MACROBENTHOS MONITORING IN MID-COASTAL ESTUARIES - 2014

by

Paul A. Montagna, Ph.D.

Texas A&M University – Corpus Christi
Harte Research Institute for Gulf of Mexico Studies
6300 Ocean Drive, Unit 5869
Corpus Christi, Texas 78412
Phone: 361-825-2040
Fax: 361-825-2050
Email: paul.montagna@tamucc.edu

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INTRODUCTION

Since the early 1970's, Texas Water Development Board (TWDB) sponsored freshwater inflow studies focused on the major bay systems of the Texas coast. These bay systems, which are influenced primarily by river inflow and exchange with the Gulf of Mexico, are now subject to greater scrutiny because of recent legislative changes. In recognition of the importance that the ecological soundness of our riverine, bay, estuary, and riparian areas has on the economy, health, and well-being of our state, the 80th Texas Legislature enacted Senate Bill 3 in 2007, which calls for creation of Basin and Bay Area Expert Science Teams (BBEST) to establish environmental flow recommendations 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." Thus, BBEST and BBASC groups will need information on freshwater inflow effects on water quality and biological indicator communities (Montagna et al. 2009, 2010).

Since 1986, researchers led by Dr. Montagna have been studying the effect of freshwater inflow on benthic communities and productivity (Kalke and Montagna 1991; Kim and Montagna 2009, 2012; Montagna 1989, 1999, 2000, 2013; Montagna et al. 2007; Montagna and Kalke 1992, 1995; Montagna and Li 1996, 2011; Montagna and Palmer 2009, 2010, 2011, 2012; Montagna and Yoon 1991; Pollack et al. 2009, 2011). These studies have demonstrated three main points: 1) freshwater inflow drives water quality and that regulates benthic abundance, productivity, diversity, and community structure, 2) there are salinity zone habitats within estuaries that are driven by inflow, and 3) long-term hydrological cycles affect biological dynamics within and among estuaries across the coast of Texas. Benthos are excellent bioindicators of environmental effects because they are very abundant and diverse, are sessile, and long-lived relative to plankton (Montagna et al. 2013). Therefore, benthos are good biological indicators of freshwater inflow effects because they integrate changes in temporal dynamics of ecosystem factors over long time scales and large spatial scales.

The benthic studies performed as part of the long-term monitoring of benthos (i.e., those listed above) have elucidated some basic principles on how inflow drives estuary and ecosystem dynamics. The Texas estuaries lie in a climatic gradient where those in the northeast receive more rainfall than those in the southwest. Consequently, freshwater inflow and nutrient loading decreases along the climatic gradient and salinity increases. In addition there is year-to-year variation in rain and inflow that results in wet and dry years. This combination of the climatic gradient and temporal variability drives variability in estuarine communities and secondary production. Among Texas estuaries, increased salinity (and thus decreased inflow) benefits deposit feeders (increased abundance and species richness), while suspension feeders are reduced (decreased abundance and species richness); thus there is a decrease in functional diversity when salinity is increased because of loss of a trophic guild. Within estuaries, the abundance and biomass of the upstream benthic community is reduced by reduced inflow, whereas, the downstream community increases in abundance and biomass with reduced inflow and higher salinities. This is because lower salinity regimes are required to support food production for suspension feeders, and polyhaline deposit feeding species increase during marine conditions.

Overall, these studies demonstrate that freshwater inflow is important in to maintain secondary productivity and functional diversity in estuaries, which is required to maintain estuarine health and sustainability (Montagna et al. 2013).

The ultimate goal of the long-term benthic data collection is to use the data to assess ecosystem health as it relates to change in freshwater inflow by assessing benthic habitat health, and benthic productivity. However, inflow itself does not affect ecosystem dynamics; it is the change in estuarine condition primarily salinity, nutrients, and chlorophyll, which drives change in biological resources (SAC 2009). Thus, the goal here is to relate changes in water column dynamics with change in benthic dynamics. The benthic data set has proven useful to date. For example, it has been used to create a model of productivity based on seven years (1988 - 1995) of data in four Texas estuaries: Lavaca-Colorado, Guadalupe, Nueces, and Laguna Madre (Montagna and Li 1996, 2010). The model was used to support inflow criteria development for Matagorda Bay in the Lavaca-Colorado Estuary (Kim and Montagna 2009). Recently, the adjusted model was rerun on 20 years (1988 - 2008) of benthic and water column data and it was shown that salinity and nutrient changes (which are caused by inflow changes) drives benthic productivity and functional diversity (Kim and Montagna 2010; 2012). In order to perform similar analyses and provide an understanding of the long-term ecosystem dynamics the San Antonio Bay system, data is needed, and the data collected during this study will support these efforts.

One surprising result is that based on a 20-year study in the Lavaca-Colorado Estuary, it appears that benthos are disappearing along the Texas coast (Pollack et al. 2011). Benthic abundance, biomass, and diversity are declining at log-scale rates. This is important because all the important commercial and recreational fishery species in Texas are bottom feeders, and the loss of potential forage must be a serious problem. These findings and implications raise several important questions: 1) Is this happening elsewhere in Texas? 2) Why is this happening at all? 3) Will it continue? 4) What are the ecosystem consequences? 5) If it is a problem, then what can we do about it? Here, we report the same trends in the Guadalupe Estuary.

METHODS

Sampling was performed in three estuaries in the Texas mid-coastal zone: Nueces, Guadalupe, and Lavaca-Colorado Estuaries (Figure 1). The study area is ideal to answer questions related to altered hydrology and climate variability occurring at different temporal scales (e.g., seasonal, annual, multi-annual), and different spatial scales of inflow along climatic (among estuary) and estuarine (within estuary) gradients (Figure 1).

Stations were located in primary bays closer to the Gulf of Mexico exchange point, and in secondary bays closer to the freshwater inflow sources (Table 1). Four stations were sampled for macrofauna and water quality in the Guadalupe Estuary, six in the Lavaca-Colorado Estuary, and five in the Nueces Estuary.

Water column and sediment samples were collected at all stations in all estuaries. However, benthic samples were analyzed only in the Guadalupe Estuary and the benthic samples from the Nueces and Lavaca-Colorado estuaries were archived for future analysis. Only the benthos from the Guadalupe Estuary are described and discussed in this report.

Sampling occurred 10 times: July 2013, October 2013, January 2014, April 2014, July 2014, October 2014, January 2015, April 2015, July 2015, and October 2015.

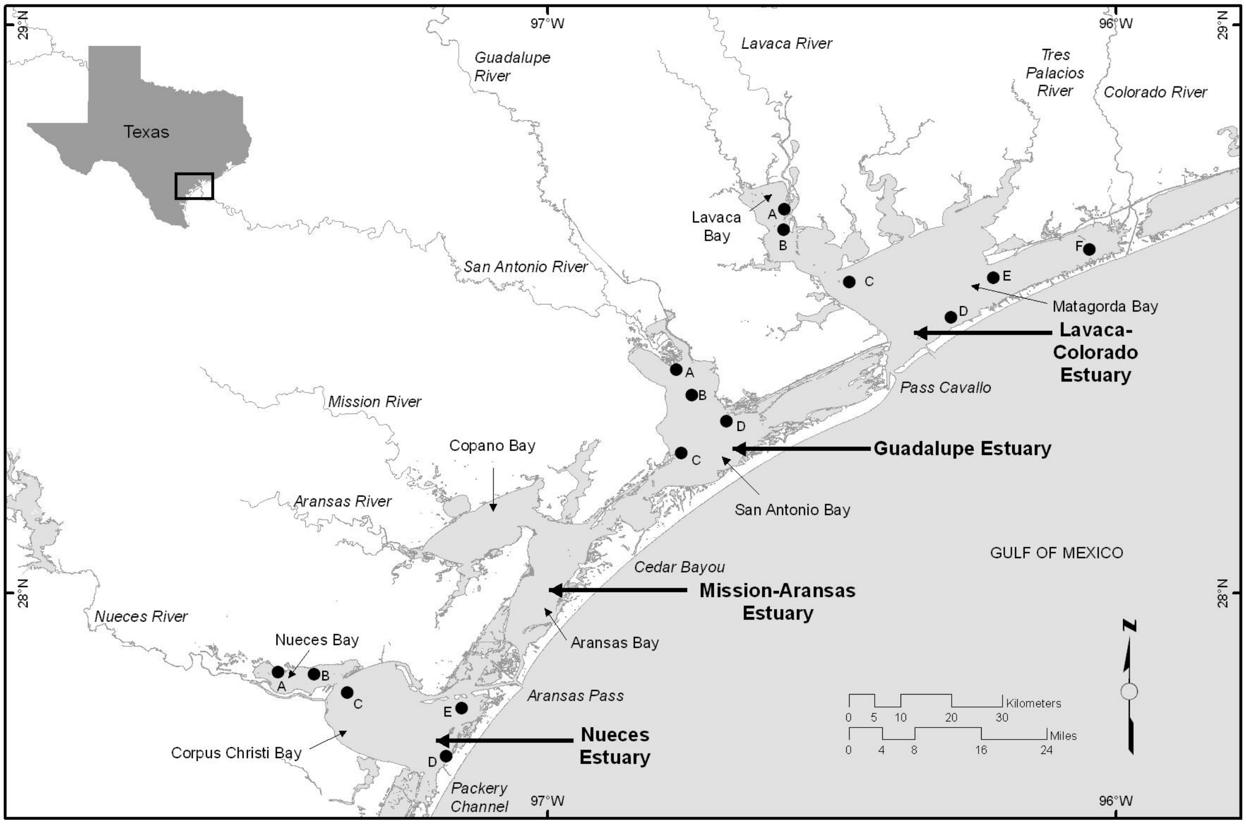

Figure 1. The three Texas Coastal Bend estuaries sampled. Station locations are along a climatic (among estuaries) and estuarine (within estuaries) gradients. Mission-Aransas estuary not sampled.

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

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

Water Quality

Physical water quality measurements in addition to chlorophyll and nutrients were sampled in duplicate just beneath the surface and at the bottom of the water column at all stations on every sampling date.

Hydrographic measurements were made at each station with a YSI 6600 multi parameter instrument. The following parameters were read from the digital display unit (accuracy and units): temperature (± 0.15 °C), pH (± 0.1 units), dissolved oxygen (± 0.2 mg l^{-1}), depth (± 1 m), and salinity (psu). Salinity is automatically corrected to 25 °C.

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

Nutrient samples were filtered to remove biological activity (0.45 µm polycarbonate filters) and placed on ice (<0.4 °C).Water samples were analyzed at the Harte Research Institute using a OAI Flow-4 autoanalyzer with computer controlled sample selection and peak processing. Chemistries are as specified by the manufacturer and have ranges as follows: nitrate+nitrate (0.03-5.0 µM; Quikchem method 31-107-04-1-A), silicate (0.03-5.0 µM; Quikchem method 31-114-27-1-B), ammonium (0.1-10 µM; Quikchem method 31-107-06-5-A) and phosphate (0.03-2.0 µM; Quikchem method 31-115-01-3-A.

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

Macrofauna

Sediment samples were collected using cores deployed from small boats. The position of all stations is established with a Global Positioning System (GPS) with an accuracy of ±3 m. Macrofauna were sampled with a 6.7-cm diameter core tube (35.4 cm^2 area). The cores were sectioned at 0-3 cm and 3-10 cm depths to examine vertical distribution of macrofauna. Three replicates are taken per station. Organisms are enumerated to the lowest taxonomic level possible, and biomass is determined for higher taxonomic groupings.

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 displayed on the MDS plot to elucidate grouping of station-date combinations. The group average cluster mode was used for the cluster analysis.

RESULTS

Guadalupe Estuary During the Study Period

Principal Components Analysis explained 73 % of the variation within the water quality data set (Figure 2). Principal Component (PC) 1 explained 42 % of the variation while PC2 explained 31 % of the variation. PC1 represents temporal changes in water quality and represents seasonal changes in water quality with high temperatures being inversely proportional to low dissolved oxygen concentrations (Figure 2A and 2C). Along the PC1 axis, high temperature is correlated with phosphate, and silicate concentrations (Figure 2A). PC2 represents an inflow gradient because the lowest salinity values are correlated to highest ammonia concentrations, and inversely correlated to Nitrite+Nitrate (NO2+3) and chlorophyll (Chl) concentrations, which occur in Stations A and B nearest the Guadalupe River mouth (Figure 2C). Interestingly, salinity is also inversely correlated with pH, which means when salinity is high, the bays are becoming more acidic.

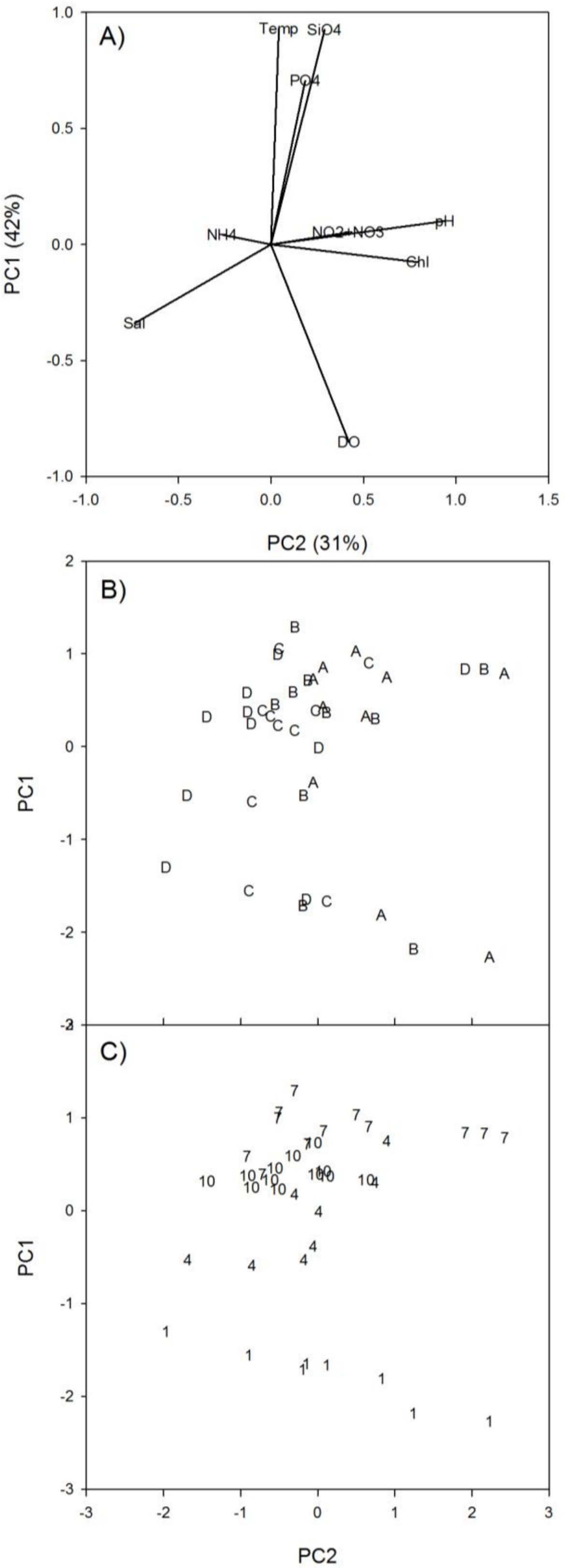

Figure 2. Principal Components Analysis (PCA) of water quality variables in the Guadalupe Estuary. Variable loading plot (A) and station scores labeled by station (B) and month (C) from July 2013 through to October 2015.

The lowest average salinity and highest average concentrations of all nutrients (silicate, phosphate, ammonia, and nitrate+nitrite), and chlorophyll concentrations occur at Stations A and B, and this is an indicator of river flow from the Guadalupe River into San Antonio Bay (Table 2). Ammonium concentrations are below detection limits for many samples, so the overall average is only near 1 umol/L. Mean chlorophyll concentrations are the highest at stations A and B, and decrease along the salinity gradient from station C to Station D. Mean dissolved oxygen concentrations are also highest at station A, and decline along the salinity gradient.

Table 2. Overall average (for both top and bottom and over the sampling period) mean water quality values for each station. Standard deviation for all samples at each station are in parentheses. Abbreviations: NH4=ammonium, NO2+3=nitrate+nitrite, PO4=phosphate, SiO4=silicate, and Chl=chlorophyll

Water Quality Variable (units)	Station (number of samples)							
	A (45)		B (51)		C (47)		D (58)	
	Mean	STD	Mean	STD	Mean	STD	Mean	STD
DO (mg/l)	8.90	(4.41)	8.94	(4.31)	7.78	(2.04)	7.53	(2.02)
Salinity (psu)	16.69	(8.97)	21.06	(8.98)	24.90	(8.71)	26.71	(8.14)
Temperature (C)	24.00	(7.56)	22.29	(8.23)	24.03	(7.47)	23.14	(7.78)
NH4 (umol/L)	2.06	(2.43)	0.97	(0.63)	1.55	(2.26)	1.84	(3.24)
NO2+3 (umol/L)	20.14	(44.75)	1.98	(3.06)	1.17	(1.55)	1.42	(1.95)
P04 (umol/L)	3.40	(4.37)	2.09	(3.14)	1.68	(2.43)	1.48	(2.50)
Si04 (umol/L)	136.73	(92.18)	100.42	(74.10)	79.61	(50.55)	72.79	(65.67)
Chl (mg/l)	27.48	(20.78)	17.50	(7.85)	9.43	(3.55)	9.10	(7.60)
pH	8.45	(0.27)	8.36	(0.28)	8.20	(0.23)	7.96	(0.30)

The sampling period was characterized by drought conditions from January 2013 to February 2015, which maintained high salinities near 28 psu over the entire estuary for the entire period (Figure 3). The high salinities were maintained even though there were 7 high inflow events where flows were greater than 1900 cfs per day because none of the events were for long periods of time. In contrast, nearly continuous flows occurred from March 2015 to July 2015, which caused salinity to average near zero over the entirety of San Antonio Bay by July 2015 (Figure 3).

Chlorophyll was uniformly low until the spring rains, after which it rose and dropped again when it became drier (Figure 3). Nutrient behavior was complex, for example ammonium peaks with lowest salinities, but also peaks in April 2014 when salinities were high. Nitrate+Nitrite and silicate generally follow patterns that are the inverse of salinity.

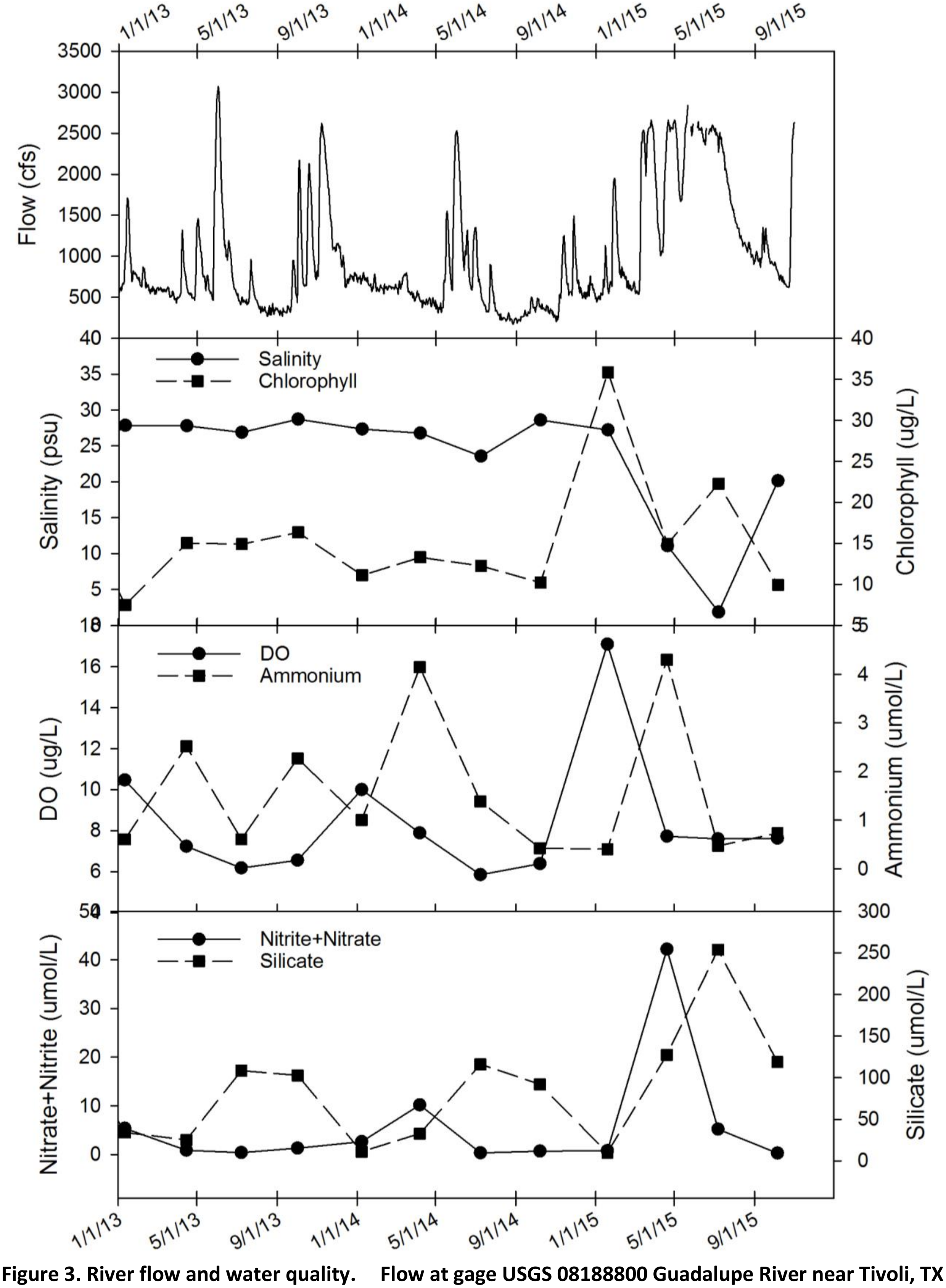

Figure 3. River flow and water quality. Flow at gage USGS 08188800 Guadalupe River near Tivoli, TX and mean estuary-wide water quality parameters during sampling periods.

The four stations (A through D) in San Antonio Bay lie along a gradient from river to marine end at the Gulf Intracoastal Waterway (Figure 1) and that is reflected in the differences in salinity among the stations as well where salinity increases from A to B, B to C, and C to D (Figure 4A). However, analysis of variance showed that the stations were all significantly different for salinity (Table 3).

Station A, closest to the river, and station D (closest to Gulf influence) had the highest macrofauna abundance (Figure 4B), and diversity (Figure 4D), but station D had the highest biomass (Figure 4C). Biomass was similar, and always low, in stations B and C, and usually at station A as well. The extreme flooding that led to near zero salinities in July 2015 resulted in a loss of benthos.

Table 3. A 2-way analysis of variance (ANOVA) of salinity, abundance, biomass, and diversity in the Guadalupe estuary during the study period.

Salinity(psu)

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Date	10	5.91E+03	5.91E+02	529.99	<.0001
Station	3	1.12E+03	3.73E+02	334.08	<.0001
Date*Station	30	3.49E+02	1.16E+01	10.43	<.0001
Error	44	4.91E+01	1.12E+00		
Corrected Total	87	7.43E+03			

Abundance (n/m²)

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Date	10	2.78E+09	2.78E+08	12.1	<.0001
Station	3	3.17E+09	1.06E+09	45.92	<.0001
Date*Station	30	3.06E+09	1.02E+08	4.44	<.0001
Error	88	2.02E+09	2.30E+07		
Corrected Total	131	1.10E+10			

Biomass (g/m²)

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Date	10	2.45E+04	2.45E+03	1.32	0.2318
Station	3	3.93E+04	1.31E+04	7.08	0.0003
Date*Station	30	7.44E+04	2.48E+03	1.34	0.1486
Error	48	2.50E+04	5.21E+02		
Corrected Total	71	4.17E+04			

Diversity (S/core)

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Date	10	1.72E+01	1.72E+00	16.89	<.0001
Station	3	2.21E+01	7.36E+00	72.14	<.0001
Date*Station	30	1.07E+01	3.56E-01	3.49	<.0001
Error	87	8.88E+00	1.02E-01		
Corrected Total	130	5.86E+01			

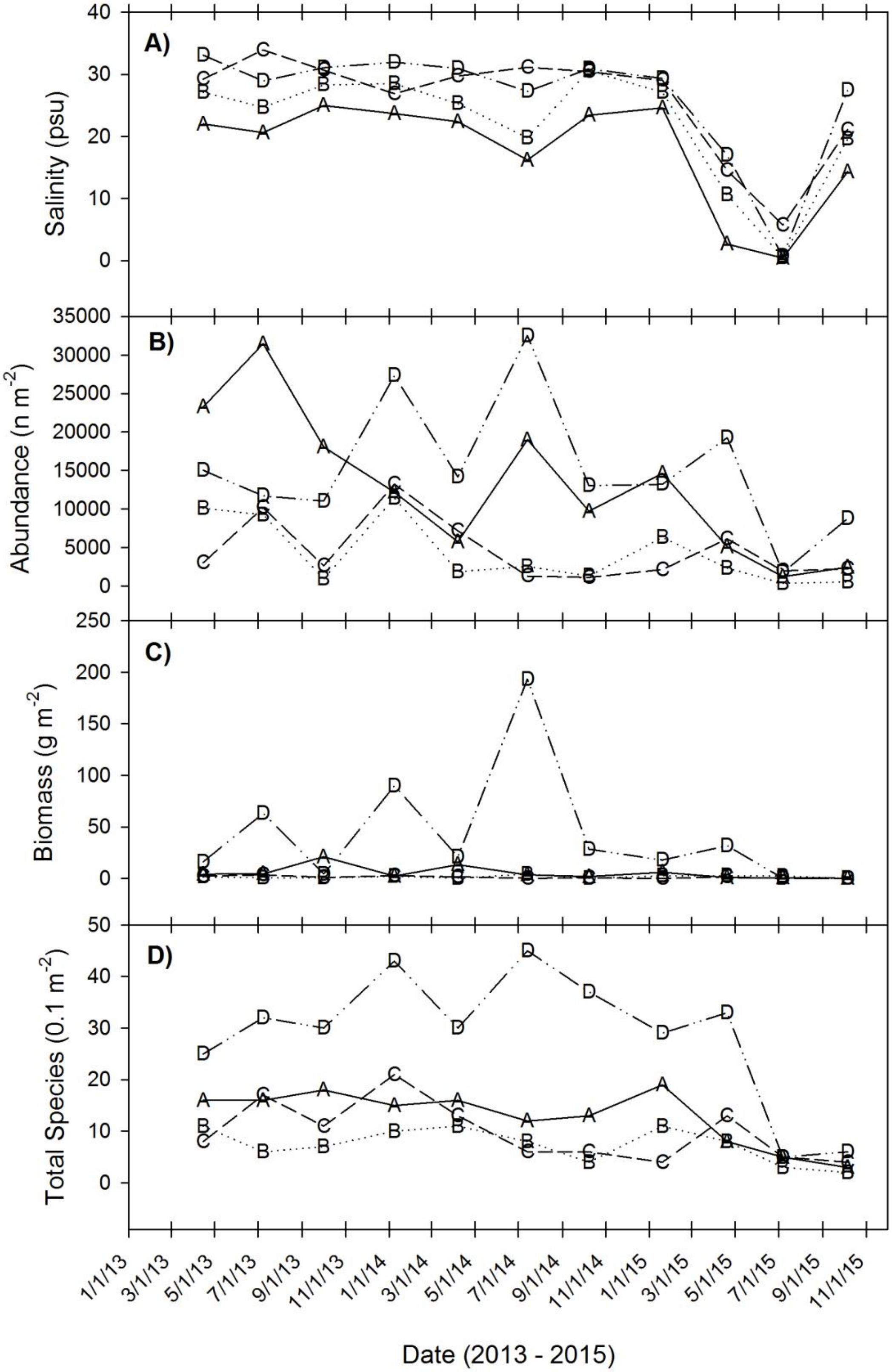

Figure 4. Macrofauna characteristics in the Guadalupe Estuary by station over the sampling period. Subfigures: A) Salinity, B) Abundance, C) Biomass, and D) Diversity.

There were a total of 126 species found over the study period (Table 4). The capitellid polychaete *Mediomastus ambiseta* was the most abundant species overall and was especially dominant at station A. Overall, *M. ambiseta* made up about 42 % of the total number of organisms found. Another polychaete *Streblospio benedicti* was the second most dominant species and it made up about 10% of the organisms. The species *Molgula manhattensis* (Tunicata, Ascidiacea) was the third dominant species at about 5%. This species was found predominantly at station D, and had a bloom between January and July 2014, when salinities were highest. Two more polychaete worms, *Dipolydora caulleryi* and *Cossura delta* made up about 4% or the community each. Together the five most dominant species made up 64% of all organisms found. Only 13 species occur at all four stations. The high diversity found in San Antonio Bay is made up of rare organisms or organisms found primarily in the marine parts of the bay, especially stations C and D. For example 67 species were found in only one station, and 39 species were found only three times once in all the samples. Together these rare species made up 53% of all species found.

Table 4. Species abundance and occurrence at stations in Guadalupe Estuary. Average abundance (n m^{-2}) over the period April 2013 to October 2015 period.

	Stations					
Species Name	**A**	**B**	**C**	**D**	**Mean**	**% Total**
Mediomastus ambiseta	7,426	2,046	1,822	4,349	3,911	41.86%
Streblospio benedicti	2,407	774	309	189	920	9.84%
Molgula manhattensis	17	0	0	1,831	462	4.94%
Dipolydora caulleryi	17	0	352	1,135	376	4.02%
Cossura delta	387	688	172	129	344	3.68%
Streblospio gymnobranchiata	559	86	77	0	180	1.93%
Axiothella sp. A	180	9	52	413	163	1.75%
Gyptis vittata	112	43	34	395	146	1.56%
Clymenella torquata	0	0	52	524	144	1.54%
Nuculana acuta	9	103	249	112	118	1.26%
Mediomastus californiensis	34	9	0	421	116	1.24%
Nemertea (unidentified)	103	26	60	258	112	1.20%
Glycinde solitaria	112	52	95	180	110	1.17%
Periploma margaritaceum	0	0	9	370	95	1.01%
Ceratonereis irritabilis	0	9	9	361	95	1.01%
Cerapus tubularis	0	0	335	9	86	0.92%
Aligena texasiana	0	0	17	327	86	0.92%
Caprellidae (unidentified)	0	9	284	34	82	0.87%
Notomastus latericeus	0	0	0	327	82	0.87%
Acteocina canaliculata	69	86	52	69	69	0.74%
Oligochaeta (unidentified)	266	0	0	0	67	0.71%
Mysella planulata	0	0	9	258	67	0.71%
Paraprionospio pinnata	34	69	77	69	62	0.67%
Melinna maculata	26	0	26	189	60	0.64%
Euclymene sp. B	9	0	0	223	58	0.62%

	Stations					
Species Name	**A**	**B**	**C**	**D**	**Mean**	**% Total**
Mulinia lateralis	95	34	26	60	54	0.57%
Sphaerosyllis sp. A	0	0	0	206	52	0.55%
Amaeana trilobata	0	0	9	198	52	0.55%
Haploscoloplos foliosus	86	69	43	0	49	0.53%
Lumbrineris parvapedata	0	0	0	189	47	0.51%
Microphiopholis atra	17	9	17	138	45	0.48%
Tharyx setigera	0	0	0	180	45	0.48%
Microprotopus sp.	146	9	9	9	43	0.46%
Spiochaetopterus costarum	0	0	9	163	43	0.46%
Haploscoloplos fragilis	69	69	26	0	41	0.44%
Hemicyclops sp.	0	26	0	138	41	0.44%
Polydora cornuta	95	0	0	60	39	0.41%
Hermundura ocularis	52	0	0	103	39	0.41%
Cyclaspis varians	60	0	52	43	39	0.41%
Diopatra cuprea	43	0	43	69	39	0.41%
Capitella capitata	112	0	34	0	37	0.39%
Clymenella mucosa	9	0	0	112	30	0.32%
Turbonilla sp.	0	0	52	69	30	0.32%
Turbellaria (unidentified)	77	0	34	0	28	0.30%
Macoma mitchelli	60	34	0	17	28	0.30%
Sabaco elongata	9	0	0	95	26	0.28%
Maldanidae (unidentified)	26	0	17	43	21	0.23%
Ampelisca abdita	77	0	0	0	19	0.21%
Listriella barnardi	0	0	0	77	19	0.21%
Glycera americana	0	0	0	77	19	0.21%
Xenanthura brevitelson	0	0	0	77	19	0.21%
Pandora trilineata	9	26	34	0	17	0.18%
Scolelepis (Parascolelepis) texana	43	0	0	26	17	0.18%
Monocorophium acherusicum	60	9	0	0	17	0.18%
Terebella sp.	0	0	0	69	17	0.18%
Listriella clymenellae	0	0	0	60	15	0.16%
Vitrinella floridana	0	0	0	60	15	0.16%
Phoronis architecta	0	0	17	34	13	0.14%
Malmgreniella taylori	0	0	0	52	13	0.14%
Batea catharinensis	9	0	0	43	13	0.14%
Tellina texana	17	0	0	26	11	0.11%
Paleanotus heteroseta	0	0	0	43	11	0.11%
Chironomidae (larvae)	26	9	0	0	9	0.09%
Heteromastus filiformis	17	0	0	17	9	0.09%
Paranaitis speciosa	9	0	17	9	9	0.09%
Ischadium recurvum	0	0	17	17	9	0.09%

	Stations					
Species Name	**A**	**B**	**C**	**D**	**Mean**	**% Total**
Megalomma bioculatum	0	0	17	17	9	0.09%
Laonome sp.	0	0	0	34	9	0.09%
Pista palmata	0	0	0	34	9	0.09%
Hobsonia florida	26	0	0	0	6	0.07%
Alitta succinea	17	9	0	0	6	0.07%
Polydora websteri	17	0	0	9	6	0.07%
Erichthonias punctatus	0	9	9	9	6	0.07%
Hauchiella sp.	0	0	0	26	6	0.07%
Pinnixa sp.	0	0	0	26	6	0.07%
Armandia sp.	17	0	0	0	4	0.05%
Oxyurostylis sp.	17	0	0	0	4	0.05%
Monoculodes sp.	9	0	9	0	4	0.05%
Pectinaria gouldii	9	0	9	0	4	0.05%
Eusarsiella texana	0	0	17	0	4	0.05%
Leucon sp.	0	0	9	9	4	0.05%
Fargoa cf. gibbosa	0	0	0	17	4	0.05%
Hydroides protulicola	0	0	0	17	4	0.05%
Magelona rosea	0	0	0	17	4	0.05%
Rictaxis punctostriatus	0	0	0	17	4	0.05%
Spirobranchus americanus	0	0	0	17	4	0.05%
Dorvilleidae (unidentified)	9	0	0	0	2	0.02%
Melita nitida	9	0	0	0	2	0.02%
Orbiniidae (unidentified)	9	0	0	0	2	0.02%
Pseudodiaptomus pelagicus	9	0	0	0	2	0.02%
Callianassa sp.	0	0	9	0	2	0.02%
Cirratulidae (unidentified)	0	0	9	0	2	0.02%
Diolydora socialis	0	0	9	0	2	0.02%
Halacaridae (unidentified)	0	0	9	0	2	0.02%
Laeonereis culveri	0	0	9	0	2	0.02%
Nassarius acutus	0	0	9	0	2	0.02%
Phascolion strombus	0	0	9	0	2	0.02%
Abra aequalis	0	0	0	9	2	0.02%
Ampelisca verrilli	0	0	0	9	2	0.02%
Assiminea succinea	0	0	0	9	2	0.02%
Bivalvia (unidentified)	0	0	0	9	2	0.02%
Brania furcelligera	0	0	0	9	2	0.02%
Caecum johnsoni	0	0	0	9	2	0.02%
Capitellides jonesi	0	0	0	9	2	0.02%
Corbula contracta	0	0	0	9	2	0.02%
Corophium ascherusicum	0	0	0	9	2	0.02%
Crassostrea virginica	0	0	0	9	2	0.02%
Dosinia discus	0	0	0	9	2	0.02%

	Stations					
Species Name	**A**	**B**	**C**	**D**	**Mean**	**% Total**
Drilonereis magna	0	0	0	9	2	0.02%
Ensis minor	0	0	0	9	2	0.02%
Eulimastoma sp.	0	0	0	9	2	0.02%
Fabricinuda trilobata	0	0	0	9	2	0.02%
Gastropoda (unidentified)	0	0	0	9	2	0.02%
Lumbrineris branchiata	0	0	0	9	2	0.02%
Macoma tenta	0	0	0	9	2	0.02%
Magelona phyllisae	0	0	0	9	2	0.02%
Marphysa sanguinea	0	0	0	9	2	0.02%
Naineris laevigata	0	0	0	9	2	0.02%
Nassarius vibex	0	0	0	9	2	0.02%
Phylo felix	0	0	0	9	2	0.02%
Placostegus sp.	0	0	0	9	2	0.02%
Potamilla cf. spathiferus	0	0	0	9	2	0.02%
Sabellidae (unidentified)	0	0	0	9	2	0.02%
Schistomeringos rudolphi	0	0	0	9	2	0.02%
Spiophanes bombyx	0	0	0	9	2	0.02%
Sthenelais boa	0	0	0	9	2	0.02%
Total	13,133	4,315	4,676	15,248	9,343	1

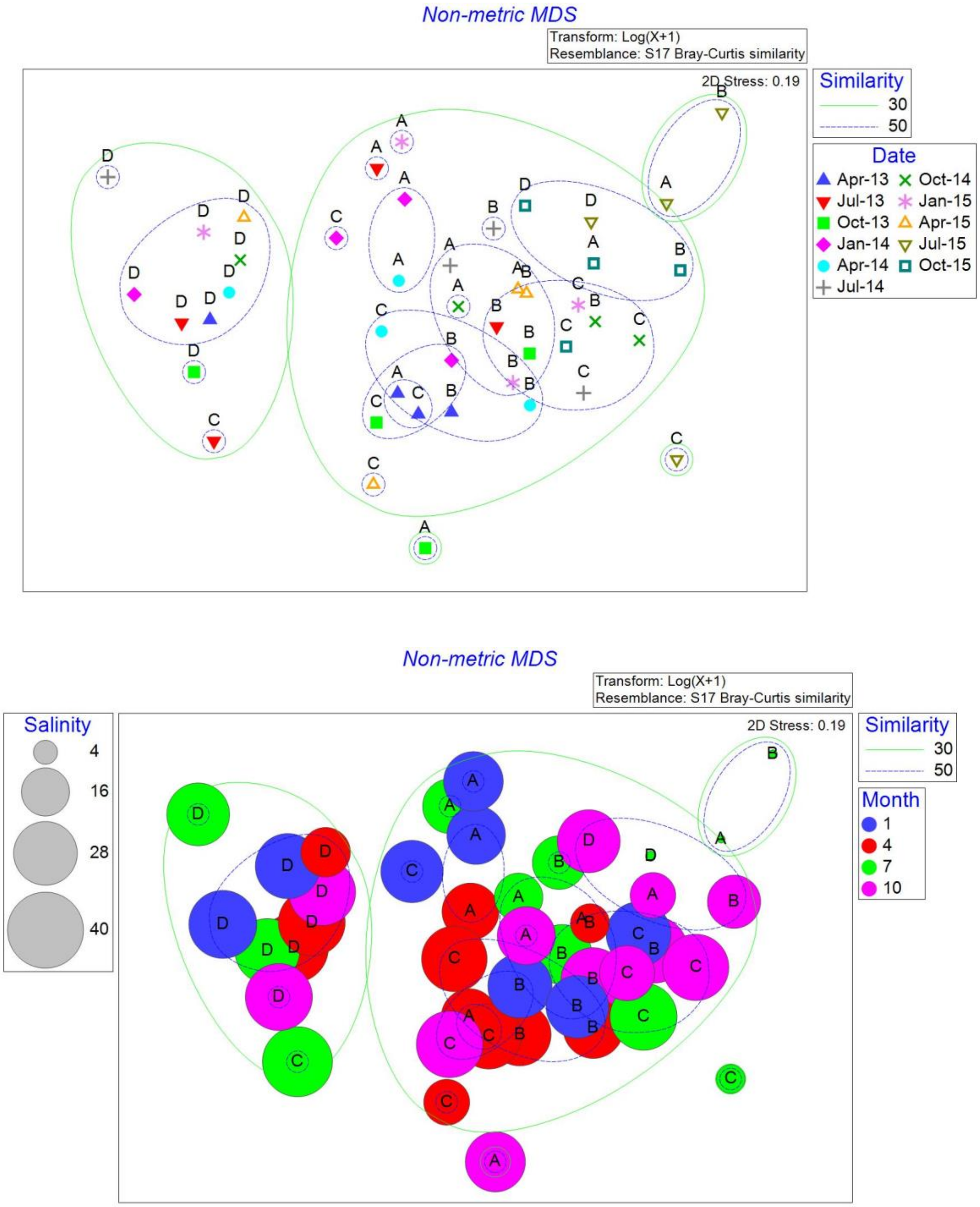

Figure 5. Multidimensional Scaling plot of macrofaunal community structure in the Guadalupe Estuary. Top: symbols are labeled by date-station combination. Bottom: Symbols are bubble plots of bottom salinity values at the sampling time. Lines indicate percent similarity of samples from a cluster analysis

Macrofauna community similarity for each station-date combination is depicted in a multidimensional scaling plot (MDS, Figure 5). Significant clustering of communities are represented by similarity contours that are overlaid on the MDS plot. In general, there is a trend in the plot from right to left of communities from the fresher stations A and B to the marine station D. These represent changes in salinity over time and space. Macrofauna communities at Station A and B in July 2015, when salinities were near zero, were significantly different from any other communities. The salinity anomaly had such a great spatial extent that even the communities at station D in July and October 2015 were clustered near stations A and B at that time.

Long-term Analyses of the Guadalupe Estuary

Benthic data has been collected in the Guadalupe Estuary since 1987 (Figure 6). The period between 2013 and 2014 was one of the most extended dry periods in the record, averaging about 28 psu over the entire estuary-bay system for the entire period. The highest estuary-wide average salinity however, reaching an average of 35 psu among all stations, occurred in October 2011. The other months when salinity was also high were October 1988 (25 psu), October 1996 (29 psu), October 1999 (25 psu), October 2008 (27 psu), and July 2009 (29 psu). So the dry period in 2013-2014 was typical of past dry periods, it was just longer. However, prior to 2011, the highest recorded average salinity was 6 psu less than observed that October 2011, which was the most acute dry period.

There has been a long-term decline in abundance over the entire range of sampling dates, and this continued during the current sampling period. Biomass has fluctuated, sometimes high biomass occurs during high salinity periods as it did between 1994 – 1996, 2000, 2005 – 2006, 2008-2009, and 2014. But high biomass always occurs following low salinity periods, indicating a lagged effect. The biomass was relatively low over the current sampling period compared to the long-term trends, but there was an anomalous peak in April 2014 when the highest biomass ever recorded (50 g/m^2) was observed. Diversity fluctuates with salinity, being higher during high salinity periods. Diversity trends also most clearly track salinity trends of all the benthic metrics.

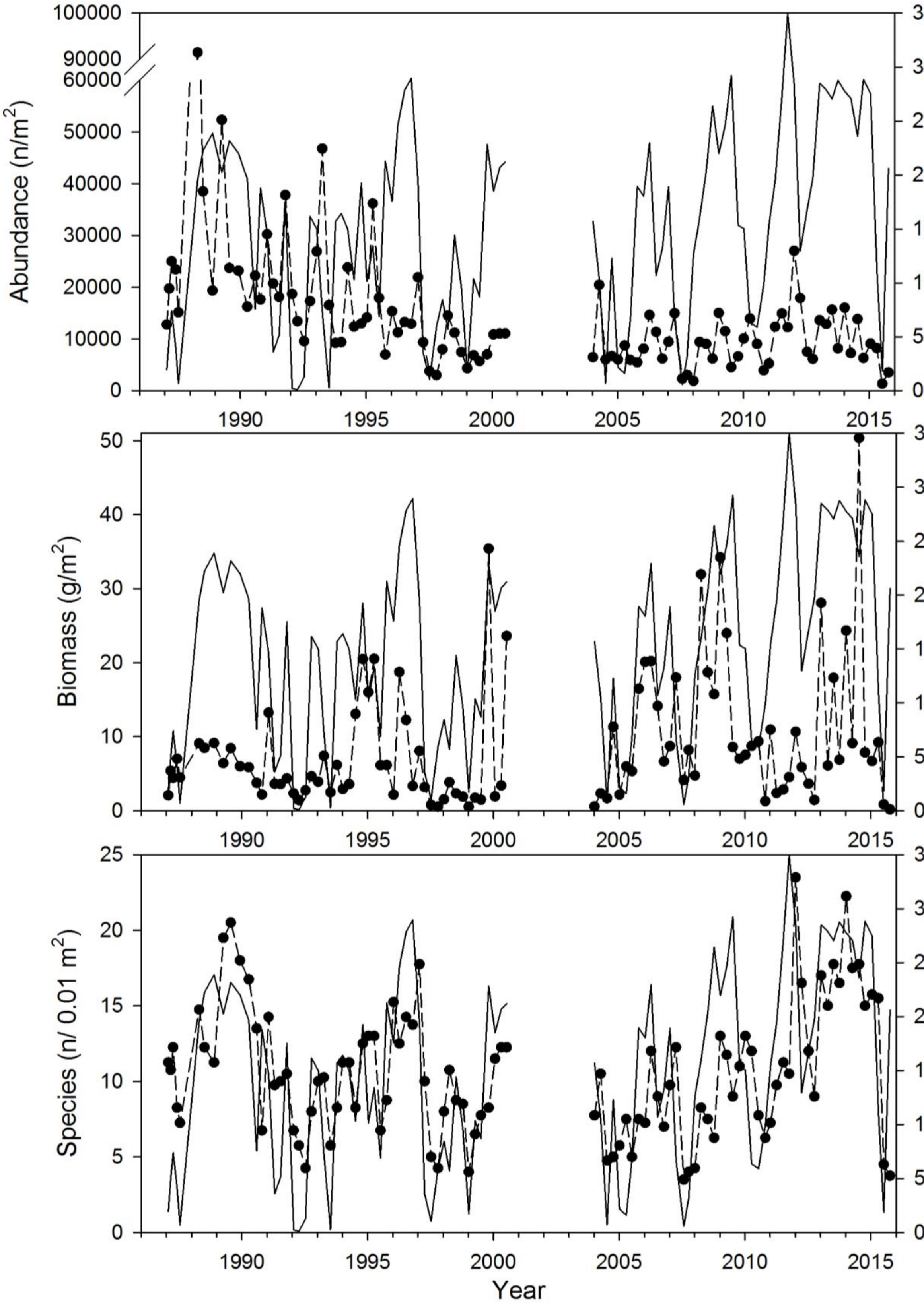

Figure 6. Long-term change in estuary-wide, average, abundance (top), biomass (middle), and diversity (bottom) with dots dashed lines and bottom salinity with a continuous line and no markers.

Water Column Conditions in Mid-Coastal Estuaries

Water quality measurements were also made in the Nueces (NC) and Lavaca-Colorado (LC) estuaries. The salinity change over time is largely parallel among the three estuaries (Figure 7). The wet period in April 2015 to July 2015 can be seen as lower salinities in all three estuaries. For the period April 2013 to October 2015, the Guadalupe Estuary GE) has the lowest mean salinity 14.5 psu, the Lavaca-Colorado Estuary has an average salinity of 22.5 psu, and the Nueces Estuary had the highest average salinity 30.2 psu.

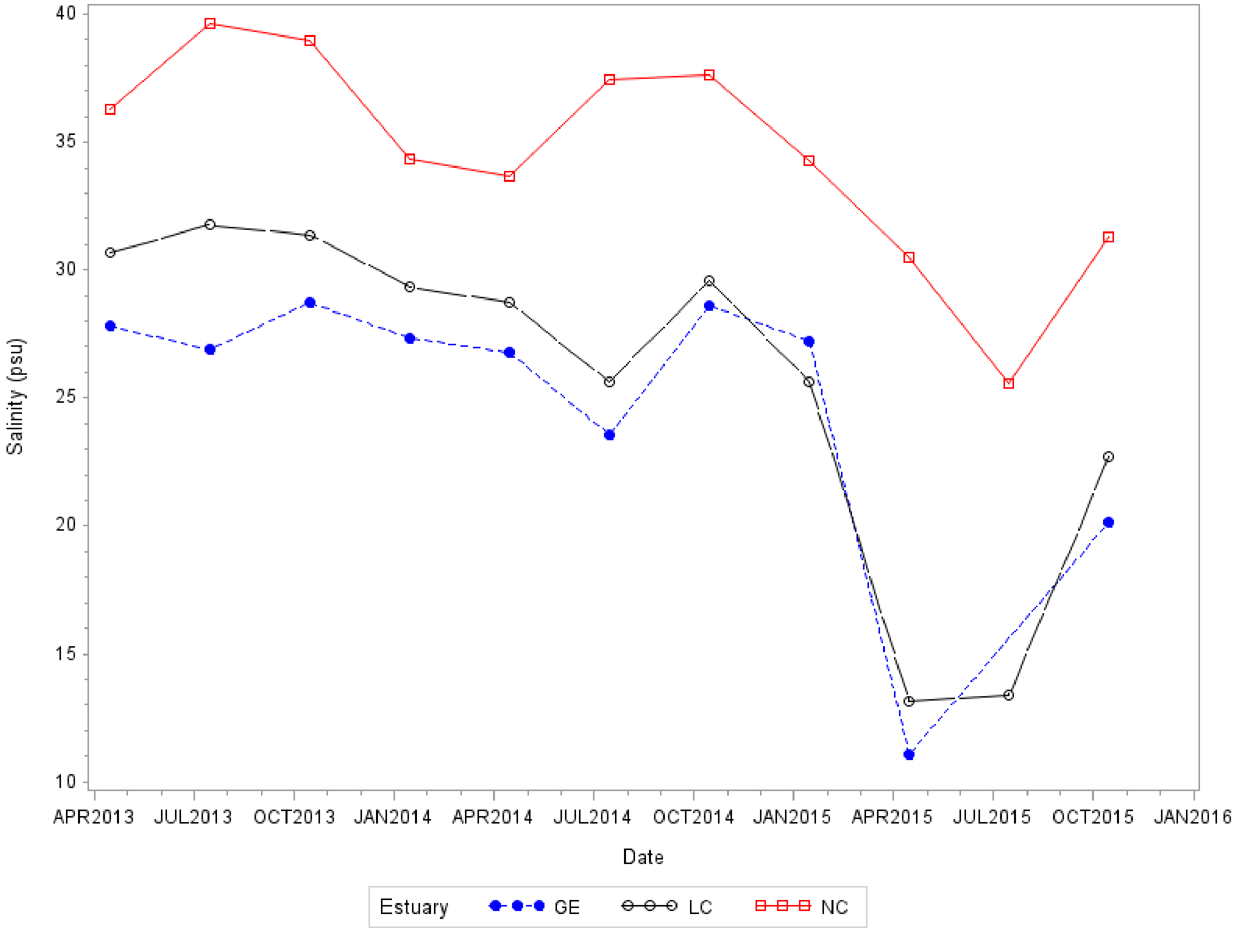

Figure 7. Average estuary-wide salinity for each sampling period during the current study in three mid-coast estuaries.

Salinity at stations generally follows the expected gradient of lower values near the freshwater input source relative to the point of exchange with the Gulf of Mexico. In the Guadalupe Estuary, station C was higher than D in July in all three years (2013 – 2015) (Figure 8).

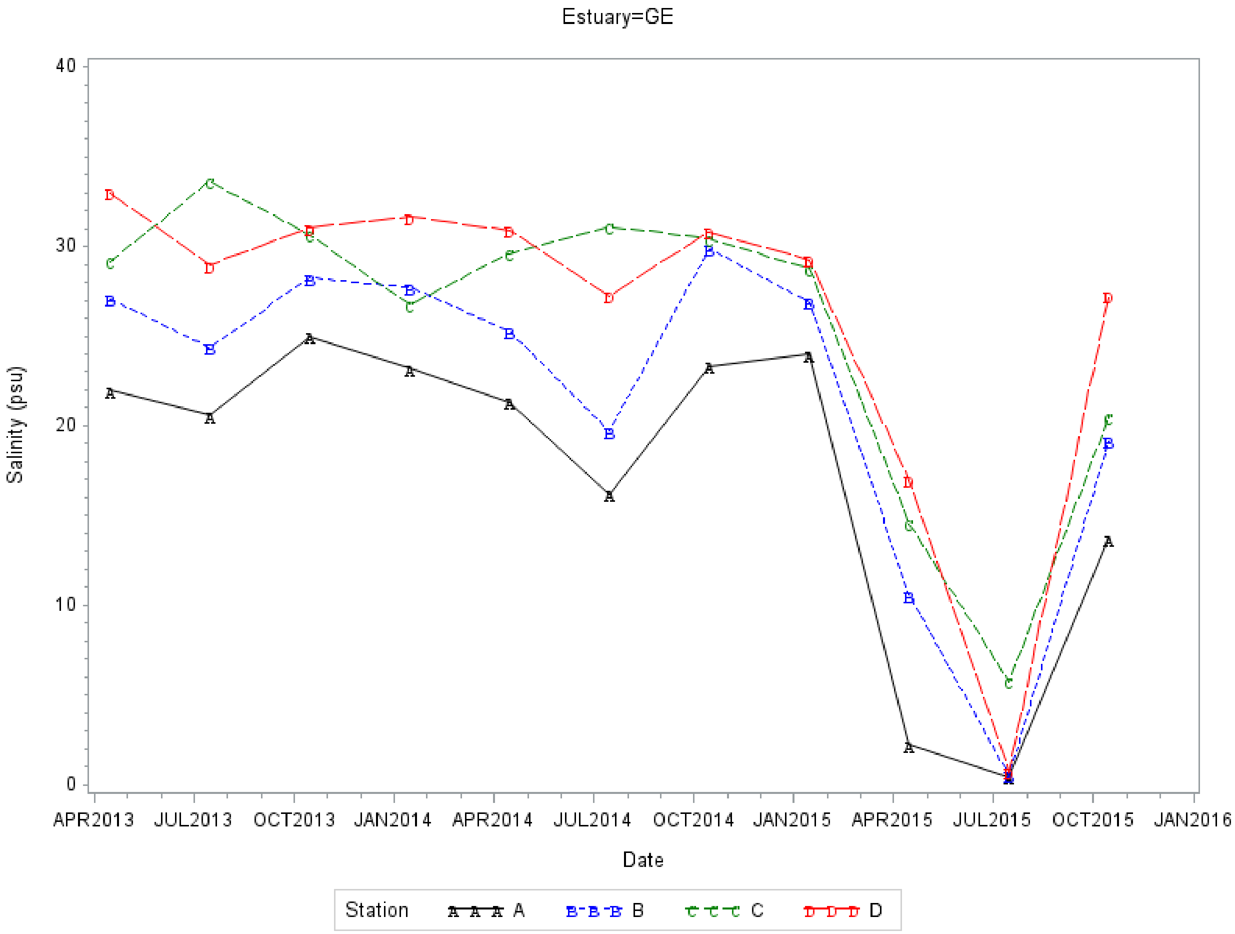

Figure 8. Salinity at stations within the Guadalupe Estuary (GE).

The Nueces Estuary is a “reverse estuary” so in dry periods the highest salinities are at stations A and B near the mouth of the Nueces River as it was in April 2013 and October 2013 (Figure 9). The Nueces River was running in July 2014 and July 2015 so salinities were lower at stations A and B during that time.

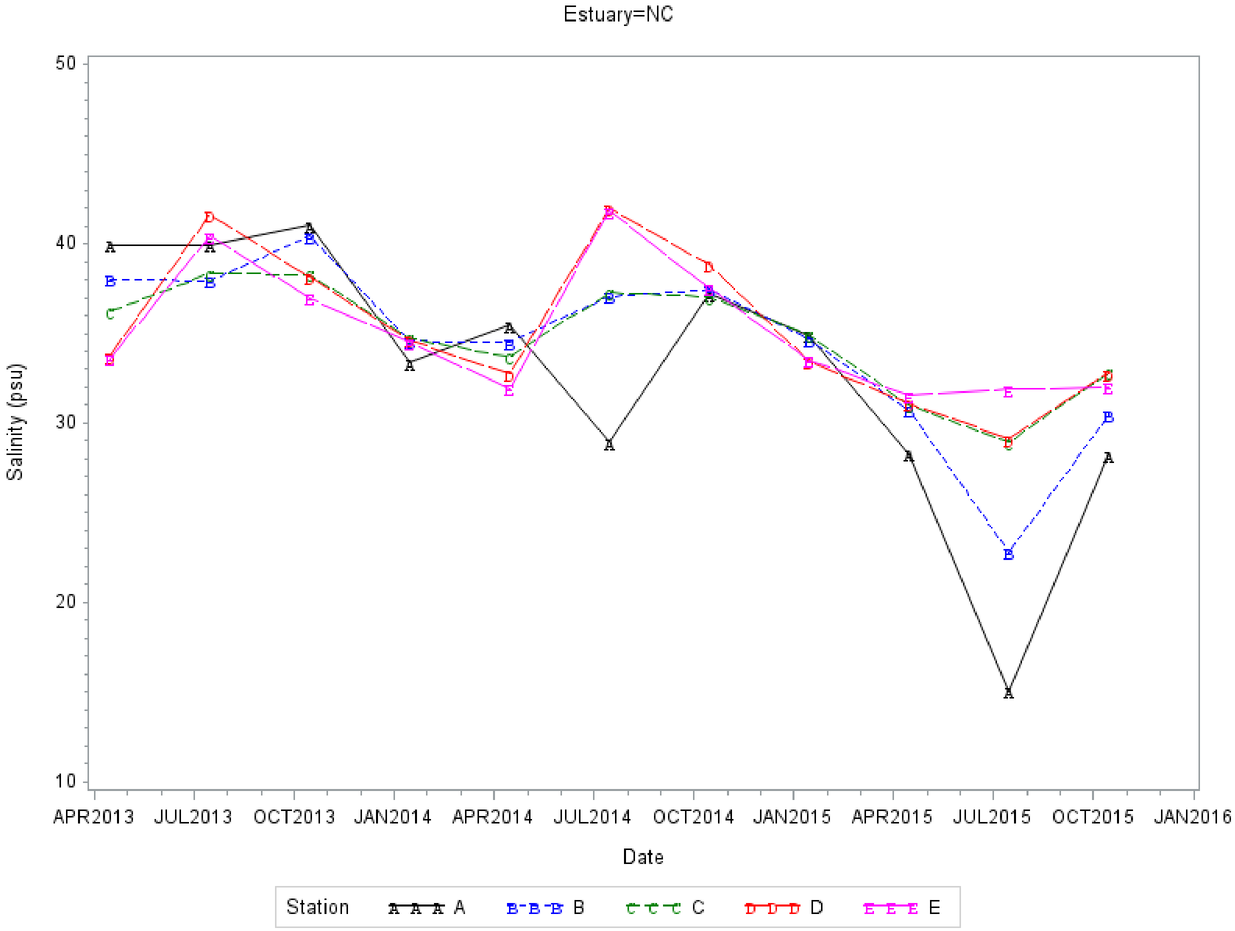

Figure 9. Salinity at stations within the Nueces Estuary (NC).

The Lavaca-Colorado Estuary has two river sources the Lavaca River, which enters Lavaca Bay (near stations A and B); and the Colorado River, which enters Matagorda Bay (near stations E and F) (Figure 1). Because of the two inflow sources, station F in Matagorda Bay sometimes takes on characteristics of stations A and B in Lavaca Bay when flows are high, as it did in April and July 2015 (Figure 10). However, when flows are lower, as in July 2014, insufficient flow goes down the Colorado River and salinity at stations E and F remain high. On only two occasions, January 2014 and January 2015, Station F had the lowest salinity values, which might indicated that more flow was coming in from the Colorado River than the Lavaca River at those times. The period between April 2013 and April 2014 was so dry that all stations had uniformly high salinities, and thus there was no estuarine gradient in the system during that period.

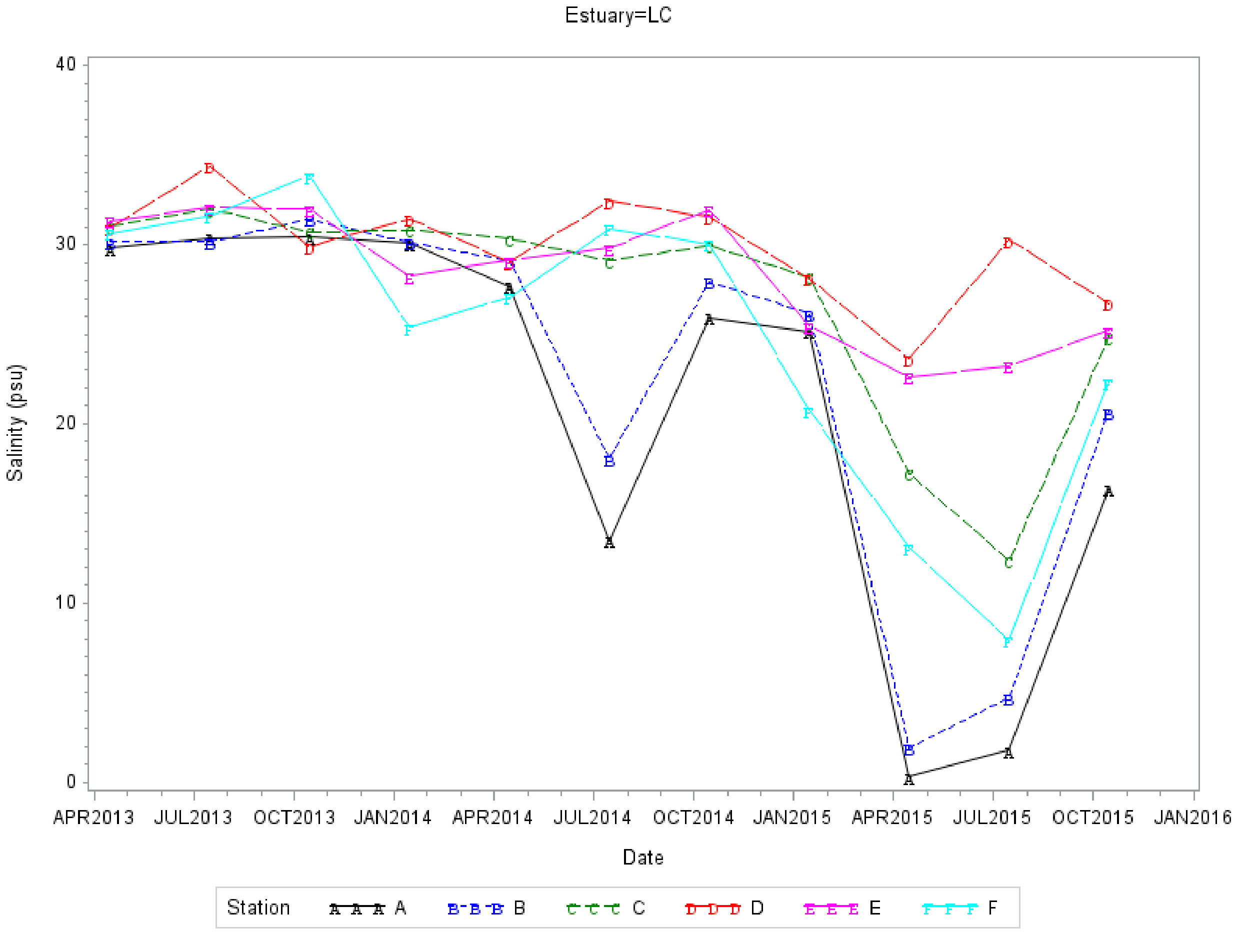

Figure 10. Salinity at stations within the Lavaca-Colorado Estuary (LC).

There is a relationship between the overall average salinity and nutrient concentrations during the study period, because the Guadalupe Estuary had the lowest average salinity and the highest average nitrate+nitrite (NO_{2+3}), phosphate (PO_4), and silicate (SiO_4) concentrations (Table 5). Concomitantly, chlorophyll a (Chl) concentrations were highest in the Guadalupe Estuary as well. These trends are true over the long-term, i.e., Guadalupe has lowest salinity (14.5 psu), highest nitrate+nitrite (14.3 uM), and highest chlorophyll (11.3 ug/L); in contrast the Nueces has highest salinity (30.2 psu), lowest nitrate+nitrite (1.43 uM), and lowest chlorophyll (5.7 ug/L) (Table 5).

Table 5. Estuary-wide average (over all dates, stations, and depths) concentrations for water quality variables for the period April 2013 - October 2015. Number station-date combinations: LC=36, GE=24, NC=30. Abbreviations: Est=estuary (LC=Lavaca-Colorado, GE=Guadalupe, NC=Nueces), n = number of observations, DO=dissolved oxygen, Temp=temperature, NH_4=ammonium, NO_{2+3}=nitrate+nitrite, PO_4=phosphate, SiO_4=silicate, Chl=chlorophyll, and turbidity (NTU).

Est	n	DO (mg/L)	Salinity (psu)	Temp (°C)	NH_4 (µmol/L)	NO_{2+3} (µmol/L)	PO_4 (µmol/L)	SiO_4 (µmol/L)	Chl (µg/L)	pH	Turbidity (NTU)
GE	220	8.3	23.1	23.3	1.67	5.32	1.97	89.70	15.4	8.22	40
LC	309	7.7	25.5	23.3	1.54	3.43	1.02	38.70	8.4	8.16	16
NC	256	7.1	34.9	23.0	1.25	1.06	1.10	46.00	7.7	8.12	13

The same trends seen in the current study period are also true for the entire long-term record (Table 6).

Table 6. Long-term, estuary-wide, average concentrations for water quality variables. Period of record: Lavaca-Colorado (LC) Estuary= April 1988 – October 2015, Guadalupe (GE) Estuary = November 1986 – October 2015, Nueces (NC) Estuary = October 1987 – October 2015. There are also many missing values in the data set. Abbreviations: DO=dissolved oxygen, Temp=temperature, NO2+3=nitrate+nitrite, PO4=phosphate, SiO4=silicate, Chl=chlorophyll, and N = number of sampling observation periods.

	Lavaca-Colorado					**Guadalupe**					**Nueces**				
Variable (unit)	**N**	**Mean**	**STD**	**Min**	**Max**	**N**	**Mean**	**STD**	**Min**	**Max**	**N**	**Mean**	**STD**	**Min**	**Max**
DO (mg/l)	108	7.34	1.58	4.60	13.33	94	7.99	1.96	5.05	17.10	111	6.80	1.50	4.19	11.00
Salinity (psu)	111	22.85	6.74	6.19	39.22	103	15.36	8.86	0.10	34.96	111	30.65	6.06	12.34	42.94
Temperature (C)	111	22.18	6.60	7.10	31.54	103	22.50	6.54	7.69	31.45	111	22.61	6.30	8.44	32.50
NH4 (umol/L)	97	2.27	2.89	0.00	23.77	93	2.56	3.90	0.00	33.46	99	1.83	2.21	0.00	13.00
NO2+3 (umol/L)	97	3.53	5.67	0.02	32.23	92	13.29	15.86	0.11	90.23	101	1.40	1.77	0.00	8.64
P04 (umol/L)	97	1.43	2.74	0.09	26.70	92	2.44	2.12	0.06	10.51	101	1.10	0.83	0.14	5.58
SiO4 (umol/L)	97	70.19	48.46	4.57	247.42	92	120.56	88.81	1.63	713.46	101	65.89	44.49	0.33	229.80
Chl (mg/L)	68	7.68	4.16	0.92	21.59	61	12.17	7.46	1.04	35.86	67	6.01	3.70	0.82	16.27
pH	104	8.14	0.37	6.76	10.31	88	8.25	0.33	7.01	9.58	102	8.12	0.21	7.63	9.27
Turbidity (NTU)	16	15.14	17.02	-12.16	52.28	16	32.73	44.30	-10.18	140.68	15	16.82	22.84	-6.11	74.74

Over the current study period, ammonia concentrations generally had parallel responses in all stations within an estuary, except for when large inflow events occurred (Figure 11). Large inflow events occurred in July 2014 and April to July April 2015, which caused spikes in concentrations. The large peak in ammonia found in station A of the Guadalupe estuary in April 2014 was replicated in Stations A of the Nueces estuary, but not in the Lavaca-Colorado estuary. In the Lavaca-Colorado estuary, the highest peaks of ammonia occurred in July 2015 in stations A and B near the Lavaca River mouth, and stations E and F near the Colorado River mouth. Typically ammonia is highest near river sources in all estuaries.

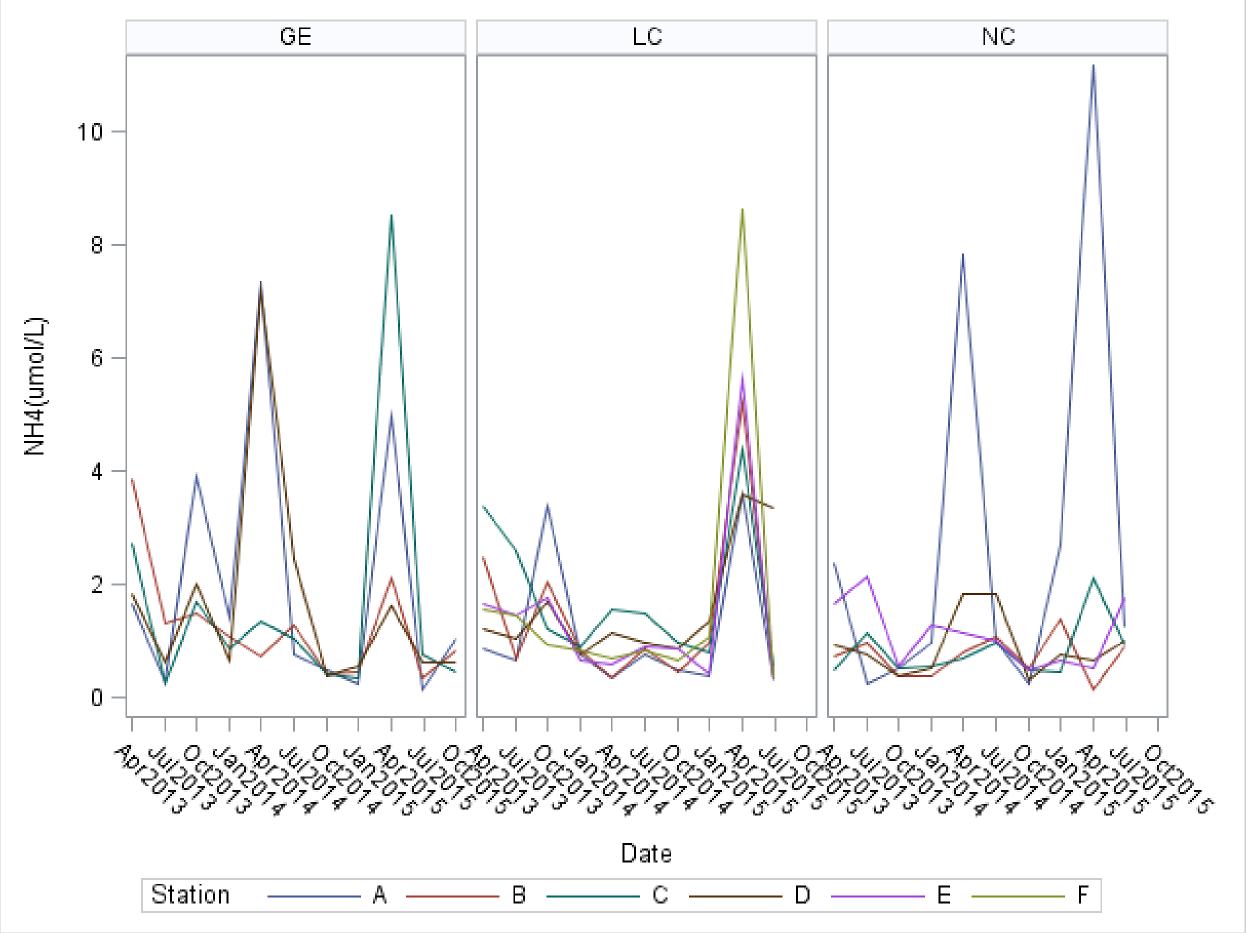

Figure 11. Ammonia concentrations in three estuaries over the reporting period. Abbreviations: LC=Lavaca-Colorado, GE=Guadalupe, NC=Nueces.

The large inflow event in April 2015 caused a large spike in nitrate+nitrite concentrations at Station A in the Guadalupe Estuary (Figure 12a). However, there was a second smaller spike for Station A in the Guadalupe Estuary in April 2014 during the drought, which was not related to an inflow event. However, except for this spike, over time, nitrate+nitrite concentrations generally had parallel responses in all stations within an estuary (Figure 12b).

The large inflow event in April 2015 manifested differently in the Lavaca-Colorado estuary with spikes in nitrate+nitrite in stations A, B, E, and F (Figure 12a). The Nueces estuary, with the lowest inflow rates always had the lowest nitrate+nitrite concentrations.

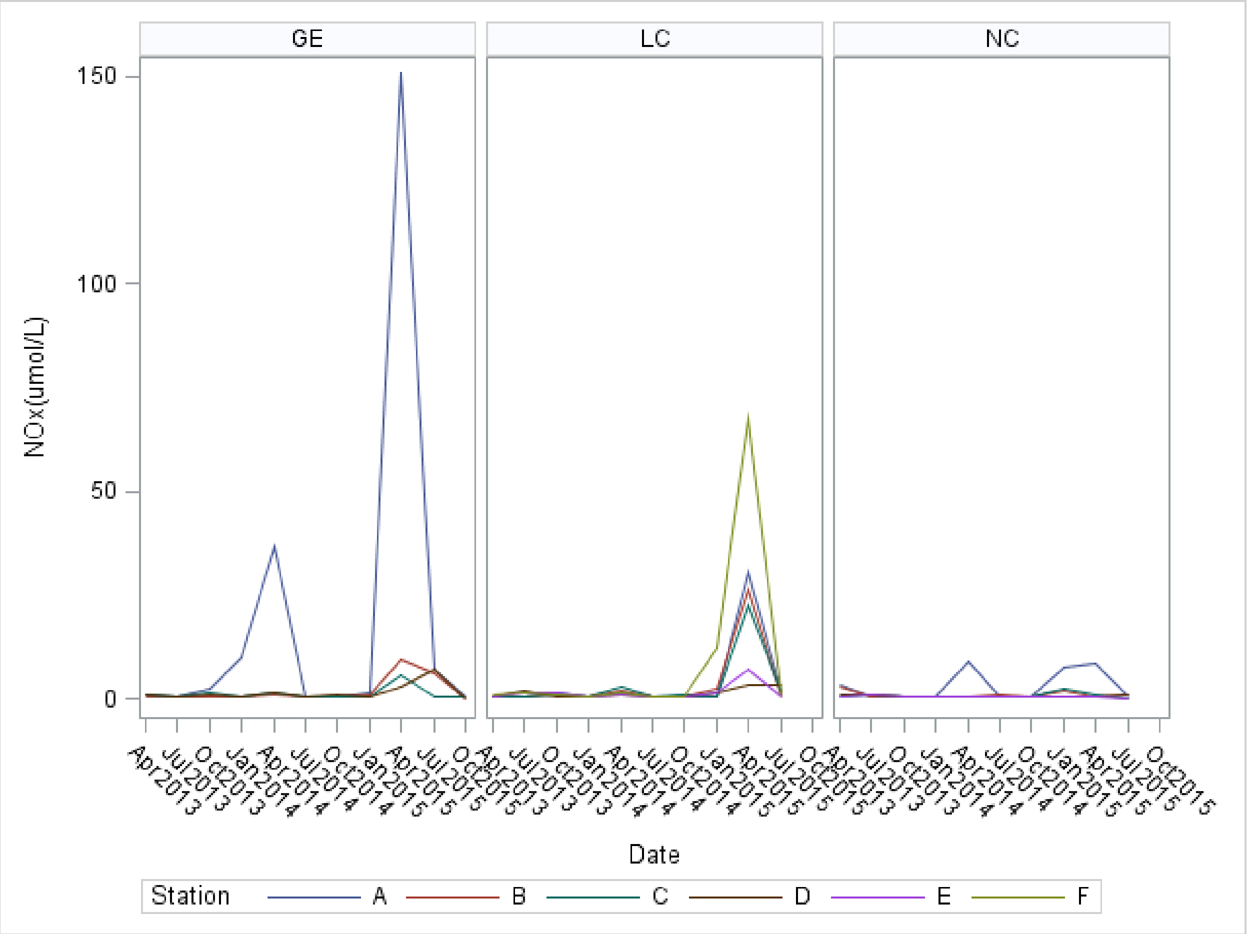

Figure 12a. Nitrate+Nitrite (NOx) concentrations in three estuaries over the reporting period. Abbreviations: LC=Lavaca-Colorado, GE=Guadalupe, NC=Nueces.

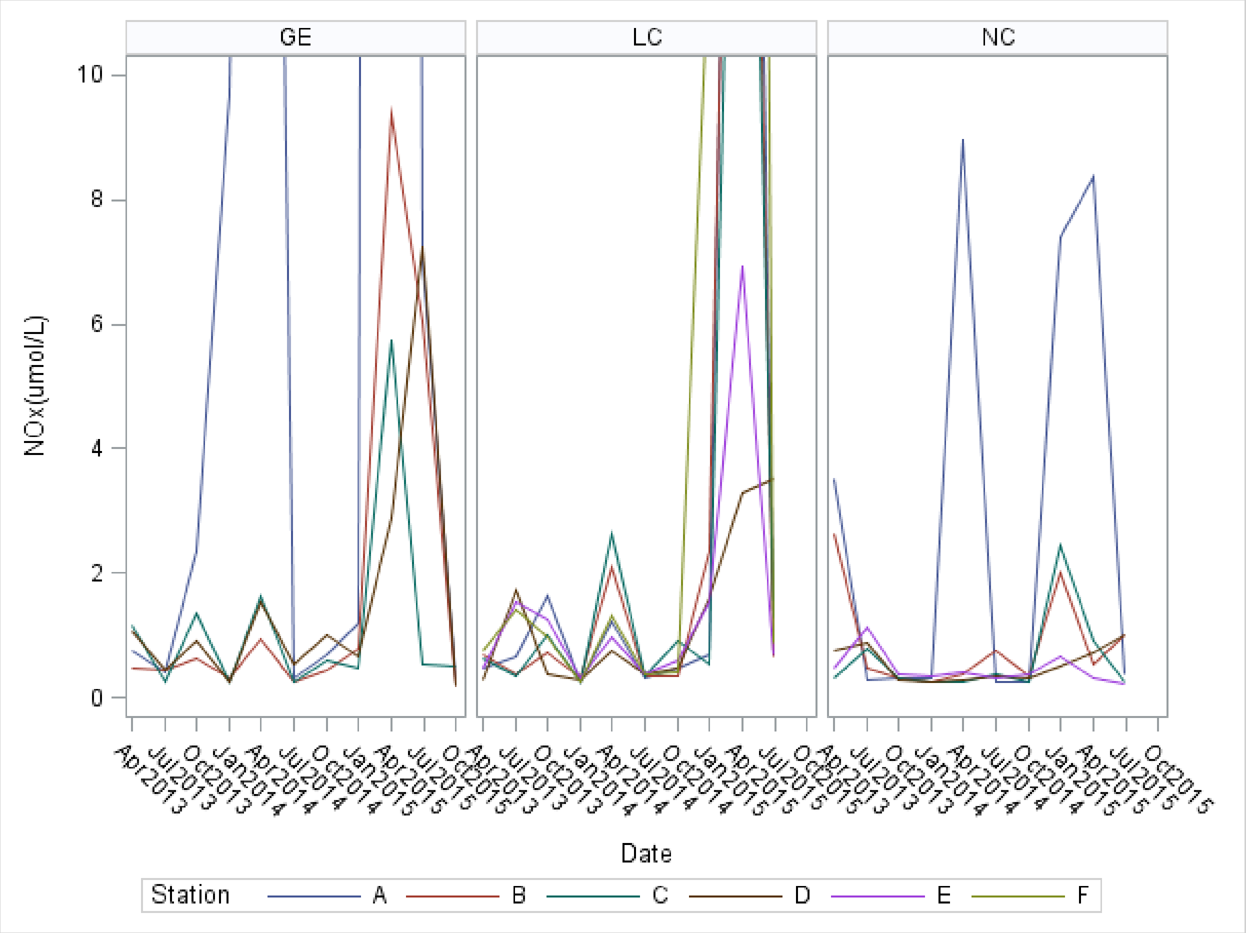

Figure 12b. Nitrate+Nitrite (NOx) concentrations in three estuaries over the reporting period. Concentration maximum is 10 umol/L to show detail for low concentrations. Abbreviations: LC=Lavaca-Colorado, GE=Guadalupe, NC=Nueces.

Over time, phosphate concentrations generally had parallel responses in all stations within an estuary (Figure 13). The parallel responses were especially evident in the Guadalupe estuary. In the Nueces Estuary, there were distinct station differences with A and B higher than C and D. In the Lavaca-Colorado estuary, the highest phosphate concentrations were found in station F, closest to the Colorado River mouth. The Guadalupe estuary generally had a higher concentrations than Lavaca-Colorado and Nueces estuaries.

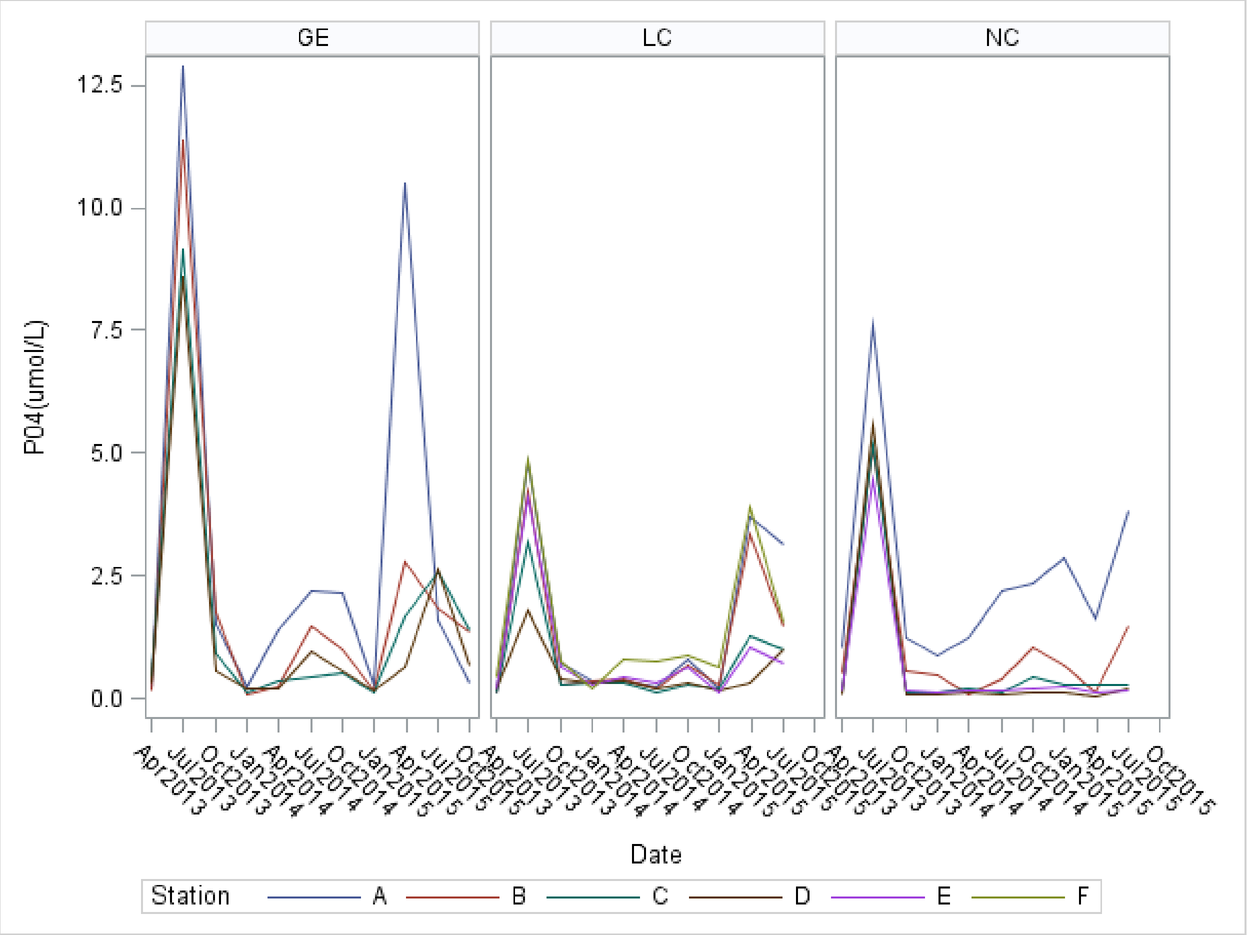

Figure 13. Phosphate (PO4) concentrations in three estuaries over the reporting period. Abbreviations: LC=Lavaca-Colorado, GE=Guadalupe, NC=Nueces.

Over time, silicate concentrations generally had parallel responses in all stations within an estuary (Figure 14). Concentrations at Stations A and B in the Nueces were higher than C and D. The temporal pattern of silicate concentrations was very similar at all stations in all estuaries with higher concentrations near the river source and lower concentrations farthest from the river source. The Guadalupe estuary had the highest concentrations.

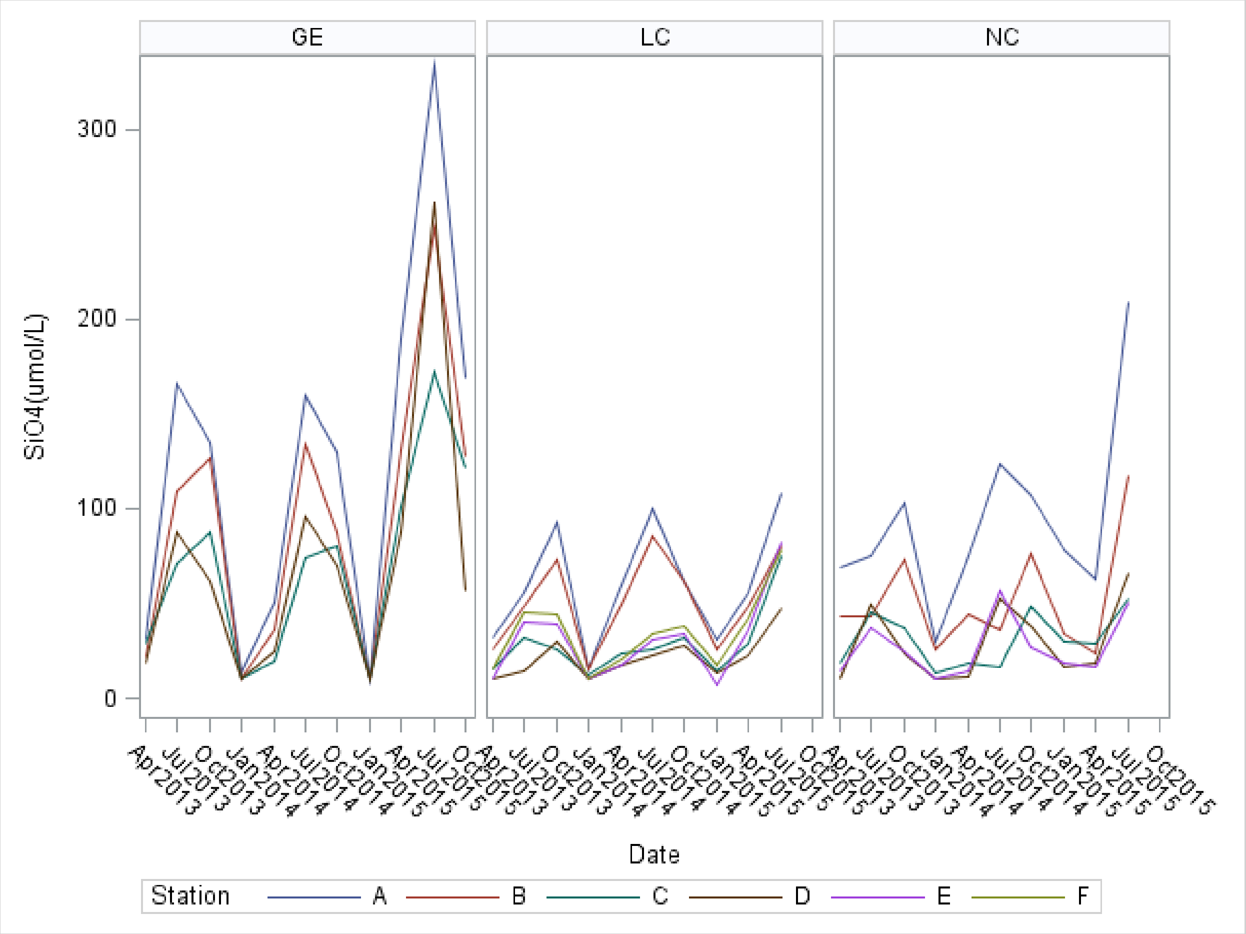

Figure 14. Silicate concentrations in three estuaries over the reporting period. Abbreviations: LC=Lavaca-Colorado, GE=Guadalupe, NC=Nueces.

Over time, chlorophyll concentrations generally had parallel responses in all stations within an estuary (Figure 15). Low values were recorded in January 2014 and 2015 and higher values were recorded in April, July and October in all estuaries. In the Guadalupe estuary, stations A and B had the highest concentrations. The highest chlorophyll values in the Lavaca-Colorado and Nueces estuaries occurred in station F for LC and B for NC.

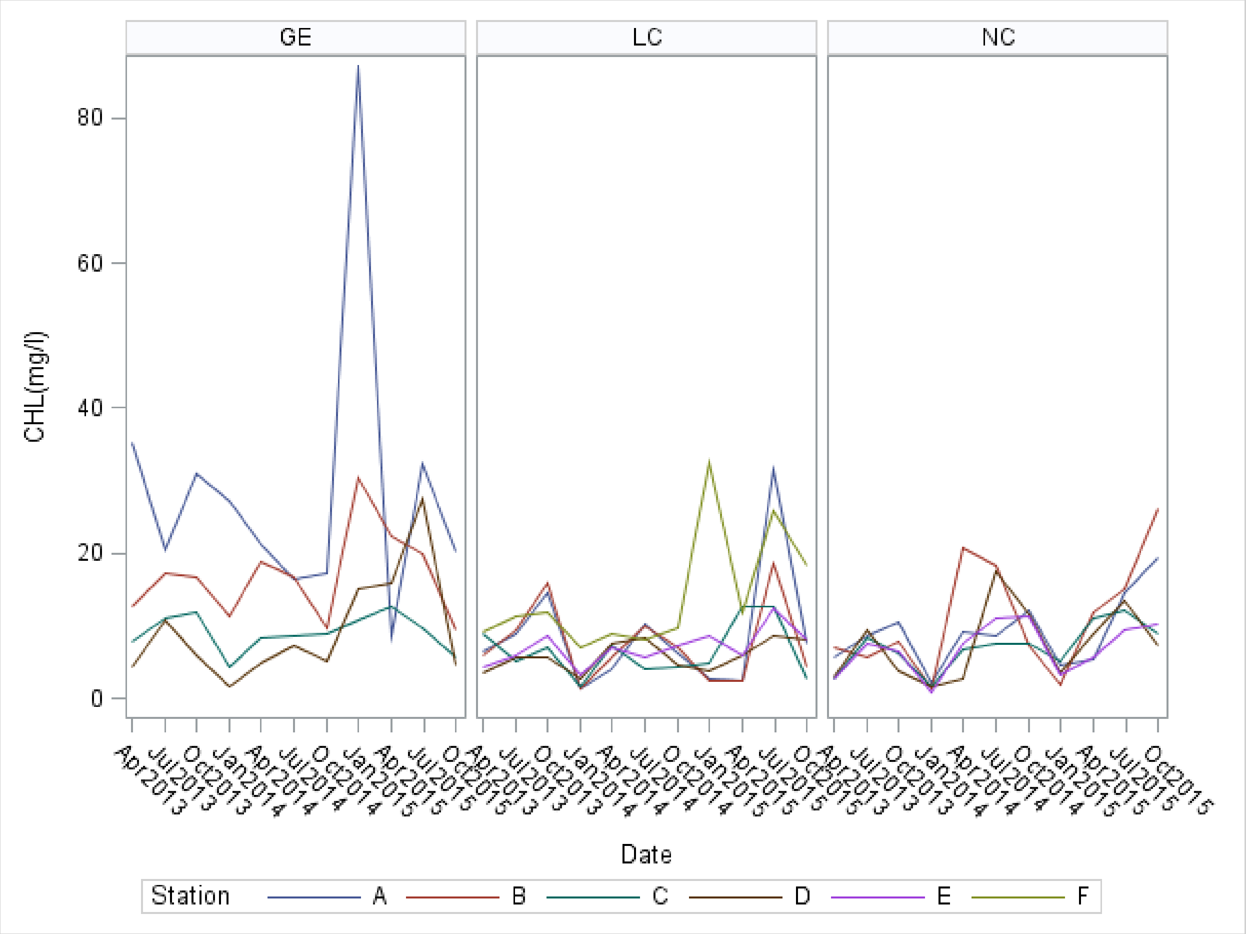

Figure 15. Chlorophyll a concentrations in three estuaries over the reporting period. Abbreviations: LC=Lavaca-Colorado, GE=Guadalupe, NC=Nueces.

Because stations typically have the same patterns, the estuary-wide average concentrations were calculated and plotted for each variable at each time point for all three estuaries (Figures 16-18). A common pattern is decrease in salinity, increases in nutrients followed by increases in chlorophyll.

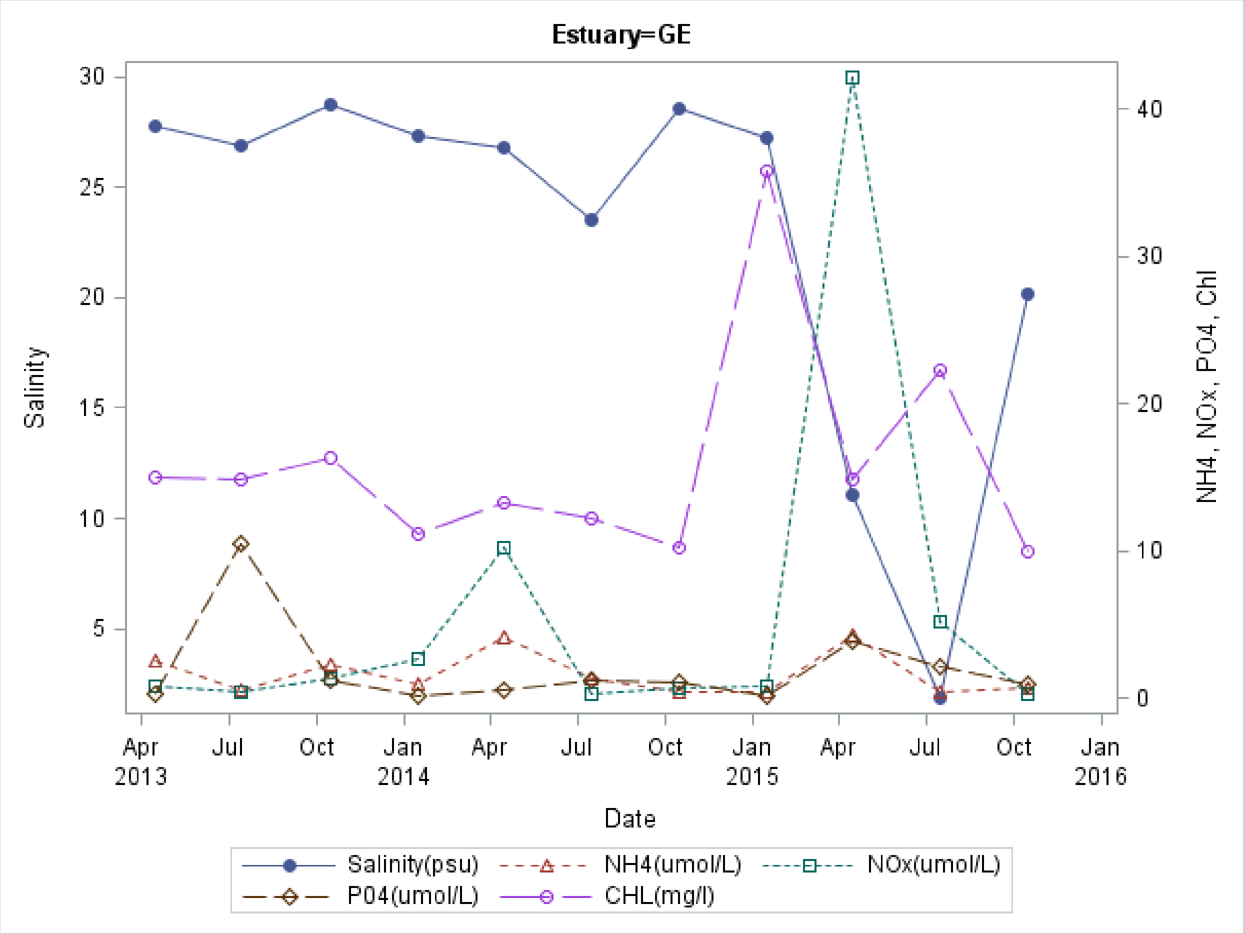

Figure 16. Estuary-wide average water quality variables in the Guadalupe Estuary (GE) over the study period.

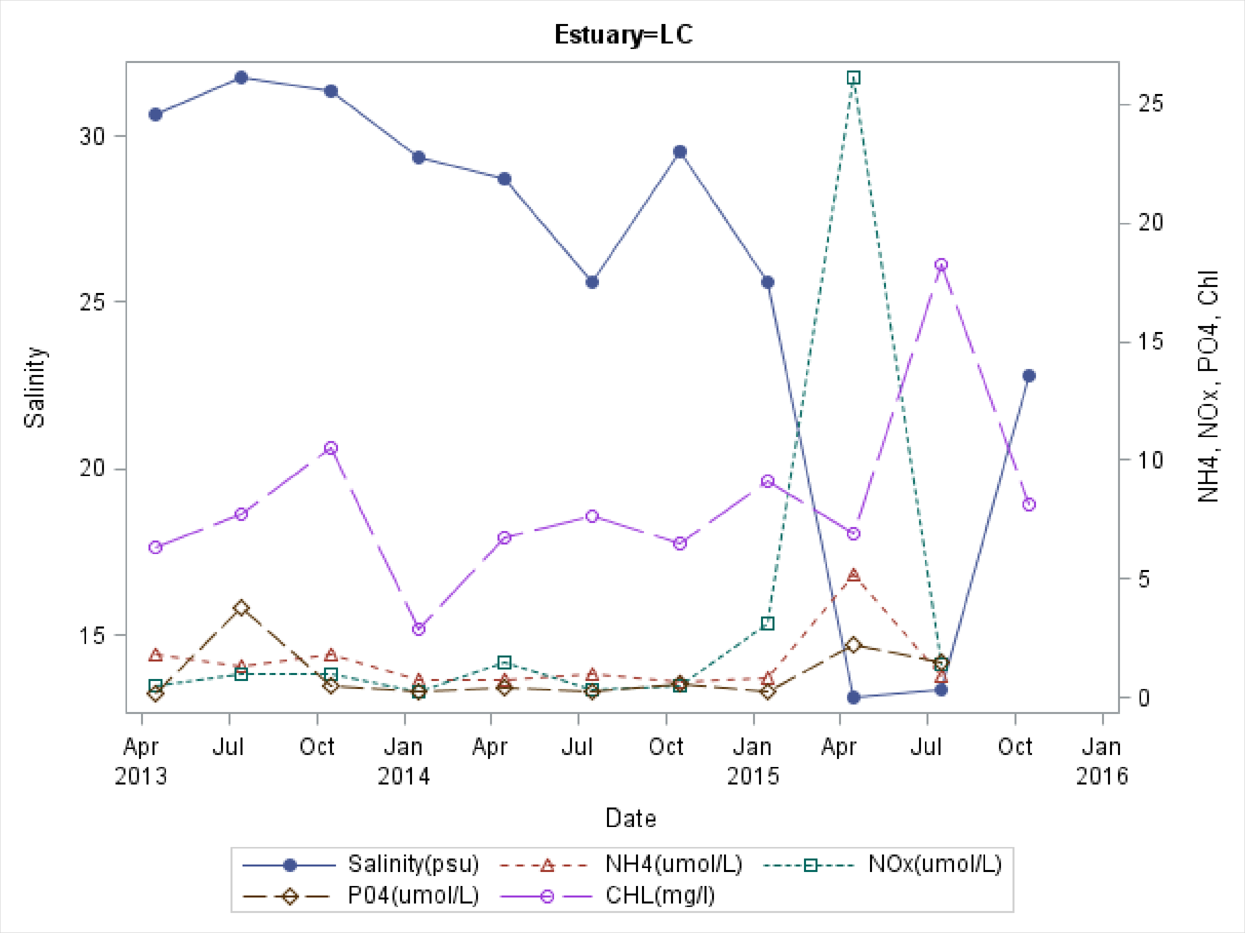

Figure 17. Estuary-wide average water quality variables in the Lavaca-Colorado Estuary (LC) over the study period.

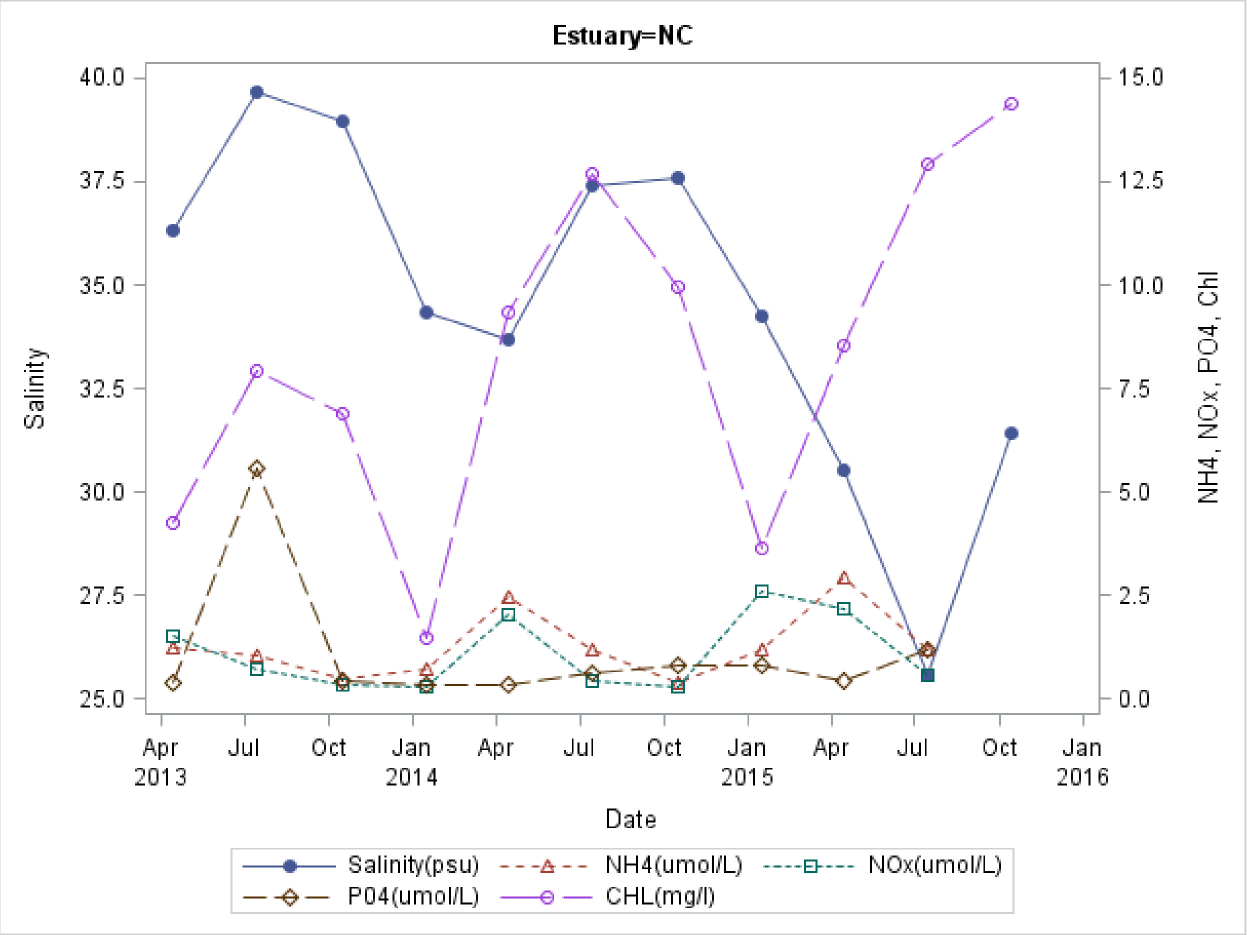

Figure 18. Estuary-wide average water quality variables in the Nueces Estuary (NC) over the study period.

DISCUSSION

Guadalupe Estuary

Overall water quality trends of station-date combinations separate stations both by season and by amount of freshwater inflow that each station receives (Figures 2b and 2c). Temperature is inversely proportional to dissolved oxygen and the separation of the station-date combinations along this gradient represents seasonal changes in water quality. The spatial difference in freshwater inflow that each station receives is represented by the inverse relationship between salinity and nutrients. Station A is the closest of the stations to the Guadalupe River mouth so had the highest nutrient concentrations and lowest salinity values. The most important trend during the current sampling period was a transition from an extended dry period to a wet period, which occurred from January 2015 to June 2015, but lowest salinities were recorded in July 2015 even though July 2015 was dry (Figs. 16 – 18).

Macrofauna communities have characteristics that are both multivariate (i.e., species differences as presented in Table 4 and Figure 5), and univariate (i.e., summary values of abundance, biomass and diversity as presented in Figures 4 and 6). There is a clear difference between macrofauna communities in environments with high and low salinities because samples from Station D always cluster together, and are distinct from other stations (Table 4 and Figure 5). Stations B and C are similar all of the time. However, station A can be like stations C and B, or it can be distinct. Freshwater inflow into the Guadalupe Estuary travels southwest along the western side of the estuary allowing lower salinities on the southwestern side to be lower than salinities on the northeastern side resulting in long-term lower salinities at station C than D (Table 7).

Table 7. Long-term average salinities at four stations in San Antonio Bay. Period from November 1986 to October 2015.

Station	Samples	Mean	Std. Dev
A	(202)	9.6	8.6
B	(216)	13.9	9.1
C	(200)	18.7	9.9
D	(198)	19.6	9.8

The period studied here (April 2013 – October 2015) was unusual in that a tunicate species, *Molgula manhattensis*, was the third most dominant species (Table 4). It occurred in January 2012 and five of the seven sampling periods. Prior to 2012 however, it occurred only four times: January 1993, January 1994, January 2000, and January 2009. Its occurrence in July 2013, July 2014 and October 2014 is the only occurrence outside of January in the record. This is a good example of a how important rare species are in maintain the high diversity of these ecosystems. *Molgula* appears to be primarily a marine species because it disappeared once the salinities dropped.

It is also apparent that total macrofauna abundance, biomass, and diversity are quite variable over time (Figure 4). Generally, station D, the most marine station has the highest diversity, and this is because of invasion by marine species. Station D also often has the highest biomass. However, Abundance was highest at station A in 2013. The community reacted to the flood of 2015 with a large decrease in abundance, biomass and diversity, however it is apparent that abundance was beginning to recover in October 2015 in Station D.

There has been a long-term decline in macrofauna abundance in the Guadalupe Estuary since 1987, but it does not appear that there is an associated decrease in macrofauna biomass or species richness (Figure 6). Diversity follows a pattern of increasing when salinity increases and decreasing when salinity decreases, and this is because of the expansion of a more diverse marine fauna that invades San Antonio Bay during dry periods. A similar decline in benthic abundance, but also biomass and diversity, in the Lavaca-Colorado estuary has been observed over the past 21 years (Pollack et al. 2011). However we do not know if this decline is a result of natural, long-term population or community cycles that span multiple decades and will reverse, or if it is due to a permanent state-shift. This decline is troubling however, because benthos are the principal food for many important commercial and recreational fishery species including shrimp, crab, red fish, flounder, black drum, and spotted seatrout. It is unknown if the disappearing benthos, which is fish forage, is affecting fish populations.

Biomass does not exhibit a clear trend, sometimes following salinity patterns, but sometimes not following salinity patterns (Figure 6). Biomass did increase following drops in salinity on six occasions: January 1991 following a 1 psu drop, October 1994 following 5 psu drop, April 1996 following a 4 psu drop, April 2007 following a 13 psu drop, and July 2009 following a 4 psu drop. However, biomass increased following a rise in salinity on six occasions: April 1995 following a 4 psu rise, October 1999 following a 16 psu rise, October 2004 following a 11 psu rise, April 2006 following a 5 psu rise, April 2008 following a 3 psu rise, January 2011 following a 7 psu rise, and January 2013 following a 5 psu rise.

Mean estuary-wide salinity in October 2011 (35 psu) was the highest it has ever been and is 2 times the long-term average salinity of 15.4 psu (Figure 6). Some of the benthic metrics are much lower than average. Average abundance in October 2011 was 12,291 n/m^2, which is 82% of the long-term average abundance of 14,899 n/m^2. Average biomass in October 2011 was 4.53 g/m^2, which is a little more than half (55%) of the long-term average biomass of 8.23 g/m^2. Average species richness is about the same, because in October 2011 it was 10.5 species/0.01 m^2, which is 4% more than the long-term average richness of 10.1 species/0.01 m^2.

The spring of 2015 had high flows continuously beginning in March 2015. The Memorial Day flood of May 2015 was one of the largest and most damaging on record. Additional rain in June and July, plus the time it takes for river water to move down to the coast, led to the lowest salinities in July 2015 (Figure 13). The large floods washed away nearly all the estuarine and marine species, and replaced them with freshwater and oligohaline species.

Mid-Coastal Estuaries

The three Texas mid-coast estuaries share a connection via large lagoons. Matagorda Bay is connected to San Antonio Bay via Espiritu Santo Bay. San Antonio Bay is connected to Corpus Christi Bay via Aransas Bay and Lydia Ann Channel. The Intracoastal Waterway enhances these connections and further facilitates water exchange among these Texas lagoons. However, because of the strong climatic gradient along the Texas coast, the three estuaries have different inflow regimes and consequently different patterns in water quality and benthic responses.

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