	0.0	0.0	4.2	0.9	0.01%	77.55%	0.00
Crustacea	Malacostraca	Amphipoda	Corophiidae	Erichthonias punctatus	0.0	0.0	0.0	0.0	4.2	0.9	0.01%	77.56%	0.00
Mollusca	Bivalvia	Myoida	Myidae	Paramya subovata	0.0	0.0	0.0	0.0	4.2	0.9	0.01%	77.57%	0.00
Mollusca	Bivalvia	Veneroida	Tellinidae	Macoma tenta	0.0	0.0	0.0	0.0	5.3	1.1	0.01%	77.59%	0.00
Mollusca	Bivalvia	Myoida	Hiatellidae	Hiatella arctica	0.0	0.0	0.0	0.0	5.3	1.1	0.01%	77.60%	0.00
Annelida	Polychaeta	Errantia	Lumbrineridae	Ninoe nigripes	0.0	0.0	0.0	0.0	5.3	1.1	0.01%	77.61%	0.00
Annelida	Polychaeta	Errantia	Polynoidae	Eunoe cf. nodulosa	0.0	0.0	0.0	0.0	18.1	3.6	0.04%	77.65%	0.00
Mollusca	Bivalvia	Veneroida	Semelidae	Abra aequalis	0.0	0.0	0.0	0.0	31.9	6.4	0.07%	77.73%	0.00
Mollusca	Bivalvia	Myoida	Corbulidae	Corbula contracta	0.0	0.0	0.0	0.0	509.9	102.0	1.18%	78.91%	0.00
Crustacea	Malacostraca	Decapoda (Reptantia)	Portunidae	Callinectes similis	0.0	0.0	0.0	1.1	0.0	0.2	0.00%	78.91%	0.00
Annelida	Polychaeta	Order Not Assigned	Paraonidae	Aricidea taylori	0.0	0.0	0.0	1.1	0.0	0.2	0.00%	78.91%	0.00
Crustacea	Malacostraca	Decapoda (Reptantia)	Xanthidae	Xanthidae (unidentified)	0.0	0.0	0.0	1.1	0.0	0.2	0.00%	78.92%	0.00
Mollusca	Bivalvia	Veneroida	Tellinidae	Tellidora cristata	0.0	0.0	0.0	1.1	0.0	0.2	0.00%	78.92%	0.00

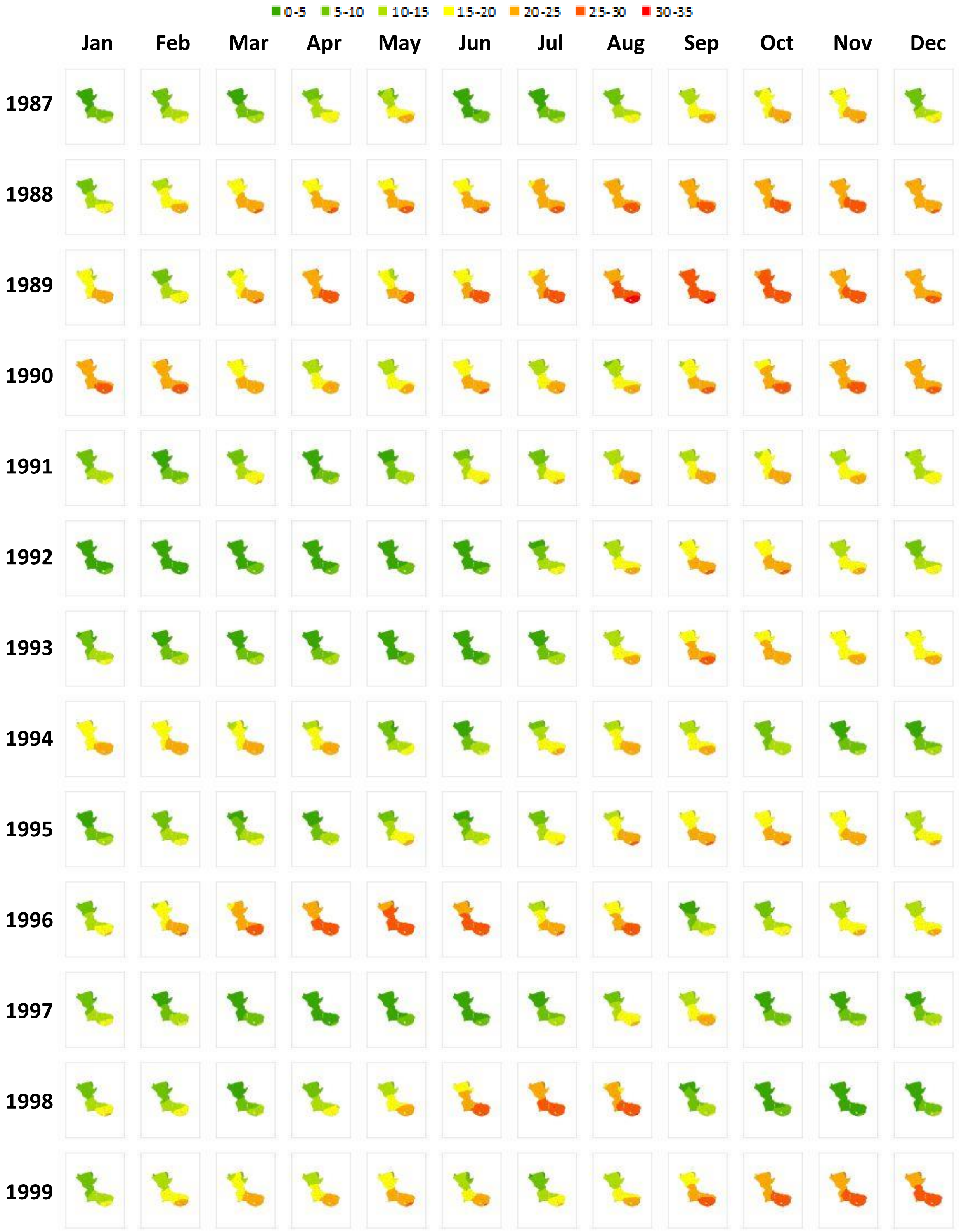
Phylum	Class	Order	Family	Species	A	FD	B	C	D	Mean	Pct	CumPct	LB>MB
Crustacea	Malacostraca	Amphipoda	Amphilochidae	Amphilochus sp.	0.0	0.0	0.0	1.1	0.0	0.2	0.00%	78.92%	0.00
Mollusca	Gastropoda	Cephalaspidea	Bullidae	Bulla striata	0.0	0.0	0.0	1.1	0.0	0.2	0.00%	78.92%	0.00
Annelida	Polychaeta	Errantia	Goniadidae	Goniadidae (unidentified)	0.0	0.0	0.0	1.1	0.0	0.2	0.00%	78.92%	0.00
Annelida	Polychaeta	Canalipalpata	Ampharetidae	Ampharetidae (unidentified)	0.0	0.0	0.0	1.1	0.0	0.2	0.00%	78.93%	0.00
Crustacea	Ostracoda	Myodocopida	Sarsiellidae	Sarsiella disparalis	0.0	0.0	0.0	1.1	0.0	0.2	0.00%	78.93%	0.00
Crustacea	Ostracoda	Myodocopida	Sarsiellidae	Eusarsiella zostericola	0.0	0.0	0.0	1.1	0.0	0.2	0.00%	78.93%	0.00
Annelida	Polychaeta	Canalipalpata	Serpulidae	Hydroides protulicola	0.0	0.0	0.0	1.1	0.0	0.2	0.00%	78.93%	0.00
Annelida	Polychaeta	Errantia	Amphinomidae	Paramphinome pulchella	0.0	0.0	0.0	1.1	0.0	0.2	0.00%	78.94%	0.00
Annelida	Polychaeta	Errantia	Syllidae	Sphaerosyllis cf. sublaevis	0.0	0.0	0.0	1.1	1.1	0.4	0.00%	78.94%	0.00
Annelida	Polychaeta	Errantia	Phyllodocidae	Paranaitis speciosa	0.0	0.0	0.0	1.1	1.1	0.4	0.00%	78.95%	0.00
Crustacea	Malacostraca	Cumacea	Diastylidae	Diastylis sp.	0.0	0.0	0.0	1.1	1.1	0.4	0.00%	78.95%	0.00
Mollusca	Scaphopoda	Dentaliida	Dentaliidae	Dentalium texasianum	0.0	0.0	0.0	1.1	2.1	0.6	0.01%	78.96%	0.00
Crustacea	Malacostraca	Amphipoda	Amphipoda	Amphipoda (unidentified)	0.0	0.0	0.0	1.1	2.1	0.6	0.01%	78.97%	0.00
Crustacea	Malacostraca	Decapoda (Natantia)	Penaeidae	Trachypenaeus constrictus	0.0	0.0	0.0	1.1	2.1	0.6	0.01%	78.97%	0.00
Crustacea	Malacostraca	Decapoda (Reptantia)	Pinnotheridae	Pinnotheridae (unidentified)	0.0	0.0	0.0	1.1	2.1	0.6	0.01%	78.98%	0.00
Crustacea	Malacostraca	Decapoda (Reptantia)	Paguridae	Pagurus annulipes	0.0	0.0	0.0	1.1	3.2	0.9	0.01%	78.99%	0.00
Crustacea	Malacostraca	Amphipoda	Ampeliscidae	Ampelisca sp. B	0.0	0.0	0.0	1.1	10.6	2.3	0.03%	79.02%	0.00
Annelida	Polychaeta	Order Not Assigned	Opheliidae	Armandia maculata	0.0	0.0	0.0	1.1	27.6	5.7	0.07%	79.08%	0.00
Annelida	Polychaeta	Canalipalpata	Spionidae	Prionospio pygmaeus	0.0	0.0	0.0	2.1	0.0	0.4	0.00%	79.09%	0.00
Annelida	Polychaeta	Canalipalpata	Sabellidae	Parasabella microphthalma	0.0	0.0	0.0	2.1	0.0	0.4	0.00%	79.09%	0.00
Crustacea	Malacostraca	Amphipoda	Corophiidae	Photis sp.	0.0	0.0	0.0	2.1	0.0	0.4	0.00%	79.10%	0.00
Crustacea	Malacostraca	Decapoda (Reptantia)	Paguridae	Paguridae (juvenile)	0.0	0.0	0.0	2.1	0.0	0.4	0.00%	79.10%	0.00
Crustacea	Malacostraca	Decapoda (Reptantia)	Pinnotheridae	Austinixa cristata	0.0	0.0	0.0	2.1	0.0	0.4	0.00%	79.11%	0.00
Crustacea	Malacostraca	Decapoda (Reptantia)	Pinnotheridae	Pinnixa rectinens	0.0	0.0	0.0	2.1	0.0	0.4	0.00%	79.11%	0.00
Annelida	Polychaeta	Errantia	Amphinomidae	Paramphinome jeffreysii	0.0	0.0	0.0	2.1	0.0	0.4	0.00%	79.12%	0.00
Annelida	Polychaeta	Errantia	Dorvilleidae	Dorvilleidae (unidentified)	0.0	0.0	0.0	2.1	0.0	0.4	0.00%	79.12%	0.00
Annelida	Polychaeta	Canalipalpata	Oweniidae	Owenia fusiformis	0.0	0.0	0.0	2.1	1.1	0.6	0.01%	79.13%	0.00
Crustacea	Ostracoda	Myodocopida	Sarsiellidae	Eusarsiella spinosa	0.0	0.0	0.0	2.1	2.1	0.9	0.01%	79.14%	0.00

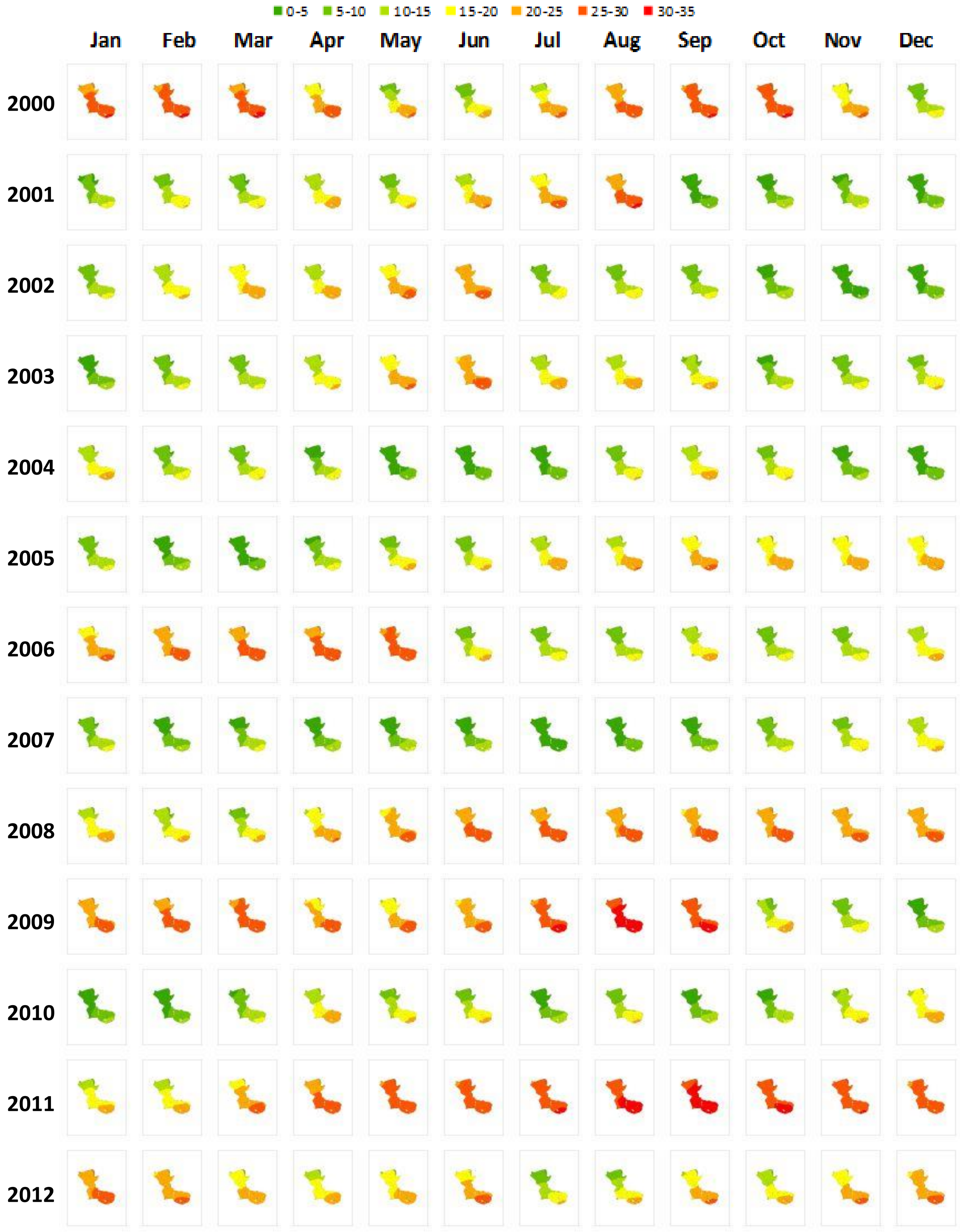
Phylum	Class	Order	Family	Species	A	FD	B	C	D	Mean	Pct	CumPct	LB>MB
Annelida	Polychaeta	Canalipalpata	Terebellidae	Terebellidae (unidentified)	0.0	0.0	0.0	2.1	5.3	1.5	0.02%	79.16%	0.00
Annelida	Polychaeta	Errantia	Hesionidae	Oxydromus obscurus	0.0	0.0	0.0	2.1	6.4	1.7	0.02%	79.18%	0.00
Crustacea	Malacostraca	Tanaidacea	Apseudidae	Apseudes sp. A	0.0	0.0	0.0	2.1	3,831.6	766.8	8.88%	88.06%	0.00
Annelida	Polychaeta	Errantia	Syllidae	Erinaceusyllis erinaceus	0.0	0.0	0.0	3.2	1.1	0.9	0.01%	88.07%	0.00
Annelida	Polychaeta	Order Not Assigned	Capitellidae	Notomastus cf. latericeus	0.0	0.0	0.0	3.2	6.4	1.9	0.02%	88.09%	0.00
Crustacea	Malacostraca	Amphipoda	Liljeborgiidae	Listriella clymenellae	0.0	0.0	0.0	3.2	0.0	0.6	0.01%	88.10%	0.00
Annelida	Polychaeta	Errantia	Pilargidae	Cabira incerta	0.0	0.0	0.0	3.2	0.0	0.6	0.01%	88.11%	0.00
Annelida	Polychaeta	Errantia	Amphinomidae	Amphinomidae (unidentified)	0.0	0.0	0.0	3.2	0.0	0.6	0.01%	88.12%	0.00
Crustacea	Malacostraca	Amphipoda	Liljeborgiidae	Listriella sp.	0.0	0.0	0.0	3.2	0.0	0.6	0.01%	88.12%	0.00
Crustacea	Malacostraca	Decapoda (Reptantia)	Pinnotheridae	Pinnixa sp.	0.0	0.0	0.0	3.2	26.6	6.0	0.07%	88.19%	0.00
Annelida	Polychaeta	Canalipalpata	Spionidae	Spionidae (unidentified)	0.0	0.0	0.0	4.2	40.4	8.9	0.10%	88.30%	0.00
Crustacea	Malacostraca	Decapoda (Reptantia)	Pinnotheridae	Austinixa chacei	0.0	0.0	0.0	4.2	17.0	4.3	0.05%	88.35%	0.00
Crustacea	Malacostraca	Amphipoda	Ampeliscidae	Ampelisca verrilli	0.0	0.0	0.0	4.2	0.0	0.9	0.01%	88.36%	0.00
Annelida	Polychaeta	Canalipalpata	Magelonidae	Magelona pettiboneae	0.0	0.0	0.0	4.2	2.1	1.3	0.01%	88.37%	0.00
Annelida	Polychaeta	Errantia	Pilargidae	Pilargiidae (unidentified)	0.0	0.0	0.0	4.2	3.2	1.5	0.02%	88.39%	0.00
Annelida	Polychaeta	Order Not Assigned	Orbiniidae	Naineris laevigata	0.0	0.0	0.0	4.2	134.9	27.8	0.32%	88.71%	0.00
Annelida	Polychaeta	Canalipalpata	Magelonidae	Magelona rosea	0.0	0.0	0.0	6.4	0.0	1.3	0.01%	88.72%	0.00
Annelida	Polychaeta	Order Not Assigned	Maldanidae	Euclymene sp. B	0.0	0.0	0.0	6.4	0.0	1.3	0.01%	88.74%	0.00
Annelida	Polychaeta	Errantia	Pilargidae	Ancistrosyllis papillosa	0.0	0.0	0.0	6.4	3.2	1.9	0.02%	88.76%	0.00
Annelida	Polychaeta	Errantia	Pilargidae	Ancistrosyllis groenlandica	0.0	0.0	0.0	6.4	10.6	3.4	0.04%	88.80%	0.00
Annelida	Polychaeta	Errantia	Syllidae	Syllidae (unidentified)	0.0	0.0	0.0	7.4	1.1	1.7	0.02%	88.82%	0.00
Annelida	Polychaeta	Errantia	Nereididae	Ceratonereis irritabilis	0.0	0.0	0.0	7.4	0.0	1.5	0.02%	88.84%	0.00
Annelida	Polychaeta	Order Not Assigned	Paraonidae	Aricidea fragilis	0.0	0.0	0.0	7.4	0.0	1.5	0.02%	88.86%	0.00
Annelida	Polychaeta	Canalipalpata	Magelonidae	Magelona phyllisae	0.0	0.0	0.0	7.4	5.3	2.6	0.03%	88.88%	0.00
Annelida	Polychaeta	Errantia	Sigalionidae	Sigalionidae (unidentified)	0.0	0.0	0.0	7.4	8.5	3.2	0.04%	88.92%	0.00
Annelida	Polychaeta	Errantia	Dorvilleidae	Schistomeringos sp. A	0.0	0.0	0.0	7.4	8.5	3.2	0.04%	88.96%	0.00
Crustacea	Malacostraca	Mysida	Mysida	Americamysis bigelowi	0.0	0.0	0.0	8.5	0.0	1.7	0.02%	88.98%	0.00
Annelida	Polychaeta	Canalipalpata	Terebellidae	Amaeana trilobata	0.0	0.0	0.0	9.6	5.3	3.0	0.03%	89.01%	0.00
Crustacea	Malacostraca	Cumacea	Diastylidae	Oxyurostylis salinoi	0.0	0.0	0.0	17.0	0.0	3.4	0.04%	89.05%	0.00
Sipuncula	Sipunculidea	Golfingiida	Phascolionidae	Phascolion strombus	0.0	0.0	0.0	18.1	34.0	10.4	0.12%	89.17%	0.00
Annelida	Polychaeta	Errantia	Polynoidae	Malmgreniella taylori	0.0	0.0	0.0	20.2	31.9	10.4	0.12%	89.29%	0.00

Phylum	Class	Order	Family	Species	A	FD	B	C	D	Mean	Pct	CumPct	LB>MB
Annelida	Polychaeta	Errantia	Chrysopetalidae	Paleanotus heteroseta	0.0	0.0	0.0	22.3	82.9	21.0	0.24%	89.54%	0.00
Mollusca	Bivalvia	Pholadomyoida	Periplomatidae	Periploma cf. orbiculare	0.0	0.0	0.0	36.1	335.7	74.4	0.86%	90.40%	0.00
Annelida	Polychaeta	Order Not Assigned	Paraonidae	Paraonidae Grp. A	0.0	0.0	0.0	48.9	4.2	10.6	0.12%	90.52%	0.00
Annelida	Polychaeta	Errantia	Syllidae	Salvatoria clavata	0.0	0.0	0.0	56.3	1.1	11.5	0.13%	90.65%	0.00
Annelida	Polychaeta	Order Not Assigned	Paraonidae	Aricidea (Acmira) catharinae	0.0	0.0	0.0	66.9	3.2	14.0	0.16%	90.82%	0.00
Annelida	Polychaeta	Canalipalpata	Sabellidae	Sabellidae (unidentified)	0.0	0.0	0.0	71.2	2.1	14.7	0.17%	90.99%	0.00
Annelida	Polychaeta	Canalipalpata	Spionidae	Minuspio cirrifera	0.0	0.0	0.0	95.6	690.5	157.2	1.82%	92.81%	0.00
Annelida	Polychaeta	Order Not Assigned	Paraonidae	Aricidea bryani	0.0	0.0	0.0	95.6	5.3	20.2	0.23%	93.04%	0.00
Annelida	Polychaeta	Order Not Assigned	Paraonidae	Paradoneis lyra	0.0	0.0	0.0	106.2	36.1	28.5	0.33%	93.37%	0.00
Echinodermata	Ophiuroidea	Ophiurida	Amphiuridae	Microphiopholis atra	0.0	0.0	0.0	111.5	294.3	81.2	0.94%	94.31%	0.00
Annelida	Polychaeta	Errantia	Lumbrineridae	Lumbrineris parvapedata	0.0	0.0	0.0	114.7	42.5	31.4	0.36%	94.68%	0.00
Annelida	Polychaeta	Order Not Assigned	Paraonidae	Paraonidae Grp. B	0.0	0.0	0.0	200.8	88.2	57.8	0.67%	95.35%	0.00
Annelida	Polychaeta	Canalipalpata	Spionidae	Dipolydora caulleryi	0.0	0.0	0.0	397.3	640.6	207.6	2.41%	97.75%	0.00
Hemichordata	Enteropneusta	Enteropneusta [unassigned]	Spengelidae	Schizocardium sp.	0.0	0.0	1.1	88.2	124.3	42.7	0.49%	98.25%	0.00
Mollusca	Bivalvia	Ostreoida	Ostreidae	Crassostrea virginica	0.0	0.0	1.1	0.0	0.0	0.2	0.00%	98.25%	0.35
Annelida	Polychaeta	Order Not Assigned	Capitellidae	Capitellidae (unidentified)	0.0	0.0	1.1	2.1	1.1	0.9	0.01%	98.26%	0.22
Mollusca	Gastropoda	Neotaeniogloassa	Naticidae	Polinices duplicatus	0.0	0.0	1.1	3.2	0.0	0.9	0.01%	98.27%	0.22
Annelida	Polychaeta	Errantia	Glyceridae	Glycera americana	0.0	0.0	1.1	8.5	15.9	5.1	0.06%	98.33%	0.03
Annelida	Polychaeta	Errantia	Oenonidae	Drilonereis magna	0.0	0.0	1.1	172.1	26.6	39.9	0.46%	98.79%	0.00
Annelida	Polychaeta	Polychaeta	Polychaeta	Polychaeta juv. (unidentified)	0.0	0.0	2.1	3.2	8.5	2.8	0.03%	98.82%	0.12
Mollusca	Gastropoda	Neogastropoda	Nassariidae	Nassarius vibex	0.0	0.0	2.1	0.0	3.2	1.1	0.01%	98.84%	0.44
Annelida	Polychaeta	Errantia	Pilargidae	Sigambra cf. wassi	0.0	0.0	2.1	0.0	4.2	1.3	0.01%	98.85%	0.33
Mollusca	Gastropoda	Heterostropha	Pyramidellidae	Turbonilla sp.	0.0	0.0	3.2	36.1	3.2	8.5	0.10%	98.95%	0.05
Crustacea	Malacostraca	Cumacea	Leuconidae	Eudorella sp.	0.0	0.0	8.5	15.9	28.7	10.6	0.12%	99.07%	0.13
Annelida	Polychaeta	Order Not Assigned	Maldanidae	Maldanidae (unidentified)	0.0	0.0	9.6	61.6	15.9	17.4	0.20%	99.27%	0.08
Phoronida	Phoronida	Phoronida	Phoronidae	Phoronis architecta	0.0	0.0	10.6	5.3	20.2	7.2	0.08%	99.36%	0.28
Annelida	Polychaeta	Canalipalpata	Spionidae	Spiophanes bombyx	0.0	3.4	0.0	0.0	0.0	0.7	0.01%	99.37%	1.13
Annelida	Hirudinea	Hirudinea	Hirudinea	Hirudinea (unidentified)	0.0	3.4	0.0	0.0	0.0	0.7	0.01%	99.37%	1.13
Crustacea	Malacostraca	Decapoda (Reptantia)	Callianassidae	Lepidophthalamus louisianensis	0.0	3.4	0.0	0.0	0.0	0.7	0.01%	99.38%	1.13
Annelida	Polychaeta	Order Not Assigned	Orbiniidae	Scoloplos texana	0.0	3.4	0.0	1.1	0.0	0.9	0.01%	99.39%	2.12

Phylum	Class	Order	Family	Species	A	FD	B	C	D	Mean	Pct	CumPct	LB>MB
Crustacea	Malacostraca	Decapoda (Reptantia)	Xanthidae	Rithropanopeus harrisii	0.0	6.8	0.0	0.0	0.0	1.4	0.02%	99.41%	2.25
Mollusca	Bivalvia	Pholadomyoida	Periplomatidae	Periploma margaritaceum	0.0	6.8	0.0	32.9	54.2	18.8	0.22%	99.62%	0.05
Crustacea	Malacostraca	Cumacea	Diastylidae	Oxyurostylis sp.	0.0	6.8	1.1	22.3	13.8	8.8	0.10%	99.73%	0.14
Annelida	Polychaeta	Errantia	Hesionidae	Microphthalmus aberrans	0.0	10.1	0.0	0.0	0.0	2.0	0.02%	99.75%	3.38
Mollusca	Bivalvia	Mytiloida	Mytilidae	Amygdalum papyrium	0.0	10.1	0.0	0.0	0.0	2.0	0.02%	99.77%	3.38
Mollusca	Bivalvia	Veneroida	Solenidae	Solen viridis	0.0	10.1	0.0	0.0	0.0	2.0	0.02%	99.80%	3.38
Annelida	Polychaeta	Canalipalpata	Terebellidae	Pista palmata	0.0	13.5	0.0	3.2	0.0	3.3	0.04%	99.84%	2.83
Annelida	Polychaeta	Canalipalpata	Sabellidae	Megalomma bioculatum	0.0	13.5	1.1	5.3	3.2	4.6	0.05%	99.89%	1.14
Crustacea	Malacostraca	Amphipoda	Corophiidae	Cerapus tubularis	0.0	16.9	0.0	0.0	0.0	3.4	0.04%	99.93%	5.63
Chordata	Tunicata	Ascidiacea	Ascidiidae	Molgula manhattensis	0.0	23.6	0.0	7.4	0.0	6.2	0.07%	100.00%	2.12

Appendix 2. Salinity distribution maps for the period 1987 to 2016. Average salinity at each node over each month.

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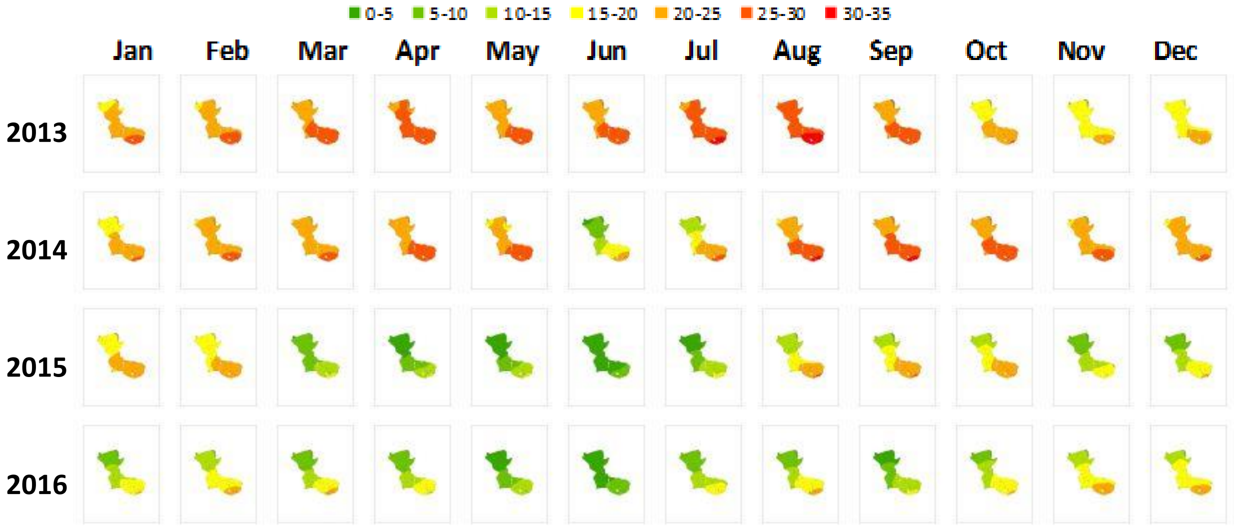
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12. TWDB Review Comments

Below is the TWDB review with a response to the review comments following directly below the comments. The response is the *italic* font.

Assessment of the Relationship Between Freshwater Inflow and Biological Indicators in Lavaca Bay

Paul A. Montagna, Ph.D., Patricia M. Cockett, M.S., Elaine M. Kurr, M.S., and Joe Trungale

Contract #1800012268
TWDB Comments to Draft Final Report

REQUIRED CHANGES

General Draft Final Report Comments:

1. Although the report is a comprehensive compendium of analysis of many datasets to understand freshwater inflow relationships, this specific contract scope of work emphasized the analysis of the Formosa dataset. Please clearly mark in the discussion section, using section headings, etc., what findings are the result of the Formosa dataset to aid the reader in locating those areas of the report. Also, please include in the executive summary what specific results were gained by including the Formosa data merged with the other datasets. As a presentation to the stakeholder groups is also planned for this project, the contractor is similarly requested to emphasize the knowledge gained from the Formosa dataset specifically.

   As mentioned in the quarterly reports the Formosa dataset was delivered as 1,223 files (most in different formats). While we have been working on collating this dataset into one analyzable file, there is still much work to be done to analyze it fully. In addition, simple quality control checks (such as undefined parameter codes, values outside possible ranges, missing data, and inability to reproduce results in the annual reports) have uncovered many problems with the dataset and it will take a major effort beyond the scope of the study to perform this data management. Nevertheless, the main reason for analyzing the Formosa data was to determine if there were confounding toxicity issues.

So, the focus has been on the contaminant data, which has now been analyzed and added to the results as a new section 8.5.

A new paragraph has been added to the Executive Summary describing results, and a new section 9.2 is added to the discussion.

2. It is hard to read text in some of the figures so please improve the resolution of those figures including font size of the text where feasible.

   Done. Many of these are called out below, so further details are listed below.

<u>Required Specific Comments:</u>

1. **Section 4.0, Executive Summary**, page 7, 2nd paragraph: 21.6 and 25.3 psu does not appear to be low. Consider editing the summary text to better describe saline conditions.

   Now says "…low or moderate salinity conditions…"

2. **Section 6.2.3**, Physical and Chemical Data (Conditions): Please provide some information on the QA/QC processes among the databases. In particular, please provide information on sampling methods, lab analyses, detection limits, outliers, normality tests and so on.

   For each data group, a description of the methodologies and a citation to the authorities is provided. While this was impossible for the TCEQ data because it is derived of multiple sources, all of the data must have been associated with a QAPP or it would not be in the database.

3. **Section 6.3.1.1**, Salinity Habitat, Page 23, first sentence: Please clarify that a mathematical model was used to identify the preferred salinity ranges for habitats or for something else.

   The first two sentences now read: "Habitats are defined here as zones with preferred salinity ranges. . A mathematical modeling technique was used to identify preferred average salinity ranges."

4. **Section 6.3.6**, Linking Inflow Events and Communities, page 27, first paragraph, first sentence: Please justify the use of Spearman rank correlation.

   Two sentence added: "Spearman's is a nonparametric measure of rank correlation (statistical dependence between the rankings of two variables). The Spearman correlation between two variables is equal to the Pearson correlation between the rank *values of those two variables; while Pearson's correlation assesses linear relationships, Spearman's correlation assesses monotonic relationships (whether linear or not)."*

5. **Section 7.1.1**, Benthic Groups Sensitive to Salinity, page 29, last sentence: Please provide more discussion to substantiate this conclusion: "Thus, different community structure between the bays is driven by salinity." In other words, while the salinities are different in the bays, please describe how that leads to different community structures.

   That sentence was a conclusion that belongs in the discussion section, not a results section. Sentence now says: "Thus, different community structure between the bays is correlated to the different salinities in the two bays because temperature and dissolved oxygen is more similar in the two bays."

6. **Section 7.1.1**, Benthic Groups Sensitive to Salinity, page 30, last sentence: Please provide more discussion to justify the selection of "4 times". Please discuss how the results might change if this number changes to 2 or 10.

   A unviariate distributional analysis was performed on the ratio, included the top 10% of species (a total of 26) and describe the percentile ranges. The new paragraph now says: "The species that are relatively exclusive to Lavaca Bay are freshwater inflow indicator species. When the number of species in Lavaca Bay is divided by the number in Matagorda Bay, there are 208 species with a ratio < 1, which means that they occur mostly in Matagorda Bay. A total of 47 species have a ratio > 1, meaning they occur mostly in Lavaca Bay. Three species (99th percentile) had ratios > 19.3, 10 species (95th percentile) had ratios between 18.8 and 7.0), and 13 species (90th percentile) had ratios between 6.7 and 3.0 (Appendix 1). So, a total of 26 species make up the top 90th percentile of species preferring Lavaca Bay and represent the freshwater inflow indicator species (Table 4)."

7. **Section 7.1.1**, Benthic Groups Sensitive to Salinity, page 33, last sentence: Please provide more discussion on this statement. For example, for the entire range of salinity, there is not much difference in the population and some values repeat over the range of salinity. Please discuss whether this is this related to detection limits.

   A new paragraph has been added prior to Table 5, which says: "The MaxBin analysis estimates three parameters: the maximum abundance (a), the initial rate of increase (b), and the salinity where the peak abundance occurs (c) (Table 5). Four of the species had salinity peaks between 8 and 13 psu. The detection limit is zero when there are no individuals found in three replicate cores, and 94.5 individuals/m^2 when there is one individual among the three cores (Figure 10 - Figure 16)."

   Also, this requires that more details are added to the first paragraph of the methods section 7.3.4 to describe how each replicate is multiplied by 283.64 to scale to n/m^2.

8. **Section 7.1.1**, Benthic Groups Sensitive to Salinity, page 34, last sentence: Please discuss whether one peak could potentially dictate the fitted curve. It is important to

address potential limitations or caveats of the applied methodologies. Please also provide some evaluation metrics for the MaxBin method.

The p-value for the regression model and R^2 is added for each species graph, Figures 9-15.

SUGGESTED CHANGES

General Draft Final Report Comments:

1. Please include a list of acronyms used throughout the report.

   Done. This is added after the list of tables and all section numbers are incremented by +1.

2. Consider providing a bathymetry map of Matagorda Bay, or the reference to locate the best available bathymetry work. If no bathymetry, or limited bathymetry is available for Matagorda Bay, that information would be valuable in the report for adaptive management.

   Done. Bathymetry is overlaid on Figure 5 (old 4).

3. Consider moving section 8.1 into either introduction or methodology and starting discussion with section 8.2 as this is where the discussion of the results begin.

   Done.

4. Consider providing more discussion of the results section. Please discuss the detection limits and outliers, and how they were treated.

   Done in new section 8.5.

5. Where possible with the analysis programs, please standardize font styles and sizes with the figures and tables used throughout the report. Additionally, many of the font sizes need to be increased for readability.

   Done.

Specific Draft Final Report Comments:

9. **Section 5.0, Introduction,** page 10, 1st sentence: The first sentence is lengthy. Please consider breaking this run-on sentence into multiple sentences. Additionally, capitalize 'state' as you are referring to the US State.

   Done.

10. **Section 5.2**, **Approach**, page 11, 3rd paragraph, 2nd sentence: Please change "A habitat is the defined as" to "A habitat is defined as".

    Done.

11. **Section 6.2.1**, Hydrology data (Inflow), page 14, last sentence: Please replace "Historical streamflows" with "Historical freshwater inflows".

    Done.

12. **Section 6.2.1**, Hydrology data (Inflow), page 15, 1st paragraph, last sentence: Please replace "Several discrepancies where identified" with "Several discrepancies were identified".

    Done.

13. **Section 6.3.5**, Event Identification, page 26, 2nd last paragraph, 2nd last sentence: Please clarify whether the dry, wet, and average conditions are defined by rainfall or flow.

    Now 7.4.5. The text now says: "… by wet, average, and dry conditions. In the past,we have defined these by quartiles, i.e., wet <25%, average is between 25 and 75%, and dry is >75% (Palmer and Montagna 2015). For the current study we will use the definition in the RFQ and define low flow as <20%, high is >75%, and average flow is between 20% and 75%."

14. **Section 6.3.5**, Event Identification, page 26, last paragraph, 2nd last sentence: Please describe very concisely what the "**detrended**" means.

    Now 7.4.5. Says: "Detrending is necessary to remove a long-term effect using linear regression to emphasize a short-term effect."

15. **Section 6.3.5**, Event Identification, page 26, last paragraph, last sentence: Please mention what the "eight hydrologic components" refer to in the sentence.

    Now 7.4.5. New last sentence says: "The nine components of hydrologic variance that vary from year-to-year are:

    10. *LSAM = low spectral anomaly magnitude*
    11. *HSAM = high spectral anomaly magnitude*
    12. *Transition time between LSAM and HSAM*
    13. *LSAF = low spectral anomaly frequency*
    14. *HSAF = high spectral anomaly frequency*
    15. *Timing for LSAM*
    16. *Timing for HSAM*
    17. *IFI =interflood interval*
    18. *IDI = interdrought interval"*

16. **Section 7.2,** Condition Identification, page 37, first paragraph: Please justify associating the PC axis with seasonal and production variables. Please provide more discussion to substantiate the conclusion that PC2 represents the seasonal effect.

    Done. Now 8.2 says: "The PC 2 axis represents a seasonal effect because it is well known that the solubility of oxygen increases with decreasing temperatures and it is cooler in winter than summer." Also, "PC 3 represents a primary production axis because high chlorophyll biomass is an indicator of productivity."

17. **Section 7.3.2**, Salinity versus flow, page 41, 2nd sentence: Please replace ".transect (Figure 21), was use in .." with "..transect (Figure 21), was used in ..".

    Done, now 8.3.2.

18. **Section 7.4.2,** Biological Responses, page 51, last paragraph, first sentence: If available, please provide some evaluation metrics on model performance.

    Done, now 8.4.2.

19. **Section 8**, **Discussion**, page 65, 2nd paragraph, 1st sentence: Please replace "This goal of the project is .." with "The goal of this project is ..".

    Done.

<u>Figures and Tables Comments</u>:

1. **Figure 4, page 16**: Please increase font size in the map. Please use a base map and provide a context map to show the location of the study area.

   Done, now Figure 17.

2. **Figure 5, page 17**: Please increase font size in the map. Please use a base map and provide a context map to show the location of the study area.

   Done, now Figure 18.

3. **Figure 7, page 21**: Please connect the boxes to the right locations for more clarity.

   Done, now Figure 22.

4. **Figure 19, page 40**: Please label the X-axis of Monthly Freshwater Inflow data as "Year or Date" instead of "Month" since there is only year labeled in the plot, and the Y-axis as "Acre-feet" only instead of using "ACFT/MON".

Done, now Figure 20.

5. **Figure 22, page 43**: Please add the unit for Salinity on the X-axis of the figure.

   Done, now Figure 23.

6. **Figure 23, page 44**: Please add the X-label as "Year" on the X-axis and remove (/YR) from (ACFT/YR) on Y-axis.

   Done, now Figure 24.

7. **Figure 23, page 44:** Please describe in the caption what the horizontal black line indicates in the figure.

   Done, now Figure 24.

8. **Figure 24, page 45**: Please improve the resolution of the figure and include X and Y-labels too.

   Done, now Figure 25.

9. **Figure 25, page 46**: It is very hard to see the scales, so please increase the font size in the Figure.

   Done, now Figure 26.

10. **Figure 28, page 49:** Please improve the resolution of the figure.

    Done, now Figure 29.

11. **Figure 32, page 56**: Please increase the size of the figure and font size. We are unable to read the labels. Consider increasing the size of the figure to full page or breaking into sub-figures.

    Done, now Figure 33.

12. **Table 4, page 31**: Please refer the points (A, FD,…) to the corresponding figures. Please provide a formula for LB/MB.

    Done.