Final Report

Sediment Quality Assessment Survey of Lavaca and Matagorda Bays

MBMT Contract 019

Contract Period: 01 February 2022 to 31 August 2024

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Abstract

The Matagorda Bay system has suffered a long-term decline in benthic abundance, biomass, and diversity since the 1980's. The purpose of this study was to examine sediment contamination to determine if pollution is a possible cause for ecosystem degradation. Degradation can be indicated by a decline in benthic integrity (i.e., diversity), decreased survival rates of organisms exposed to sediments, and sediment chemical contaminant concentrations over threshold limits. These methods form the Sediment Quality Triad, which is an interdisciplinary approach to assess ecological effects. There were no persistent organic contaminants above threshold limits, but 46% of the stations had chemical detections over threshold limits for seven trace metals: arsenic, cadmium, mercury, copper, lead, nickel, silver, and dibenzo (a,h) anthracene. Mostly near river mouths, 16 of the 24 stations had moderate to high toxicity, and 17 out of the 24 stations had fair to low diversity. Toxicity was inversely correlated with diversity (r = 0.54), but there were no correlations between sediment chemistry and toxicity (r = -0.27) or benthic metrics (r = -0.22), indicating there is no evidence that pollution from chemical contamination is causing estuary-wide degradation. This system is subject to multiple stressors (i.e., changes in temperature, dissolved oxygen, freshwater inflow, salinity, nutrient levels, and contamination) that combine to affect benthic communities. Because pollution appears to be entering from rivers and creeks, management plans for the watershed and non-point sources are likely the main activity needed to restore or protect this ecosystem.

Introduction

The Lavaca-Colorado Estuary (LCE), which is also known as the Matagorda Bay System, is one of seven major estuarine systems along the Texas coast and provides agricultural, industrial, residential, and recreational benefits. It is the second largest estuary in Texas and is comprised of Lavaca Bay and Matagorda Bay, in addition to four smaller bays: Keller, Carancahua, Chocolate, and Tres Palacios Bays. Lavaca Bay is the main source of freshwater inflow to Matagorda Bay because it is connected to the Lavaca River. Freshwater inflow is vital to the health of the ecosystems and species living in the estuary (Pollack et al. 2009). Lavaca and Matagorda Bays provide critical feeding, habitat, and nursery areas for various pelagic and benthic species. Specifically, benthic organisms are important to maintain sediment and water quality, and function as a food source for many other species in the bay.

For the last 30 years, the Matagorda Bay system has been suffering from ecosystem degradation indicated by declines in benthic macroinvertebrate abundance, biomass, and diversity (Pollack et al., 2011; Montagna, 2022). Benthic organisms, commonly referred to as benthos, are a key bioindicator of degradation because they tend to be sessile, very abundant, diverse, and long-lived relative to plankton (Montagna et al., 2012). Estuaries receive freshwater inputs from bayous, creeks, and rivers, which may carry pollutants via diffuse runoff from watersheds, and there may also be direct permitted discharges into creeks, rivers, and estuaries (Pollack et al. 2009). Persistent chemical contaminants from point and nonpoint sources could be deposited in estuarine sediments where benthic organisms living in the surface sediments are directly exposed. Such a pollution pathway could be causing this observed and consistent decline in the condition of the estuary.

In the LCE, there are two known point sources directly discharging various contaminants into the bay: Formosa Plastics Co. (Harris et al., 2023) and the former aluminum smelting ALCOA plant, a superfund site that closed in 1980 and has been remediated over the past two decades (Bissett et al., 2008). Many studies have been conducted in this estuary; however, they were all focused on natural stressors (temperature, salinity and nutrient fluctuations, changes in dissolved oxygen, freshwater inflow etc.), or focused on one area of concern (i.e., ALCOA discharges) instead of a system-wide assessment (Carr et al., 2001; Kim et al., 2009; Pollack et al., 2011). Thus, a holistic approach is needed to assess pollution-induced degradation of the benthos as a measure of ecosystem health systemwide in the LCE.

The purpose of the current study was to determine if sediment contamination in the LCE has contributed to the observed ecosystem degradation indicated by long-term decline of benthic communities. This study will answer environmental questions about the LCE: Is pollution the main cause for long-term decline in the benthic population observed in previous studies? Is there greater contamination in Lavaca Bay near the industrial and superfund sites rather than Matagorda Bay? If so, are the benthos being affected more near the contaminated sites, or is the effect constant throughout the estuary? The approach to answer these questions is to use the Sediment Quality Triad (SQT), which is a commonly used to assess ecological health of estuaries (Chapman 1987, Hyland et al. 2000). The three SQT components are: 1) measures of chemical contaminants to indicate dose, 2) sediment toxicity tests to measure biological effects at the exposure levels, and 3) benthic community structure data to measure ecological effects in the environment and indicate community status. The three components of the SQT are integrated using multivariate analyses to classify samples and form a “weight-of-evidence” assessment of sediment quality (Long et al., 2003). The overall goal of the present study is to determine which parts of the estuary are being most affected, and to draw robust conclusions regarding ecosystem health across the entire LCE.

Purpose

There was one overarching goals of this project: to perform an assessment of sediment quality in the Lavaca-Colorado Estuary (i.e., the Matagorda Bay system).

Tasks

There were two tasks for this project:

Task 1): Collection of sediment samples and laboratory analyses for sediment contaminant chemistry, sediment exposure toxicity, and benthic macrofaunal community metrics. The sediment samples were collected in May 2022. All analyses are listed in Appendix I.

Task 2): Data Management, Reporting, and Outreach Engagement. Quarterly Progress Reports were submitted, peer-reviewed manuscripts were published, and public presentations were made. All deliverables are listed in Appendix I.

Methods

Study sites

Twenty-four stations were sampled, from May 15-19, 2022 (Fig. 1). Seventeen of the stations were chosen because they had been sampled in past long-term studies conducted by the Harte Research Institute for the Lavaca-Colorado Estuary (LC), the Formosa Plastics Corporation monitoring study (FPC), and they were supplemented by an additional seven stations in Lavaca Bay (L) and Matagorda Bay (M) (Table S1). Earlier studies were focused on mercury contamination from the ALCOA site in Lavaca Bay only (Carr et al. 1999). At each station, a Hydrolab multi-parameter sonde was lowered into the water and temperature (± 0.15 ˚C), pH (± 0.1 units), dissolved oxygen (± 0.2 mg l-1), depth (± 0.1 m), and salinity (practical salinity units, psu) were read from the digital display.

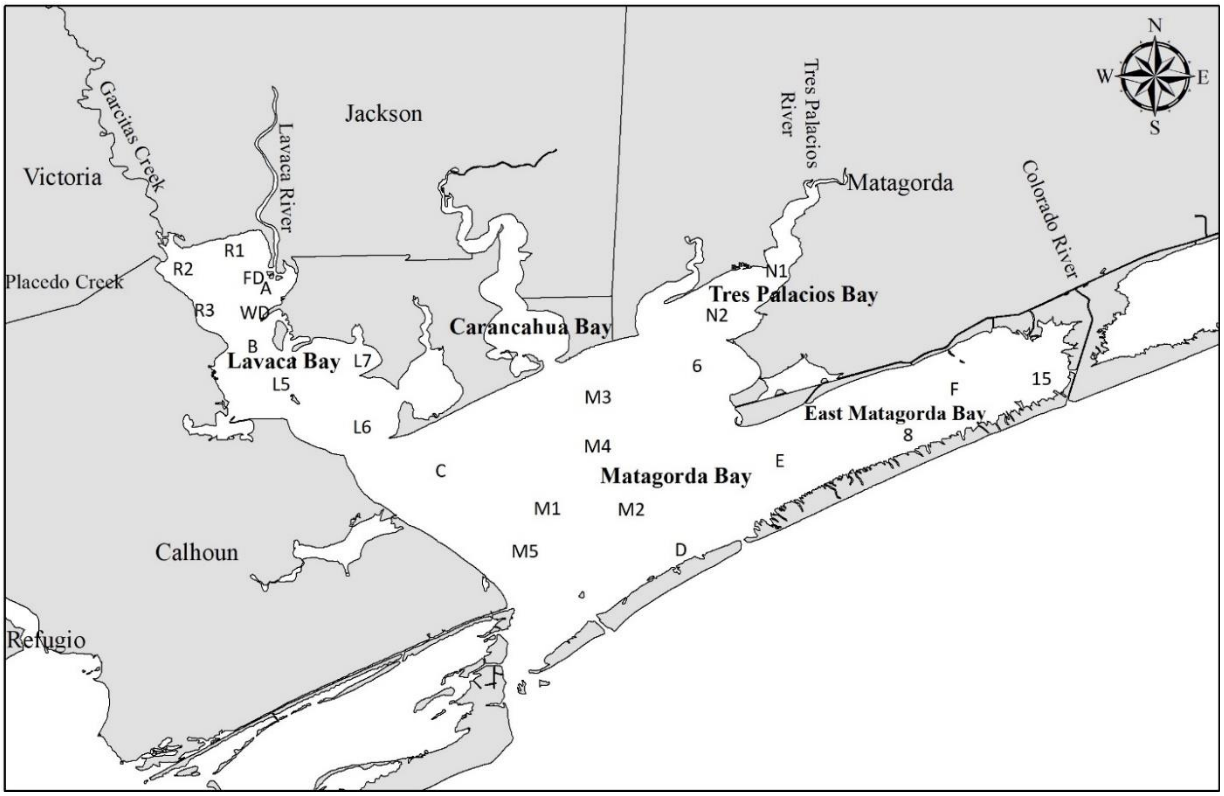

Figure 1. Map of the Lavaca-Colorado Estuary with station, river, and county locations. Average location of all stations is 28.608, -96.391 (Table S1 for locations).

Sediment collection

Using core tubes ensures that the surface layer where 85% of organisms occur, and where recently deposited contaminants might occur, remains intact. A hand-held core, 6.715 cm diameter, covering an area of 35.4 cm^2 was used to collect sediment for separate benthos, sediment, and chemical samples. The core was extruded and then sliced into two depth sections: 0 - 3 cm deep for chemical, benthic community structure and grain size analyses; and 3 - 10 cm deep for further analysis of benthic community structure and diversity at depth. The samples were each preserved separately: benthic samples were preserved in formalin, samples for sediment grain size analysis were refrigerated, and samples for chemical contaminant analyses were frozen. In between samples, cores were rinsed with acetone using a 500-mL fluorinated ethylene propylene (FEP) squirt bottle, making sure to cover all areas of the cores (Pisarski et al. 2021). Cores were rinsed thoroughly with distilled water, then set in a clean bucket to air dry until the next set of samples. Three replicates were collected for each analysis.

A second hand-held core that is 10 cm diameter (78.54 cm^2) was used to collect the sediment for toxicology exposures. The sediment was extruded to collect only the surface 0 - 3 cm depth. A total of 12 cores were collected and the 2827 cm^3 of sediment was placed in large jugs. The toxicology samples were kept refrigerated up to 16 days prior to exposures.

Chemical contaminant assessment

Sediments were analyzed for aliphatic hydrocarbons (HC), total petroleum hydrocarbons (TPH), polycyclic aromatic hydrocarbons (PAH), total organic carbon (TOC), organochlorine pesticides (OC's), polychlorinated biphenyls (PCBs), and trace metal elements (TM) (B&B Laboratories, Inc., College Station, Texas). Grain size analysis was performed by Azimuth Geo Services (Fairfield Bay, Arkansas), and TM analysis was performed by ALS Environmental (Kelso, Washington). The data and detailed descriptions of analytical methods are available online at https://doi.org/10.7266/9syzmzrd (Montagna et al., 2023).

Toxicity tests

The jug sediment samples were sent to the NOAA Laboratory (Charleston, SC) for toxicity testing where they were held under refrigeration for no more than 4 weeks at 4 ºC until analysis. Three estuarine species were assessed: the grass shrimp (*Palaemon pugio)*, the amphipod (*Leptocheirus plumulosus)*, and the polychaete (*Neanthes arenaceodentata).* An additional standard toxicity test, The Microtox ® assay was also conducted using whole sediment.

The grass shrimp (*P. pugio*) is used as a bioindicator of anthropogenic impacts and other changes happening in the environment (Key et al., 2006). Grass shrimp are one of the most sensitive organisms, but specifically they are more sensitive to heavy metals and a variety of pesticides (Anderson 1985). Ovigerous grass shrimp were collected in the field (Leadenwah Creek, SC) and staged in the laboratory to obtain larval shrimp. The larval shrimp (24 - 48 h old) were assessed using the sediment elutriate method (Key et al., 2006). Grass shrimp exposures were 96 h tests, with renewal at 48 h, with three replicates for each site, and ten shrimp in each replicate. The test parameters were: 28 S, 25 °C, 16 L:8D photoperiod, 48-h renewal. Sediment samples were stirred in the gallon jars until homogenized, and then placed on a roller for 20 minutes. 200 mL of sediment was then removed, placed in a 1000 mL beaker and, mixed with 80 mL of 28 S seawater and placed on an orbital shaker table for 60 minutes (100 rpm). Afterwards, the samples were centrifuged at 3000 rpm for 20 min, to separate the elutriate from the sediment. 200 ml of elutriate was placed into each jar. Water quality (pH, salinity, dissolved oxygen (DO), and temperature) was taken from one replicate before the larval shrimp were put in and then every 24 h. At 48hr the water was renewed with fresh elutriate and mortality was assessed at 96 h when the test ended.

Leptocheirus plumulosus, an amphipod, is widely distributed and commonly found in marine and freshwater sediments. Living in sediment for the entirety of their lifespan makes them more susceptible to the toxic effects of contaminated sediment (DeWitt et al., 1992; McGee et al., 1993). Similarly, *N. arenaceodentata*, a polychaete, is widely distributed in shallow marine and estuarine benthic habitats of Europe, North America, and the Pacific. They are sediment dwelling organisms (in the upper 2 to 3 cm of sediment) and are known to affect the physiochemical characteristics of sediments (Reish 1972; Pesch et al., 1981).

L. plumulosus were shipped from Aquatic Biosystems Inc. and *N. arenaceodentata* were shipped from Aquatic Toxic Support and both were allowed 24 hr to acclimate to laboratory conditions prior to testing. Whole sediment tests were conducted with juvenile amphipods, (body length 2 - 4 mm) and juvenile polychaetes (2 - 3 weeks old and body length 10 - 15 mm). The amphipod assay used five replicates per station with 20 amphipods in each replicate and the polychaete assay used five replicates with 5 polychaetes/replicate. Samples were stirred until homogenized, and then placed on the roller for 3 minutes. A 175 g aliquot of sediment was added to each 1000-mL beaker. The beaker was then filled with 800 mL of 28 S seawater, using a petri dish as a baffle. The beaker was placed in the incubator for 24 h covered and aerated. After 24 h, the amphipods and polychaetes were placed in their respective beakers, and water quality was taken daily from two replicates at each station, randomly picked. Ammonia levels were measured on day 0, 2, and 8. On day ten, samples were sieved, and survival assessed.

Microtox® solid phase test

Microtox assays were conducted according to the standardized solid phase protocols with the Microtox Model 500 analyzer (Modern Waters Inc., Newark, DE). Sediment was homogenized and a 7.0-g to 7.1-g sediment sample was used to make a series of sediment dilutions with 3.5% NaCl (sodium chloride) diluent. Test samples were placed in a 15 ºC water bath for 10 min incubation. Luminescent bacteria (*Vibrio fisheri*) were added to the test concentrations for 20 min incubation. At the end of the incubation period, a column filter was used to separate the liquid phase from the sediment phase, and bacterial post-exposure light output was measured using Microtox Omni Software. An EC50 (the sediment concentration that reduces light output of luminescent bacteria by 50% relative to the controls) value was calculated for each sample in triplicate.

Benthic diversity

The samples for macrobenthos were preserved in formalin, extracted from sediment using a 0.5 mm mesh sieve, and sorted via microscopy. Benthos were enumerated using a dissecting microscope and identified to the lowest taxonomic level possible. Biomass was measured at the identification level. Samples were dried at 50 °C for 24 hours and weighed to the nearest 0.01 mg. For mollusks, the tissue was removed from shells by dissection before weighing, and shell lengths were measured.

Species diversity is calculated by replicate and by pooling all three replicate cores for each site. Diversity is calculated using Hill's diversity number 1 (N1), which is a measure of the effective number of species in a sample and indicates the number of abundant species (Ludwig & Reynolds 1988). It is calculated as the exponentiated form of Shannon diversity index (H'). 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 & Weaver 1949; Hutcheson 1970). Hill's N1 is used in most analyses because it is easier to interpret than H'. Pielou's evenness index (J') represents equitability, expressing how evenly the individuals are distributed among different species (Warwick & Clarke 1995).

Statistical analyses

Macrofauna community structure is analyzed using non-metric multidimensional scaling (nMDS) and ABC (Abundance-Biomass-Curve) plots (Clarke and Gorley, 2015). The nMDS is based on ordination of Brey-Curtis similarities of square root transformed abundances among stations. The ABC plots are an assessment method based on succession theory where stressed (i.e., polluted environments) are less diverse communities that are dominated by small but numerous r-selected species (Figs. S1 - S3). In contrast, more diverse and larger but less numerous, k-selected species are more common in unstressed (unpolluted, more diverse) communities (Table S2).

The SQT concept is designed to integrate the biological and ecological responses to the environmental setting as characterized by the quantity of sediment contaminants and the natural background. The statistical approach is based on the concept that the experiment-wide error rate must be controlled and that the easiest way to do this is to reduce the number of variables in the analysis (Carr et al., 2003; Long et al., 200). Thus, a series of multivariate analyses are performed to reduce the data set to three variables based on the chemical, biological, and ecological data sets, and is presented as a percent quartile index to classify chemistry, benthic structure, and toxicity data, from most degraded to least degraded stations based on ranks. The quartile ranges were 0- 25% for most degraded, 25%-75% is average conditions, and >75% is most healthy stations with greatest metrics (i.e., highest diversity and lowest toxicity and contaminant concentrations). Then the data were organized in a ranked system, ranking the 24 stations based on the chemical contamination, survival percentages, and benthic diversity: 1 is the most degraded site and 24 is the least degraded sites. Lastly, the chemistry data were reduced to principal components (PCs) using principal components analysis (PCA) (Fig. S4). The last step was to perform multivariate regression, PCA, and correlation analysis on the PCs using the means of the chemical measured.

Results

Physical factors

The water temperatures ranged from 27.34 ^{o}C to 28.73 ^{o}C among stations (Fig. S5), and the salinity (S) ranged from 26.17 to 29.88 S (Fig. S6). The maximum water depth was 4.1 m and dissolved oxygen ranged from 5.84 to 8.84 mg/L. Half of the sites in Upper Lavaca, Lower Lavaca, and Tres Palacios Bays (15, A, B, F, FD, L6, L7, M5, N1, N2, R2, and R3) were composed of mostly sand, and the other half, mostly in Matagorda Bay, were composed of mud or soft sediment.

Chemical factors

The detailed results of all chemical analysis can be found in the online data repository (Montagna et al. 2023). A summary of sediment concentrations of PAHs, PCBs, TPH, TOC, OC, and trace metals is presented in (Table 1). There were no elevated levels of PAH, PCB, TPH, TOC, or OC at any of the 24 stations. Concentrations of the organic pollutants were below ERM and PEL threshold levels at all stations.

There were elevated levels of seven trace metals (arsenic, cadmium, copper, lead, mercury, nickel, and silver) mostly located in the lower part of Lavaca Bay (Table 1). Chromium and zinc had concentrations below all targeted bioeffect guidelines (Balthis et al., 2012). Silver was the only metal with concentrations above the upper-threshold ERM or PEL guideline values, which only occurred at stations 6, E, and M3. Four stations (6, 8, E, M3) had elevated levels in excess of the lower threshold ERL or TEL values for all the above seven metals. Four of the stations located in Matagorda Bay had elevated levels of arsenic (M1, M2, M3, M4) above ERL or TEL guidelines. Station R1 had elevated levels of arsenic, cadmium, and nickel. There were six stations that had elevated levels of mercury (6, B, D, M2, R1, and WD). Mercury is known to be common near the ALCOA plant in historical studies (stations WD & B), so it is expected the levels would be elevated (Carr et al., 2001).

Table 1 Probable effects level (PEL), effects range median (ERM), threshold effects level (TEL), and effects range low (ERL) values. Abbreviations: PAH = Polycyclic aromatic hydrocarbons (ug/kg), Pesticides/PCB = Pesticides and polychlorinated biphenyl's (ug/kg), Metals = Trace Metals (mg/kg).

Substance	PEL	ERM	TEL	ERL	Stations > PEL	Stations > ERM	Stations > TEL	Stations > ERL
PAH								
Acenaphthene	88.9	500	6.71	16				
Acenaphthylene	128	640	5.87	44				
Anthracene	245	1100	46.85	85.3				
Fluorene	144	540	21.17	19				
Naphthalene	391	2100	34.57	160				
Phenanthrene	544	1500	86.68	240				
LMW PAHs	1442	3160	311.7	552				
B(a)Anthracene	690	1600	74.83	261				
Benzo(b)fluor	710	1 880						
Benzo(k)fluor	610	1 620						
Benzo(a)pyrene	762	1600	88.81	430				
Dibenzo (a, h) anthracene	135	260	6.22	63.4			WD	WD
Chrysene	846	2800	107.77	384				
Fluoranthene	1494	5100	112.82	600				
Pyrene	1398	2600	152.66	665				
HMW PAHs	6676	9600	655.34	1700				
Total PAHs	1677	44792	1684.06	4022				

Substance	PEL	ERM	TEL	ERL	Stations > PEL	Stations > ERM	Stations > TEL	Stations > ERL
Pesticides/PCB								
p,p -DDD	7.81	20	1.22	2				
p,p -DDE	3.74	27	2.07	2.2				
p,p -DDT	4.77	7	1.19	1				
Total DDT	51.7	46.1	3.89	1.58				
Total Chlordane	4.79	6	2.26	0.5				
Dieldrin	4.3	8	0.715	0.02				
Endrin	62.4	45		0.02				
Heptachlor epoxide	2.7							
Lindane	1.38		0.32	0.32				
Total PCBs	189	180	21.55	22.7				
Metals								
Arsenic	41.6	70	7.24	8.2			6, E,M1,M2, M3,M4,R1	6, E,M3,R1
Cadmium	4.21	9.6	0.68	1.2			6, E,M3,R1	6, E,M3,R1
Chromium	160	370	52.3	81				
Copper	108	270	18.7	34			6, E,M3	
Lead	112	218	30.2	46.7			6, E,M3	
Mercury	0.7	0.71	0.13	0.15			6, B,D,M2,R1, WD	B, D,M2,WD
Nickel	42.8	51.6	15.9	20.9			6,8, D,E,M3,R1	6, E,M3
Zinc	271	410	124	150				
Silver	1.77	3.7			6, E,M3			

Toxicity tests

The three organisms evaluated had different survival patterns at stations near river inlets compared to the primary bay which is visualized in a heat map (Fig. 2). The darker (red) color represents more survival in that station and the lighter (blue) color represents less survival. The shrimp, *Palaemon pugio*, had the highest survival rate, *N. arenaceodentata* had moderate survival, and *L. plumulosus* had the lowest survival, especially at stations in the Upper Lavaca Bay.

Upper Lavaca had the lowest survival rates (< 80 %) and the highest survival (> 80%) was in Matagorda Bay (Fig. 2). Station R2, which is directly across from the industrial plants and in front of Placedo Creek and Garcitas Creek, had the lowest survival rate (4 %). The highest survival rate (100% survivability) was at station C, which is at the edge of the lower Lavaca Bay and beginning of the Matagorda Bay. Overall, all stations near rivers/creeks had survival rates ≤ 80%.

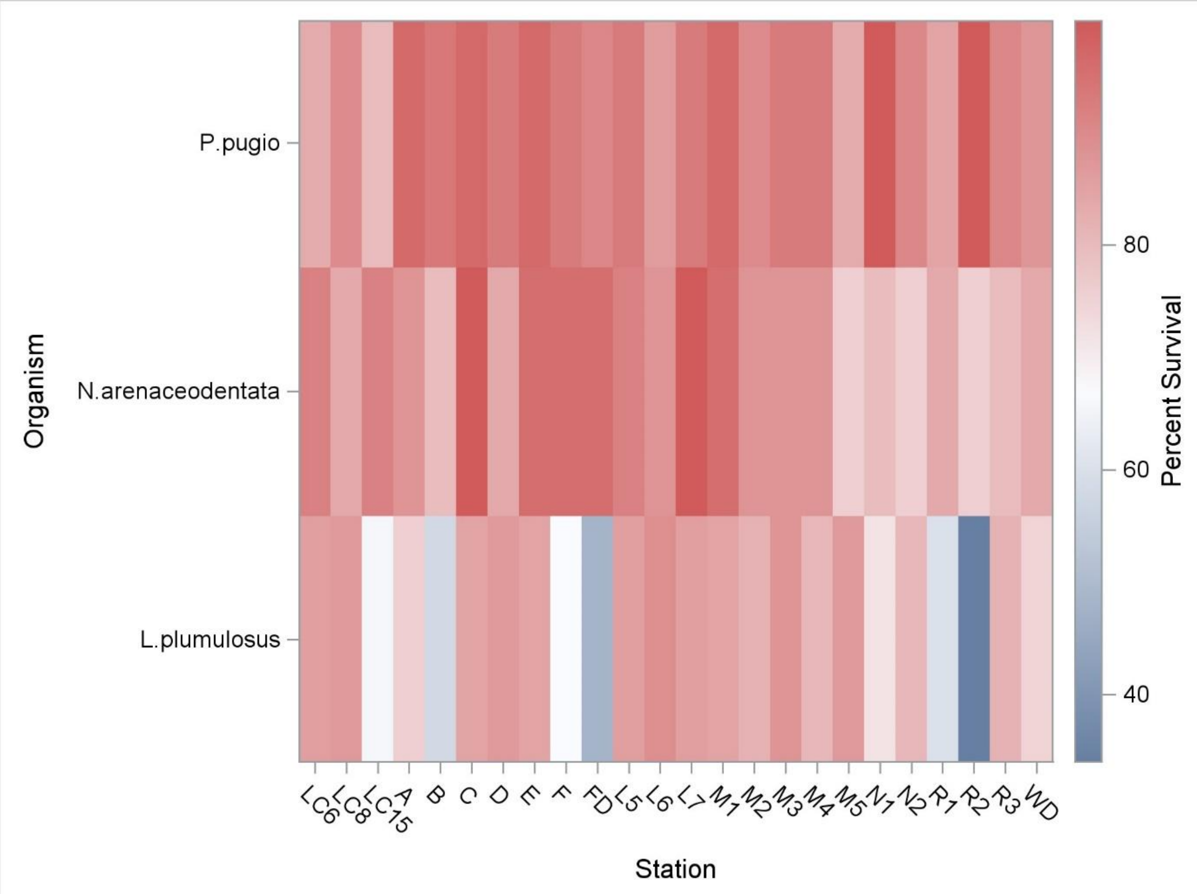

Figure 2. Heat map of average percent survival for three species: *Leptocheirus plumulosus*, *Neanthes arenaceodentata*, and *Palaemonetes pugio*.

Microtox® solid phase assessment

The criteria for Microtox® sediment toxicity was evaluated by the following: (1) Sites with an EC50 1.0% were classified as toxic, (2) sites with an EC50 0.75% but < 1% were classified as toxic, (3) sites with EC50s that fell below the prediction intervals established using silt normalization techniques were classified as toxic, (4) sites with EC50s that fell below the confidence limits established using silt normalization techniques were classified as toxic, (5) EC50 <0.5 % and Silt/Clay <20 % was classified as toxic, and (6) EC50 < 0.2 % and Silt/Clay > 20 % was classified as toxic (Ringwood et al., 1997). Ten stations (M1, M2, D, L6, E, 15, 8, 6, M3, and N2) fell within the sixth criteria and were classified as toxic. Typically, silty sediment has very low EC50 values (indicating toxicity), whereas sandy sediments had very high EC50 values (indicating not toxic). Stations 15, L6, and N2 had sandy sediment, and the other seven stations were classified as silty sediment (Montagna et al 2023). All ten stations were either directly in front or near creek or river mouths, indicating there is an influence of creeks or rivers on the survival and diversity of benthic communities (Table 2).

Table 2 Mean percent effect concentration causing 50% survival (EC50) and percent silt+clay. Highlighted rows are stations classified as toxic because EC50 < 0.2 % and Silt/Clay > 20 % was classified as toxic (Ringwood et al., 1997). Bay abbreviations: EMatagorda= Eastern arm of Matagorda, UpLavaca= Upper Lavaca, LoLavaca= Lower Lavaca.

Station	Bay	Mean EC50 (%)	% Silt+Clay
6	Matagorda	0.1021	85.2742
8	EMatagorda	0.0891	93.0477
15	EMatagorda	0.1323	85.9741
A	UpLavaca	0.6667	41.5806
B	LoLavaca	0.4768	69.7600
C	Matagorda	0.2129	95.1125
D	Matagorda	0.1490	88.3004
E	Matagorda	0.0820	94.3709
F	EMatagorda	0.2775	37.3484
FD	UpLavaca	1.2756	17.9438
L5	LoLavaca	0.3385	93.3979
L6	LoLavaca	0.1937	67.3671
L7	Matagorda	0.3160	82.0682
M1	Matagorda	0.1491	88.9518
M2	Matagorda	0.1333	93.5105
M3	Matagorda	0.1661	91.5527
M4	Matagorda	0.2050	89.7895
M5	Matagorda	0.2535	73.2482
N1	TresPalacios	0.5908	73.5858
N2	TresPalacios	0.1990	64.0504
R1	UpLavaca	0.4282	68.5137
R2	UpLavaca	0.3908	67.3719
R3	UpLavaca	0.4153	74.7563
WD	LoLavaca	0.2072	99.6530

Benthic diversity

A total of 47 species were found among 24 stations, from the 72 samples collected (Table 3). *Mediomastus ambiseta* was the dominant species (468 total estuary-wide) found in all stations except M2, with mean abundance 1847.60 n/nm^2. The second most dominant species was *Paraprionospio pinnata* with a total of 37 species estuary wide (mean abundance 145.76 n/nm^2), found in 16 out of 24 stations commonly found in Upper and Lower Lavaca and Tres Palacios Bay. The most common class of organisms was Polychaeta, accounting for a little over half of the organisms collected. Benthic diversity, evenness, richness, and distinctness were all calculated. Station D had large species richness with 15 species, and L5 had only two species *Mediomastus ambiseta* and *Macoma mitchelli.* The station that had the highest amount of

Mediomastus ambiseta was LC15 located in eastern Matagorda Bay. The stations that have low species abundance were in the Upper Lavaca Bay and the Matagorda Bay.

Table 3 Taxonomic list of all species found with average and standard error (SE) abundance (n/m^2) and biomass (g/m^2) Taxa name abbreviations: P = Phylum, C = Class, O= Order, F= Family, GS= Genus Species.

Taxa Name	**Abundance**		**Biomass**	
P C O F GS	**Mean**	**SE**	**Mean**	**SE**
Cnidaria				
Anthozoa				
Anthozoa (unidentified)	7.88	5.45	0.05377	0.03748
Platyhelminthes				
Turbellaria				
Turbellaria (unidentified)	3.94	3.94	0.00236	0.00236
Nemertea				
Nemertea (unidentified)	94.55	27.88	0.06075	0.02907
Phoronida				
Phoronidae				
Phoronis architecta	27.58	14.49	0.00642	0.00388
Mollusca				
Gastropoda				
Heterostropha				
Pyramidellidae				
Eulimastoma sp.	3.94	3.94	0.00004	0.00004
Neotaeniogloassa				
Calyptraeidae				
Crepidula sp.	3.94	3.94	0.00154	0.00154
Cephalaspidea				
Cylichnidae				
Acteocina canaliculate	39.39	12.62	0.01655	0.00710
Bivalvia				
Adapedonta				
Hiatellidae				
Hiatella arctica	11.82	11.82	0.00225	0.00225
Nuculoida				
Nuculanidae				
Nuculana acuta	3.94	3.94	0.01501	0.01501
Veneroida				
Mactridae				
Mulinia lateralis	126.06	34.93	0.08237	0.03774

Taxa Name **P C O F GS**	**Abundance**		**Biomass**	
	Mean	**SE**	**Mean**	**SE**
Tellinidae				
Macoma mitchelli	47.27	18.88	0.62767	0.26339
Annelida				
Polychaeta				
Errantia				
Pilargidae				
Hermundura ocularis	11.82	11.82	0.00638	0.00638
Sigambra tentaculate	11.82	11.82	0.00760	0.00760
Hesionidae				
Gyptis brevipalpa	11.82	6.52	0.00355	0.00241
Nereididae				
Ceratonereis irritabilis	3.94	3.94	0.00059	0.00059
Goniadidae				
Glycinde solitaria	122.12	24.46	0.02612	0.00877
Onuphidae				
Diopatra cuprea	11.82	8.65	0.01355	0.00940
Lumbrineridae				
Lumbrineris parvapedata	7.88	5.45	0.00087	0.00060
Canalipalpata				
Spionidae				
Dipolydora caulleryi	31.52	27.69	0.00362	0.00354
Paraprionospio pinnata	145.76	42.58	0.18015	0.05639
Streblospio benedicti	102.43	36.85	0.00414	0.00163
Magelonidae				
Magelona phyllisae	7.88	7.88	0.00559	0.00559
Magelona rosea	3.94	3.94	0.00122	0.00122
Chaetopteridae				
Spiochaetopterus costarum	15.76	7.35	0.01359	0.00789
Ampharetidae				
Melinna maculate	3.94	3.94	0.01619	0.01619
Sedentaria				
Capitellidae				
Capitella capitata	3.94	3.94	0.00162	0.00162
Mediomastus ambiseta	1847.60	499.52	0.15510	0.04623
Notomastus latericeus	3.94	3.94	0.00134	0.00134
Cossuridae				
Cossura delta	157.58	39.29	0.02084	0.00615
Orbiniidae				
Haploscoloplos foliosus	55.15	25.40	0.08623	0.04987

Taxa Name P C O F GS	Abundance		Biomass	
	Mean	**SE**	**Mean**	**SE**
Naineris laevigata	3.94	3.94	0.00232	0.00232
Paraonidae				
Aricidea bryani	15.76	9.29	0.02056	0.01200
Paradoneis lyra	3.94	3.94	0.00008	0.00008
Oligochaeta				
Oligochaeta (unidentified)	23.64	14.23	0.00016	0.00009
Crustacea				
Malacostraca				
Decapoda (Natantia)				
Ogyrididae				
Ogyrides alphaerostris	15.76	7.35	0.01627	0.01010
Decapoda (Reptantia)				
Pinnotheridae				
Pinnixa sp.	3.94	3.94	0.01627	0.01627
Megalopa larvae	3.94	3.94	0.00110	0.00110
Cumacea				
Bodotriidae				
Cyclaspis varians	3.94	3.94	0.00024	0.00024
Leuconidae				
Leucon sp.	23.64	10.26	0.00102	0.00059
Amphipoda				
Ampeliscidae				
Ampelisca abdita	86.67	48.60	0.00382	0.00201
Liljeborgiidae				
Listriella barnardi	23.64	13.04	0.00205	0.00111
Listriella clymenellae	3.94	3.94	0.00024	0.00024
Isopoda				
Idoteidae				
Edotia montosa	3.94	3.94	0.00047	0.00047
Tanaidacea				
Apseudidae				
Apseudes sp.	3.94	3.94	0.00374	0.00374
Echinodermata				
Ophiuroidea				
Ophiurida				
Amphiuridae				
Microphiopholis atra	7.88	5.45	0.02045	0.01702
Chordata				
Actinopterygii				

Taxa Name P C O F GS	Abundance		Biomass	
	Mean	**SE**	**Mean**	**SE**
Elopiformes				
Megalopidae				
Megalops atlanticus	3.94	3.94	0.00036	0.00036
Hemichordata				
Enteropneusta				
Enteropneusta [unassigned]				
Spengelidae				
Schizocardium sp.	177.28	141.74	1.23060	1.00016
Total all species	3340.65	1202.19	2.74	1.70

The benthic community structure was similar in composition within bays and among stations (Fig. 3). Station WD (Witco Discharge site) is mostly related to stations in Matagorda Bay. Station R1, R2, and FD (Upper Lavaca Bay) are similar to stations in eastern Matagorda Bay and Tres Palacios Bay. Stations that are near industrial sites are similar in benthic community structure as the stations that are on the opposite side of the estuary (Fig. 3, left top circle).

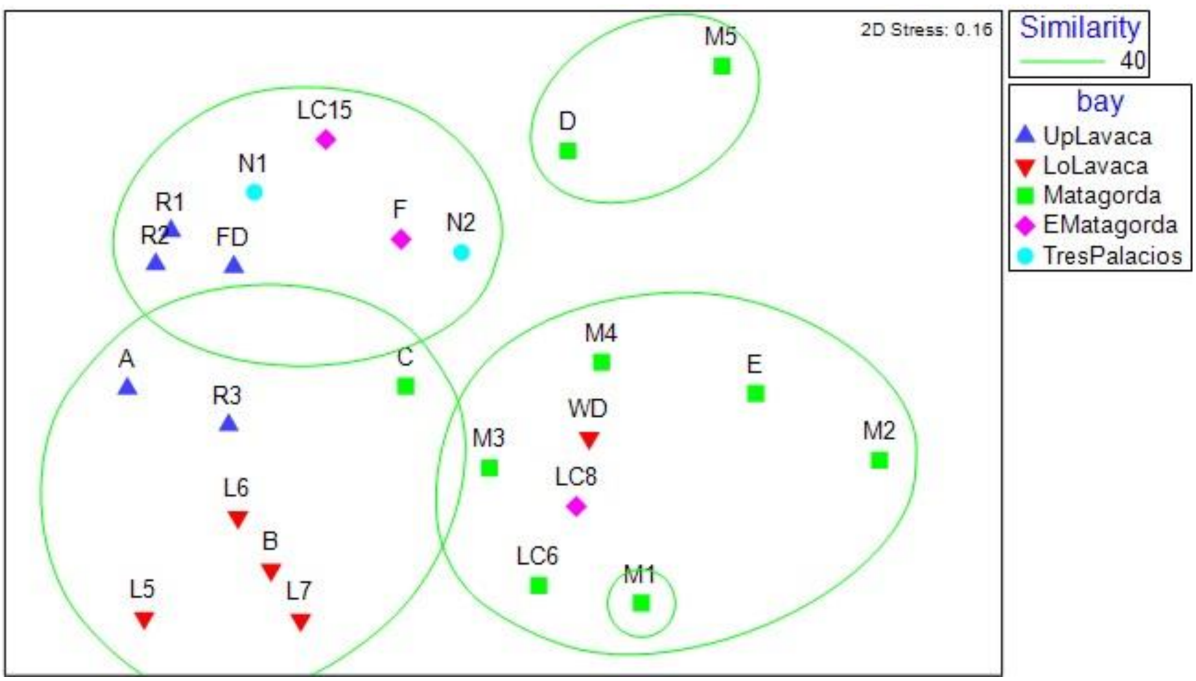

Figure 3. Similarity of benthic community structure among stations based on non-metric multidimensional scaling and cluster analysis. Symbols are bays within the Lavaca-Colorado Estuary. Bay region abbreviations: EMatagorda= Eastern arm of Matagorda, UpLavaca= Upper Lavaca, LoLavaca= Lower Lavaca.

The three components of diversity (richness, evenness, and diversity) demonstrated a correlation between evenness and diversity ($r = 0.743$, $p < 0.001$), which was inversely correlated to species richness ($p < 0.001$) (Table S3). Richness (S) was very low with the highest number of species found in station D (15 species). Yet, evenness (J') and diversity (H') indicated that for all stations diversity was above 0.05 and there was a large number of species from similar families (evenness all stations > 0.4). Evenness and diversity compared to richness had coefficients of less than 0.05 meaning that there is little to no correlation between the number of species and how evenly they are distributed around the bay.

SQT analysis

The SQT data are summarized in (Fig. 4) for each station based on a ranking system (Table 4). The rank of each component from 0 – 25 % (red) indicates high contamination, or low survival or diversity; ranks between 25 % and 75 % (yellow) indicate average contamination, toxicity, or diversity; and ranks >75 % (green) indicate low contamination, and high survival or benthic diversity. In terms of chemical contaminant concentrations and contamination in the area, the least contaminated station was FD, and the most contaminated station was WD (Fig. 4). All stations near river inlets or creeks had poor-moderate survival and diversity. The Matagorda Bay System had a combination of results, but overall, the contamination of the estuary was localized and had moderate diversity and survival.

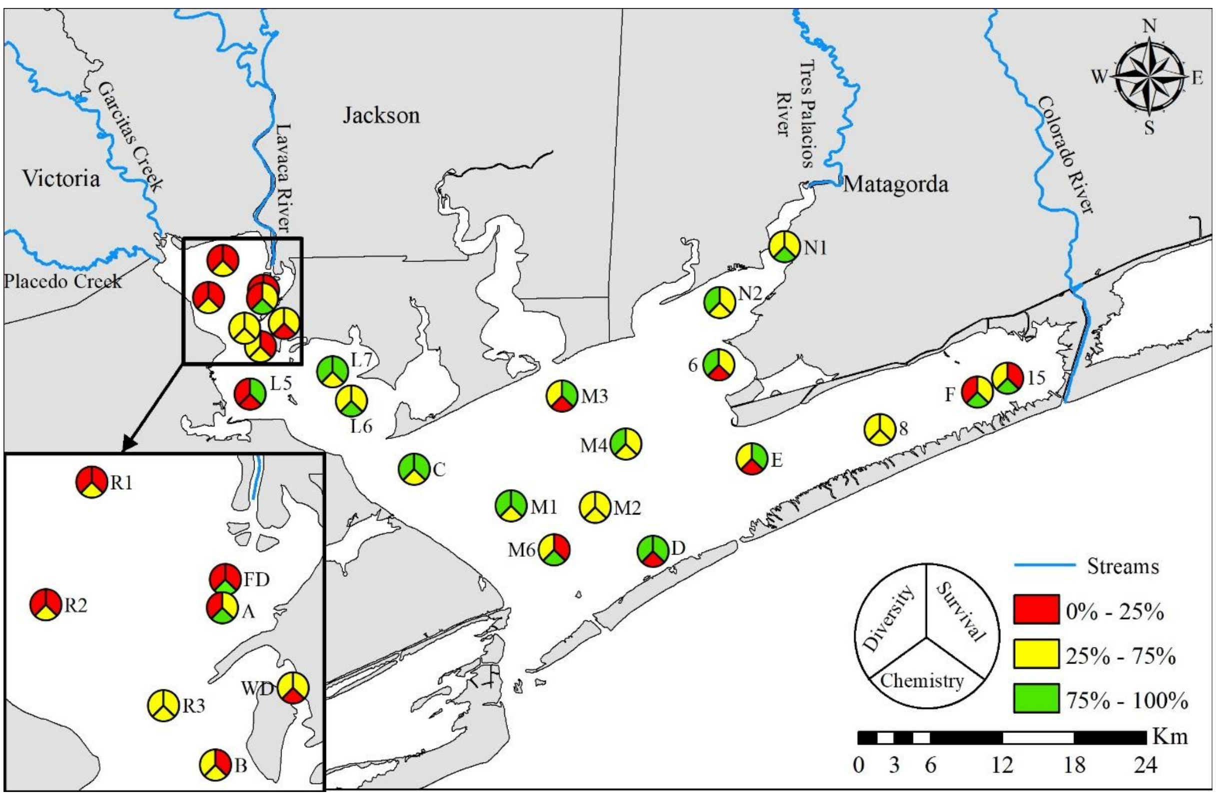

Figure 4.Map of summarized average sediment quality triad quantiles of ranks at stations. Ranks based on Table 4.

Table 4 Ranking of stations for the sediment quality triad. Chemistry rank based on average rank of As, Cd, Cr, Hg, Pb, total alkanes, total PAH, total TPH, total DDT, and total PCB. Survival rank based on average survival of three species. Diversity rank based on Hill's N1 diversity index. Bay region abbreviations: EMatagorda= Eastern arm of Matagorda, UpLavaca= Upper Lavaca, LoLavaca= Lower Lavaca.

Station	**Bay**	**Rank**		
		Chemistry	**Survival (%)**	**Diversity (N1)**
6	Matagorda	4	15	21
8	EMatagorda	11	14	15
15	EMatagorda	21	5	7
A	UpLavaca	22	13	4
B	LoLavaca	16	3	12
C	Matagorda	8	24	22
D	Matagorda	3	18	18
E	Matagorda	2	21.5	13
F	EMatagorda	23	11	6
FD	UpLavaca	24	4	5
L5	LoLavaca	6	20	1
L6	LoLavaca	19	17	8
L7	LoLavaca	13	23	19
M1	Matagorda	12	21.5	24
M2	Matagorda	10	12	14
M3	Matagorda	5	19	17
M4	Matagorda	7	16	23
M5	Matagorda	20	6	16
N1	TresPalacios	18	9	10
N2	TresPalacios	17	8	20
R1	UpLavaca	9	2	2
R2	UpLavaca	15	1	3
R3	UpLavaca	14	10	11
WD	LoLavaca	1	7	9

Discussion

The primary objective was to conduct a sediment quality triad assessment to determine if chemical contamination is causing degradation that could explain the long-term benthic decline in the Matagorda Bay System. The results indicate that 16 of the 24 stations had fair to poor survival in sediment toxicity test, and 17 out of the 24 stations had fair to low benthic diversity. However, there was little correlation of these conditions with evidence of high sediment contamination. As described in the study, the least contaminated, Station FD (ranked 24), was accompanied by high sediment toxicity and poor benthic condition (coded red in Fig. 4), while the most contaminated station WD (ranked 1) was accompanied by only moderate levels of benthic condition and sediment toxicity. Most stations had low to moderate levels of the measured contaminants, but only very few of these stations rose above the chemical threshold limits. Od the six stations with high sediment contamination, thus coded red in Fig.4, four showed intermediate levels of benthic condition or sediment toxicity (6, M3, E, WD) and only one (L5) was accompanied by poor benthic condition yet also having low sediment toxicity. None of the six stations with high sediment contamination were accompanied by both poor benthic condition and high sediment toxicity. Moreover, none of the 24 stations had all three components of the SQT coded the same way.

A total of 46 % of the stations had chemical contaminant detections over TEL and ERL thresholds for seven trace metals (arsenic, cadmium, copper, lead, mercury, nickel, silver) and one PAH (dibenzo (a,h) anthracene). Sites near river inlets and creeks indicated contaminant induced degradation, but the other areas away from rivers and industrial sites (Matagorda Bay) are not being affected by sediment contamination as much. In general, toxicity was correlated with diversity (r = 0.53, Table S3), whereas there were no correlations between sediment chemistry and toxicity or benthic metrics. The chemical contaminants found throughout the entire estuary are just one possible explanation for consistent benthic declines. However, one limitation in this study was not being able to measure additional contaminants such as phthalates, dioxins, furans, alkylphenols and polybrominated diphenyl ethers (PBDE) as some of these contaminants could be the main driver causing the benthic decline (Lee & Kim 2022; Moon et al., 2008a; Khim et al., 1999a). Estuaries are naturally stressed environments, experiencing dramatic salinity fluctuations; thus, benthic community diversity is generally lower in estuarine systems than freshwater systems. The species (*Mediomastus, Capitella, and Steblospio*) were the most abundant in the Matagorda Bay system study (Table 4). These species can indicate a chemically and physically stressed environment, but other factors such as salinity fluctuations, physical disturbances, and nutrient declines must be taken into consideration as well.

There was also an obvious influence of river discharge on survival and benthic community diversity. Overall, toxicity had little to no relationship to sediment chemistry, but there were a few stations that were more sensitive to contamination than others (Carr et al., 2000). Since there was no relationship between sediment chemistry and toxicity, unless near rivers and creek, means that contaminants are not bioavailable, or the benthic response is not due to contaminants (Chapman, 1990) (Table 5). If the toxic response was not due to contaminants, then there could have other natural stressors that are having more of an effect on overall benthic survival (Pollack et al., 2011). Stations with the lowest survival were directly in front of the two river mouths in the Upper Lavaca Bay, meaning various contaminants coming from runoff to the rivers could be affecting the benthic community (Fig. 4). Grass shrimp had the highest survival rate, but this might be due to the shrimp not being directly exposed to the sediment and only to the pore water extracted from the sediment. The sites where both *N. arenaceodentata* and *L. plumulosus* were impacted, but grass shrimp were not, which indicates the contaminants were not water soluble, and thus not bioavailable to the grass shrimp.

Table 5 Summary of sediment quality triad data conclusions.

Chemistry	Toxicity	Benthic	Stations	Possible Conclusions
-	-	-	WD, R1	Evidence of contaminant-induced degradation.
+	+	+	M1, L7	No evidence of contaminant-induced degradation.
-	+	+	D, 8, A, M3,6, M4,C, E	Contaminants are not bioavailable.
+	-	+	M5, B, N2	Unmeasured chemicals or conditions exist with the potential to cause degradation.
+	+	-	L6	Benthic response probably not due to contaminants.
+	-	-	FD, R2,15, N1, F, R3	Unmeasured contaminants or other conditions are causing degradation of benthos.
-	+	-	L5	Contaminants are not bioavailable or benthic response not due to contaminants.
-	-	+	M2	Some stress, but no connection between adverse biological and exposure conditions.

There have been sediment quality triad studies performed in Texas estuaries, including Galveston Bay, one of the largest and most productive estuaries (Carr et al. 1996a). This study found some elevated levels of chemical contaminants (PAH, total PCB, TOC, and trace metals) indicating localized areas were affected by anthropogenic contaminants in Galveston Bay. It was concluded that the entirety of Galveston Bay was not affected by contaminants, and the same can be concluded for this current study in the Lavaca-Colorado estuary (Fig. 4, Table 1).

Another Texas study was performed in the Lavaca-Colorado Estuary using the SQT approach, but it was limited to Lavaca Bay and focused on one chemical (mercury) (Carr et al., 2001). The current study sampled across the entirety of the Lavaca-Colorado estuary producing a result that there was a cumulative effect of multiple chemicals occurring in the estuary, which is one explanation for the long-term decline in benthic communities within the entire estuary. Additionally, in this current study there is no longer an indication of mercury contamination in Matagorda Bay (Table 1, Fig. 4), so these effects were localized to only the Lavaca Bay. Carr et al. (2001) also found that more than half of the PAHs measured exceeded ERM and PEL values for most of the stations. The current study of the entire Matagorda Bay system had no stations exceeding PEL or ERM values, and the highest PAH value was 1087 µg/kg and the other PAH chemicals measured were 50 µg/kg or less (Montagna et al., 2023) (Table 1). In the Carr et al. (2001) study total PAH values ranged from a low of 65.9 µg/kg to 77,000 µg/kg, and the current study's highest value was 1087 µg/kg (Table 1). Total PCBs in the Lavaca study ranged from 0.5 µg/kg to 583 µg/kg and the current study only went up to 6.17 µg/kg (Table 1). The Carr et al. (2001) study did not address the long-term decline in the entire bay system. In contrast, the current study has expanded the spatial assessment to encompass the entire estuarine system, and overall concluded that there is no significant evidence of pollution induced degradation of the benthic community due to the targeted contaminants alone nor consistently system-wide throughout the estuary (Fig. 4).

Another explanation for low abundance and diversity of benthic communities along the Texas Coast may be that the estuary is at ecological equilibrium. Estuaries are referred to as environmentally naturally stressed and highly variable ecosystems that are well adapted to the variation of physio-chemical characteristics already occurring (Carr et al., 2000; Elliot & Quintino 2007; Tweedly et al., 2015). As well as being naturally stressed, estuaries can be anthropogenically stressed from a variety of sources such as industrial discharge, storm-water outfalls, non-point sources, etc. Because the Lavaca-Colorado Estuary is naturally stressed (with fluctuations in nutrients, salinity, and freshwater inflow), and is consistently affected by anthropogenic stressors, it is likely that this ecosystem has reached a lower-diversity equilibrium state. For about 80 years, point source pollution (e.g., ALCOA and Formosa) has impacted thus estuary and influenced benthic community structure temporally (Carr et al., 2001). Yet, this ecosystem has had decades to adapt to these anthropogenic pressures, so it could be that this is the new equilibrium or new normal state for this estuary.

The decline of benthos in the Matagorda Bay System is likely a result of multiple stressors, when two or more stressors interact with each other causing ecological change that neither stressor would cause alone. In the Matagorda Bay System, previous studies have only assessed additive effects (climate variability, freshwater inflow, salinity fluctuations, reduced dissolved oxygen) or how one of these stressors was causing stress to ecosystem health and benthic communities (Carr et al. 2000; Pollack et al.2011; Montagna 1991; Kim & Montagna 2012). Instead, synergistic interactions (chemical, biological, and physical factors) must be quantified together to explain the degradation and declines observed in the estuary. It is not possible to explain long-term benthic decline in the entire bay system by assessing the overexposure of one chemical, without considering other variables affecting the ecosystem.

A unique feature of estuaries is their range of salinities which depends on the freshwater inputs and tidal exchange with the Gulf of Mexico. Salinity levels in the Matagorda Bay system can fluctuate depending on the time of year, river discharge, and precipitation. In a 20-year study of the LCE, the salinity ranged from 2.1 to 34.2 S with a steady decrease over time (Pollack et al., 2011). In Texas, more marine influenced bays with stable salinity habitats have increased diversity, and more freshwater influenced bays with more varying salinity have decreased diversity (Van Diggelen and Montagna 2016). The current study was performed during a dry period (May 2022), and the salinities varied little and ranged from 26.2 to 29.9 S. The drought also likely reduced freshwater inflow into Lavaca Bay.

Riverine inputs of chemical contaminants (PAHs, heavy metals, etc.) through non-point source (NPS) runoff from farm fields, streets, fertilizers, animal waste, construction sites, etc. may play a role in estuarine degradation and benthic decline. The Lavaca-Colorado Estuary has three freshwater inflow sources (Lavaca River, Tres Palacios River, and Colorado river), which can increase the amount of pollution that can enter the secondary and tertiary bays. While freshwater inflow is needed to maintain the health and sustainability of the estuarine communities, NPS can decrease benthic diversity and ecosystem health and shift trophic relationships (Boesch et al., 2001). It would be informative for future sampling to be conducted in a wet season with higher freshwater inflow to compare the levels and spatial distribution of chemical contamination.

Overall, pollution in the Matagorda Bay System can be categorized as localized near the industrial sites and river inlets. Therefore, focusing on watershed or NPS management plans can improve or protect ecosystem health of the Lavaca-Colorado Estuary.

Conclusion

There is little evidence in the current study that pollution is the cause for the decline of benthic communities observed in previous studies. It is possible the decline is caused by chronic effects of some contaminants with small concentrations. There were higher contamination levels near industrial sites relative to the open bay sites. But site near river inlets and creeks are about 23.3% more contaminated than in open bay sites. Ironically, the least contaminated site is the Formosa industrial discharge site, which was expected to have the most contamination. This may be due to solids deposited by the discharge. The benthic community was reduced in abundance and diversity by 66% near river inlets and creeks. This is likely due to a combination of contamination and low salinity values. Past work has shown that freshwater inflow is important to maintain coastal productivity by transporting nutrients and sediments to estuaries. But rivers and creeks also transport non-point source pollution, which could lead to chronic pollution. While industrial and wastewater discharge permitting appears to be working to limit pollutants, non-point sources should be a regulatory focus in the future. Future restoration goals should include a watershed management plan to limit non-point source pollution. Future studies in the Matagorda Bay system should focus on river an creek inlets to determine which chemicals are flowing into the bay. The exact cause of the long-term decline in the benthic community is still uncertain.

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Appendix I: Study Reports and Accomplishments

Task 1): Sediment Quality Triad (SQT) analysis:

- 24 stations sampled in May 2024, with hydrographic measurements of water quality (salinity, temperature, dissolved oxygen, and pH).
- Toxicity tests for three species plus Microtox analyses completed at all 24 stations.
- Chemical analyses for priority pollutants completed for 72 stations (= 24 stations * 3 replicates/station).
- Sediment characteristics (grain size,) completed for 72 stations (= 24 stations * 3 replicates/station).
- Macrofauna abundance, biomass, and diversity analyses completed for 72 stations (= 24 stations * 3 replicates/station).

Task 2): Data Management, Reporting, and Outreach Engagement.

Quarterly reports submitted:

- April, July, and October 2022; January, April, July, and October 2023; January, April, and July 2024.
- Final report was submitted August 2024.

Presentations related to the project:

- Paul Montagna participated and made a presentation about coastal habitat concerns in the meeting for "Community Concerns about the Matagorda Ship Channel Dredging Project" with Jaime Pinkham (Deputy Assistant Administer for the ACOE), and Carlton Waterhouse (Deputy Assistant Administrator for Land and Emergency Management for EPA). Port Lavaca, TX, 17 March 2022.
- Audrey Douglas made a presentation to the Calhoun County Groundwater Conservation District Board of Directors, entitled, "Potential effects of widening and deepening the Matagorda Ship Channel on groundwater resources." Port Lavaca, TX, 25 April 2022
- Montagna, P.A., E.K. Harris, A. Douglas, L. Vitale, D. Buzan. Influence Of the Formosa Discharge on Long-Term Dynamics of Abiotic and Biotic Resources in Lavaca Bay, Texas. Lavaca Bay Foundation, Port Lavaca, Texas, 16 June 2022, 25 participants.
- Montagna, P.A. Freshwater Inflow and Bay Health. Environmental Issues Forum, Calhoun County Democratic Club, VFW Hall, Port Lavaca, Texas, August 20, 2022, 40 participants. https://www.youtube.com/watch?v=AQjjLWKwwy0
- Jasmine Caillier, Paul Montagna, Marie DeLorenzo, and Pete Key. A Sediment Quality Triad Approach to Determine Benthic Condition in the

Matagorda Bay System. Society of Environmental Toxicology and Chemistry (SETAC) meeting, Pittsburg, PA, 17 November 2022.

- Jasmine Caillier. "An Assessment of Benthic Condition in the Matagorda Bay System using a Sediment Quality Triad Approach," NOAA Center for Coastal Marine Ecosystems, Virtual Meeting, 28 November 2022.
- Montagna, P.A. Long-term change in Lavaca and Matagorda Bays related to freshwater inflow change. The Future State of Water in the Matagorda Bay System, Palacios, TX, 24 March 2023, 58 participants.
- Caillier, J. Sediment Quality Assessment Survey of Lavaca and Matagorda Bays. The Future State of Water in the Matagorda Bay System, Palacios, TX, 24 March 2023, 58 participants.
- Caillier, Jasmine. Sediment quality assessment of Lavaca and Matagorda Bays. 51st Benthic Ecology Meeting, Miami, FL, April 26 – 29, 2023.
- Montagna, Paul. Long-term effects of freshwater inflow on benthos at regional scales. 51st Benthic Ecology Meeting, Miami, FL, April 26 – 29, 2023.

Data submitted:

- Montagna, P.A., J. Caillier, M.E. DeLorenzo, and P. Key. 2023 Sediment Quality Triad (SQT) Assessment Survey of Lavaca and Matagorda Bays. Distributed by: Gulf of Mexico Research Initiative Information and Data Cooperative (GRIIDC), Harte Research Institute, Texas A&M University–Corpus Christi. https://doi.org/10.7266/9syzmzrd

Thesis completed:

- Caillier, Jasmine. 2023. An Assessment of Benthic Condition in The Matagorda Bay System Using A Sediment Quality Triad Approach. Masters Thesis, Marine Biology Program, Department of Life Science, College of Science, Texas A&M University-Corpus Christi. Jasmine graduates 12 August 2023. https://www.proquest.com/docview/2864464936

Journal article submitted:

- "An assessment of contaminants and benthic condition in the Matagorda Bay system" was submitted to the journal *Environmental Monitoring and Assessment* on April 14, 2024. Unfortunately, it was rejected. It is currently being revised and will be resubmitted to another journal.

Supplementary Figures and Tables

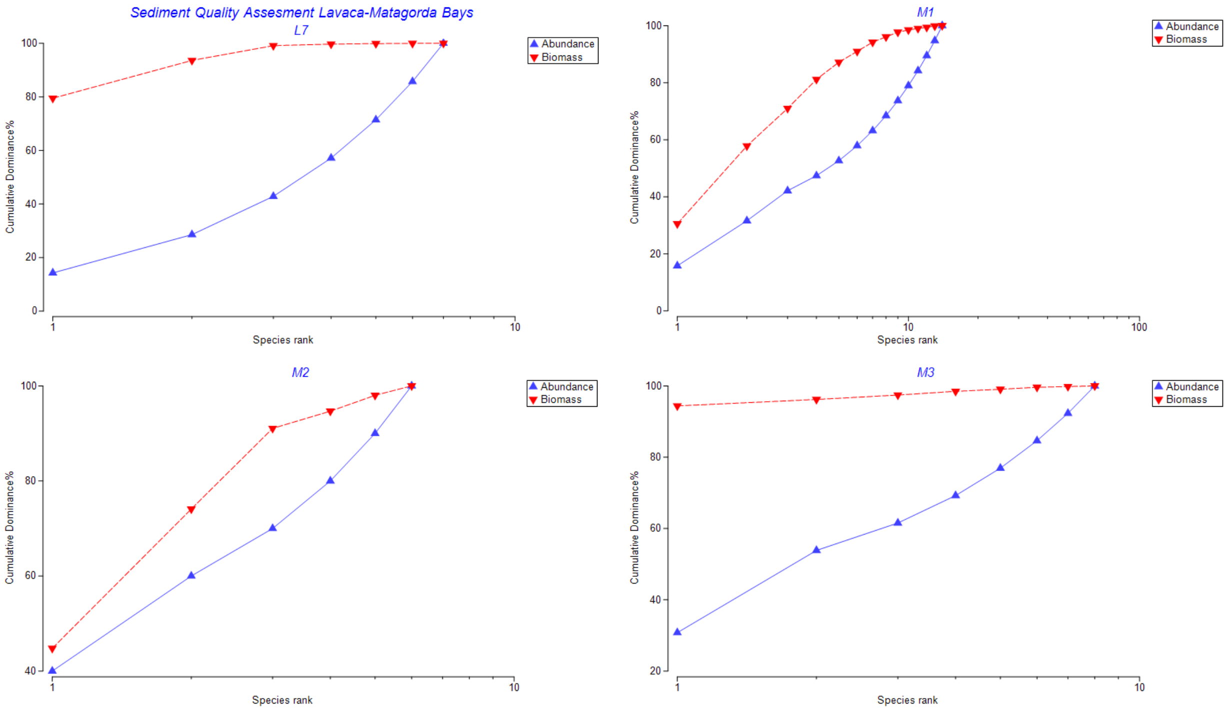


Figure S1. Abundance Biomass plot of stations describing unstressed environments, L7, M1, M2, and M3. Abundance (blue) over Biomass (red) indicates the station is stressed and vice versa, biomass over abundance indicates unstressed environment.

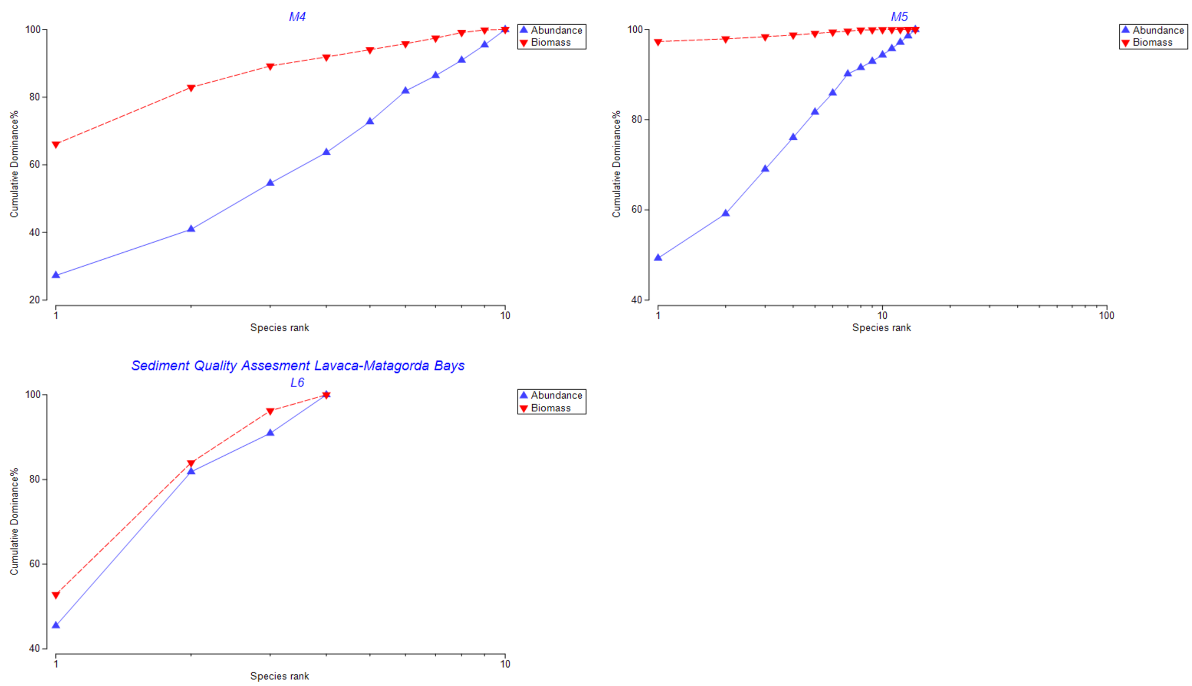


Figure S2. Abundance Biomass plot of stations describing unstressed environments, M4, M5, and L6. Abundance (blue) over Biomass (red) indicates the station is stressed and vice versa, biomass over abundance indicates unstressed environment.

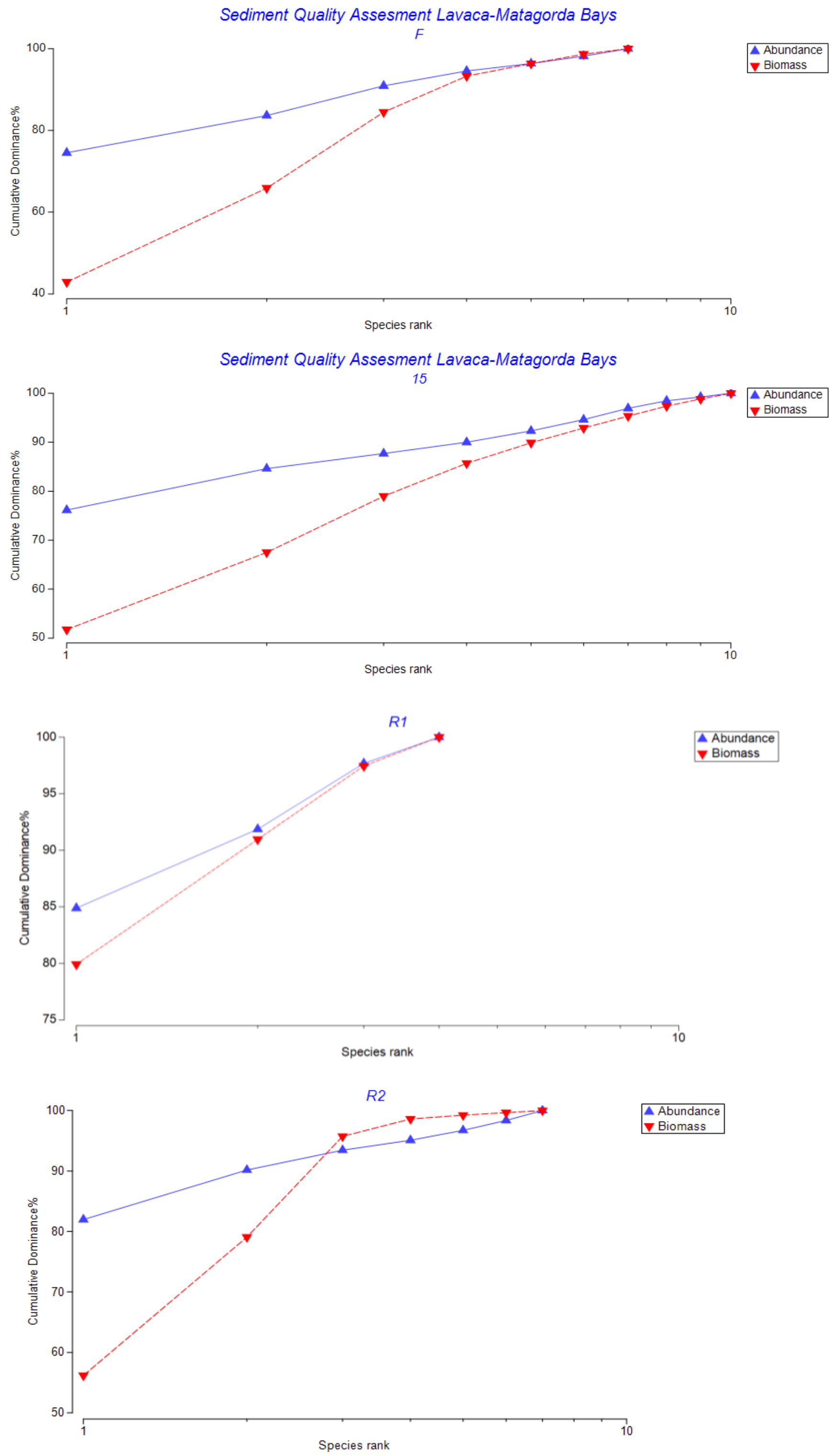


Figure S3. Abundance Biomass plot of stations (F, 15, R1, R2) describing highly stressed ecosystems indicated by current benthic conditions. Abundance (blue) over Biomass (red) indicates the station is stressed and vice versa, biomass over abundance indicates unstressed environment.

Three principal components (PC) were extracted from the chemistry data using averages of each chemical component and grain size of each station (Figure S1). PC1 represents the variability between stations with TPH and silt/clay are found together while sandier stations are vastly different and found in different areas of the bay (Figure S6-A). TPH is found in crude oil which will sink to the bottom of the sediment, especially mud which is less coarse than sand.

PC2 shows all the metals but there was no inverse relationship with the metals found above threshold limits. All the metals stayed consistent throughout all stations and bay areas they were located at. Stations 6, E, and M3 are congregated because these three stations had the most metal contamination (Figure S6-B).

PC3 represents organic pollution as an indicator of synthetic contaminants because PCB and DDT were inversely related to each other with high PC3 absolute values (Figure S6-C). PCBs and DDTs have almost identical characteristics and can be used as pesticides, and the main difference being PCBs are more commonly found in industrial infrastructure while DDTs were made for agricultural use. The places that had more DDT were found in East Matagorda, Tres Palacios, and Upper Lavaca bays all near creek or river mouths. The stations where PAH, PCBs, and mercury (especially station WD) were frequently found at stations in the Matagorda and Lower Lavaca Bay.

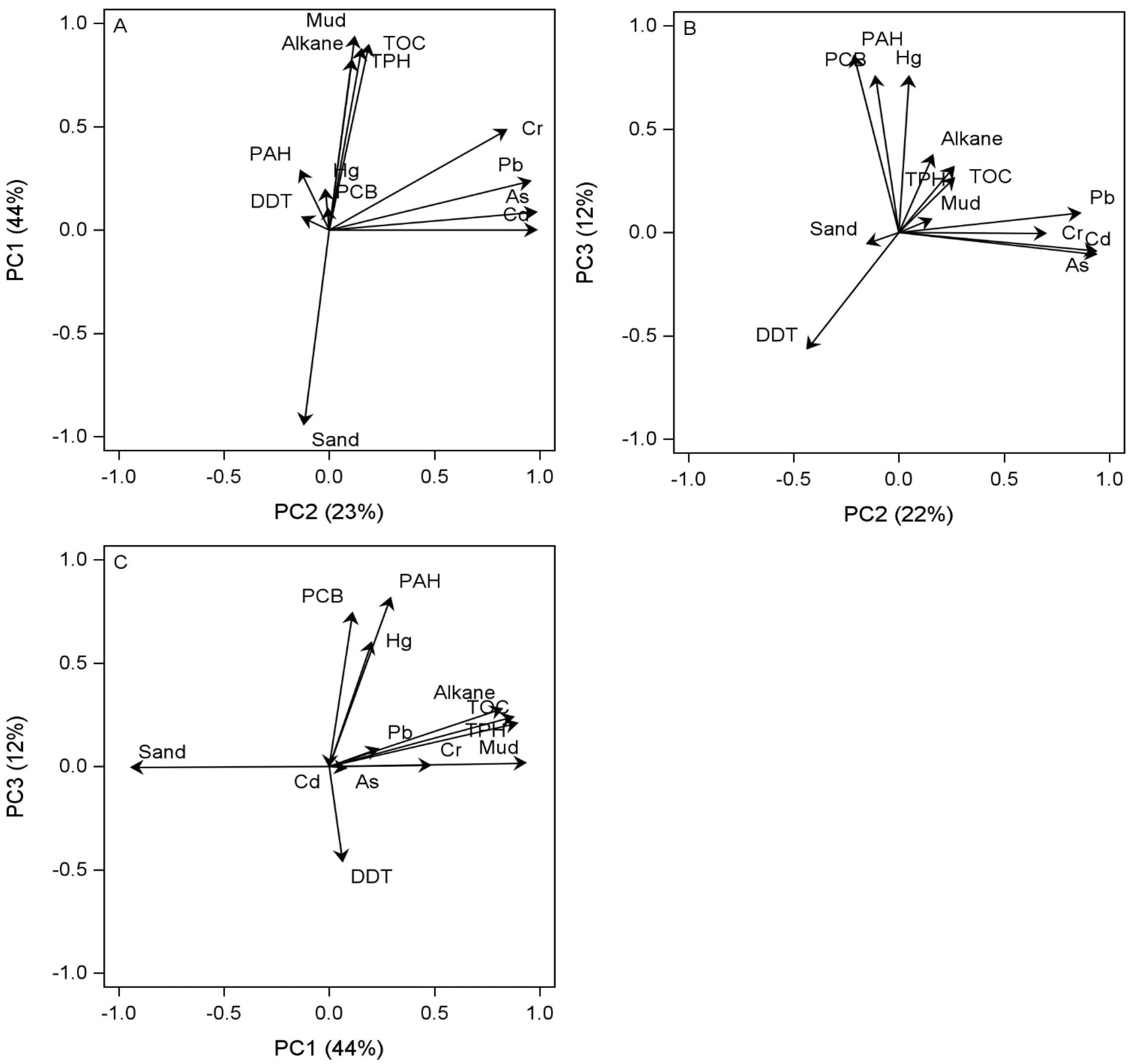
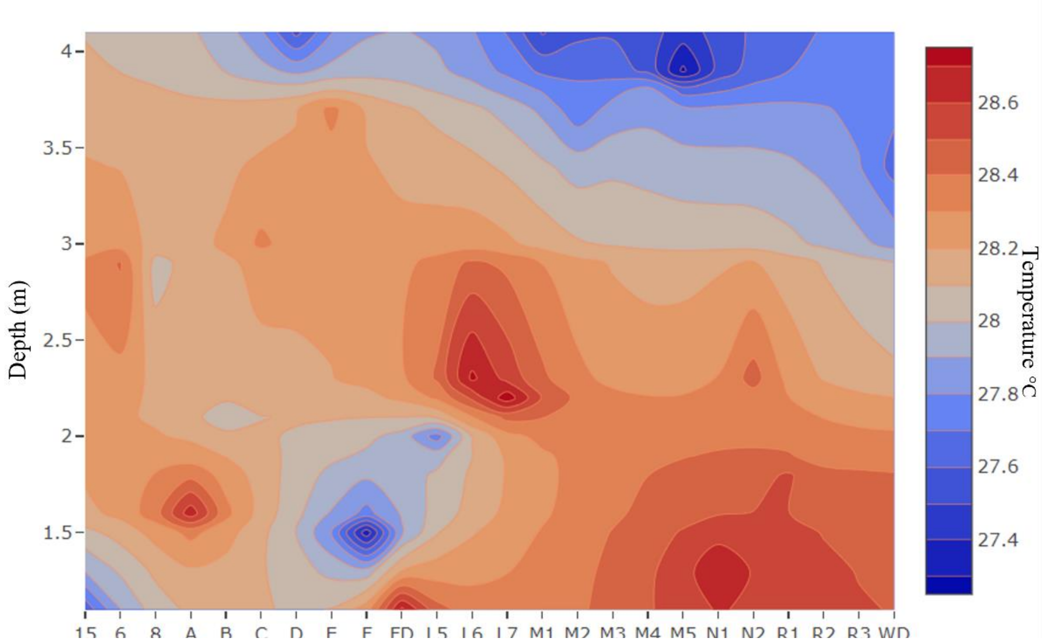


Figure S4. PCA of chemical compounds measured**. A**. PC1(sediment texture (sand versus mud) vs hydrocarbons) compared to PC2 (metals). **B**. PC3 (DDT versus PAH, PCB, Hg) compared to PC2 (metals). **C.** PC3 (DDT versus PAH, PCB, Hg) compared to PC1(sediment texture (sand vs mud) versus TPH).



F

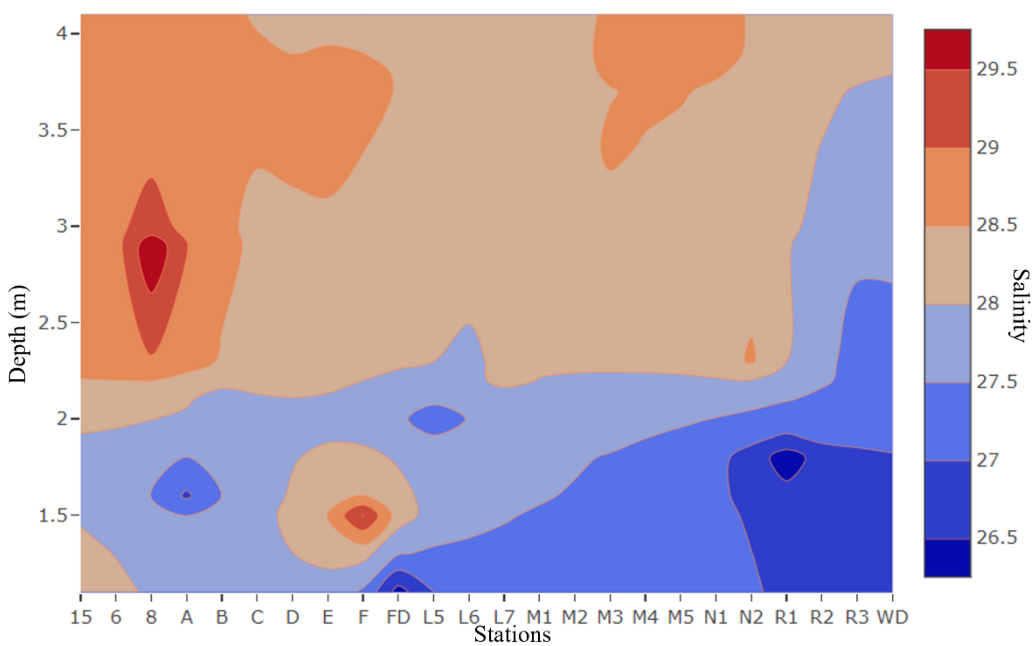


Figure S6. Contour map of salinity (S) at each station.

Table S1: Station names, locations, and comments on station choice. Abbreviations: FPC = Formosa Plastics Corporation, LB = Lavaca Bay, NFWF = National Fish and Wildlife Foundation, MB = Matagorda Bay, TCEQ = Texas Commission on Environmental Quality.

Station	**Latitude**	**Longitude**	**Description of Stations**
6	28.62479	-96.2402	Long term monitoring station (Montagna 2022)
8	28.57639	-96.1192	Long term monitoring station
15	28.61493	-96.0236	Long term monitoring station
A	28.67467	-96.58268	Long term monitoring station
B	28.63868	-96.58437	Long term monitoring station
C	28.54672	-96.46894	Long term monitoring station
D	28.48502	-96.28972	Long term monitoring station
E	28.5545	-96.2155	Long term monitoring station
F	28.60463	-96.046	Long term monitoring station
FD	28.68096	-96.58218	Long term monitoring station Formosa Discharge
L5	28.60293	-96.59201	New LB station
L6	28.59769	-96.51602	TCEQ station – (Russell et al. 2006)
L7	28.61975	-96.53019	New LB station
M1	28.519	-96.396	New MB station
M2	28.518	-96.333	New MB station
M3	28.60166	-96.35788	New MB station
M4	28.56538	-96.31	New MB station
M5	28.486	-96.364	New MB station
N1	28.71369	-96.19079	NFWF (TCEQ14680) Tres Palacios
N2	28.67166	-96.23936	NFWF (TCEQ14680) Tres Palacios
R1	28.70327	-96.61273	FPC Monitoring station (Harris et al. 2023)
R2	28.6752	-96.62315	FPC Monitoring station
R3	28.65215	-96.59625	FPC Monitoring station
WD	28.65621	-96.56664	Alcoa Witco Discharge monitoring station

Table S2. ABC analysis of each station indicating: +1 unstressed -1 Highly stressed

Station	**ABC Index**	**Stress Level**
6	0.45	Unstressed
8	0.147	Unstressed
15	-0.317	Highly Stressed
A	0.131	Unstressed
B	0.33	Unstressed
C	0.189	Unstressed
D	0.277	Unstressed
E	0.715	Unstressed
F	-0.189	Highly Stressed
FD	0.04	Partially Stressed
L5	0.251	Unstressed
L6	0.099	Partially stressed
L7	0.906	Unstressed
M1	0.467	Unstressed
M2	0.251	Unstressed
M3	0.616	Unstressed
M4	0.451	Unstressed
M5	0.321	Unstressed
N1	0.267	Unstressed
N2	0.301	Unstressed
R1	-0.041	Highly Stressed
R2	-0.091	Highly Stressed
R3	0.079	Partially Stressed
WD	0.537	Unstressed

Each station in Table S2 was categorized depending on the ABC analyses (Figs S1 – S3), where negative numbers represent stressed communities, and positive numbers represent unstressed communities.

Table S3. Spearman correlation (r) and probability level (p). Bolded p values are <0.05. A) benthic community metrics. Abbreviations: S = Richness, N = number of organisms n/m^2, d = Margalef richness, J' = Pielou's Evenness, H' = Shannon's diversity, N1 = Hill's diversity number 1, ABC = ABC index (Table S2), Survival = Average survival among all species (toxicity). B) Benthic metrics correlated to environmental principal components (PC) (Fig. S4). PC1 interpreted as sediment texture (sand) vs. hydrocarbon concentrations (TPH and alkanes), PC2 interpreted as metal concentrations, and PC3 interpreted as PAH, PCB, and Hg vs. DDT concentrations.

A)	**S**		**N**		**d**		**J'**		**H'**		**N1**		**ABC**	
	r	**p**	**r**	**p**	**r**	**p**	**r**	**p**	**r**	**p**	**r**	**p**	**r**	**p**
S	1													
N	0.438	**0.0321**	1											
d	0.970	**<.0001**	0.240	0.2585	1									
J	0.149	0.4859	-0.702	**0.0001**	0.355	0.0889	1							
H	0.726	**<.0001**	-0.184	0.3895	0.851	**<.0001**	0.743	**<.0001**	1					
N1	0.726	**<.0001**	-0.184	0.3895	0.851	**<.0001**	0.743	**<.0001**	1	**<.0001**	1			
ABC	0.148	0.4891	-0.611	**0.0015**	0.333	0.1122	0.879	**<.0001**	0.650	**0.0006**	0.650	**0.0006**		
Survival	0.201	0.3465	-0.531	**0.0076**	0.330	0.1157	0.603	**0.0018**	0.530	**0.0077**	0.530	**0.0077**	0.502	**0.0125**

B)	**S**		**N**		**d**		**J'**		**H'**		**N1**		**ABC**	
	r	**p**	**r**	**p**	**r**	**p**	**r**	**p**	**r**	**p**	**r**	**p**	**r**	**p**
PC1	0.164	0.4430	-0.355	0.0884	0.286	0.1753	0.637	**0.0008**	0.485	**0.0162**	0.537	**0.0069**	0.485	**0.0162**
PC2	0.067	0.7541	-0.334	0.1112	0.192	0.3683	0.586	**0.0026**	0.425	**0.0383**	0.490	**0.0150**	0.425	**0.0383**
PC3	-0.140	0.5148	-0.524	**0.0086**	-0.006	0.9775	0.460	**0.0237**	0.250	0.2379	0.270	0.2012	0.250	0.2379