Long-term water quality trends in Texas estuaries: relationships with climatic variability and watershed land use change

Final Report

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Executive Summary

Coastal watersheds in Texas have experienced significant human population growth over the past two decades. Yet to date, there have been no comprehensive assessments of water quality trends that could otherwise guide proactive management and/or watershed restoration efforts. In this study, analysis of long-term, spatially extensive water quality data indicates regional "hot spots" of change in Texas estuaries. Several Texas estuaries with highly urbanized watersheds, specifically Galveston Bay and Oso Bay, currently exhibit symptoms of eutrophication. Symptoms of eutrophication were also found in Baffin Bay and the Upper Laguna Madre, which have a sparsely populated watershed. Aside from water quality issues related to nutrient pollution, the other major challenge facing Texas coastal ecosystems is a long-term decline in freshwater inflow. This manifests as increasing salinity levels, which was observed in every estuary from the Upper Laguna Madre to Matagorda Bay. Another artifact of decreasing freshwater inflow levels are changes to the carbonate chemistry system of estuaries. This study found numerous sites along the central Texas coast, often overlapping with sites of increasing salinity, where pH and alkalinity exhibited a long-term decrease. Unlike coastal systems in other regions of the U.S. and elsewhere, there was no indication of widespread annual water temperature increases in this study. With findings from this study, targeted studies can now be directed at the estuaries that are experiencing water quality degradation in order to guide future management efforts.

Outreach Efforts

Education and outreach were vital components of this study. One high school intern, one M.S. student and one Ph.D. student participated in the study. Results from this study were presented in a number of venues including classroom presentations, public seminars, and scientific conferences. Below is a complete list of outreach and education efforts that were undertaken as part of this study. Supporting documents will be provided to GLO separately.

Presentations (scientific conferences):

1. Bugica, K., Wetz, M., and Sterba-Boatwright, B. "Long-term water quality trends in Texas estuaries: relationships with climatic variability and watershed land use change." Presented at 2017 ASLO Ocean Sciences Meeting in Honolulu, Hawaii.

2. Bugica, K., Wetz, M., and Sterba-Boatwright, B. "Long-term water quality trends in Texas estuaries: relationships with climatic variability and watershed land use change." Presented at 2017 Texas Bays & Estuaries Meeting in Port Aransas, Texas.

3. Bugica, K. "Long-term water quality trends in Texas estuaries: relationships with climatic variability and watershed land use change." Presented at 2018 Gulf Estuarine Research Society Meeting in Galveston, Texas.

Presentations (public, local):

1. Wetz and high school intern Amya Reynoso presented results to the Riviera High School Aquatic Sciences class on 1/27/2019.

2. Wetz presented findings at the Harte Research Institute seminar series on 2/1/2019.
3. Wetz gave a presentation to the local chapter of the Coastal Conservation Association on 2/1/2017.
4. Wetz gave a presentation to the Kleberg County Commissioners in March 2017.
5. Wetz gave a presentation to the Baffin Bay Stakeholder Group in both March and June of 2018.

University Classes:

1. Wetz presented findings in a class he teaches at TAMU-CC, “Marine Organisms and Processes”, in November 2018.

Other:

Project results were used to assist efforts (led by Harte Research Institute) aimed at developing a water quality “report card” for Texas coast. A final “report card” will be submitted to GLO when it is completed.

Introduction

Estuaries provide critical habitat for important fish and shellfish species and play a vital role in the economy of coastal states. Water quality is a major determinant of the health of estuaries. In Texas, coastal watersheds have experienced significant human population growth over the past several decades. For example, from 1997 to 2012, the population in Texas coastal counties increased by 29% (Texas A&M Natural Resources Institute 2014). Projections suggest that there will be an additional 34% population increase by 2050 (Texas State Data Center, http://txsdc.utsa.edu/Data/TPEPP/Projections/Index.aspx). Urbanization associated with population growth is known to cause water quality degradation in downstream waterbodies, primarily through enhancement of pollutant loadings (e.g., nutrients, organic matter, bacterial pathogens) (Peierls et al. 1991; Vernberg et al. 1992; Hopkinson and Vallino 1995; Handler et al. 2006). Population growth also affects freshwater inflows to, and ultimately salinity levels in estuaries through water usage and withdrawals (reviewed by Montagna et al. 2013). Freshwater inflows and salinity are also affected by natural climate variability as well as longer-term anthropogenic climate change (reviewed by Montagna et al. 2013). Studies in estuaries have noted deleterious effects from long-term declines in freshwater inflows (reviewed by Montagna et al. 2013).

To date, there has only been one study, the National Estuarine Eutrophication Assessment, to quantify water quality patterns and trends along the entire Texas coast. That study found low or moderate expression of eutrophication symptoms in six bay systems, but did not have enough information to assess three other bays (Bricker et al. 2007). The Texas coast consists of seven major estuaries, each of which has one primary bay and one or more secondary bays. Each system is likely to have a unique water quality signature given the diversity of watershed land usages and relative influence of riverine inputs of pollutants. Given the sharp increases in human populations in Texas' coastal communities, along with climatic changes that are happening regionally and globally, an integrated assessment of water quality conditions in all Texas estuaries is warranted to properly inform management efforts. Here we quantify spatial patterns and long-term trends in the water quality of Texas estuaries. Using results from this analysis, we offer an assessment of drivers of observed water quality changes with a goal of informing future management efforts.

Materials & Methods

Data sources

To quantify long-term water quality trends along the Texas coastline, data were obtained from the Texas Commission on Environmental Quality's (TCEQ's) Surface Water Quality Monitoring (SWQM) program (https://www.tceq.texas.gov/waterquality/monitoring). The SWQM program collects water samples on a quarterly basis from all bay systems on the Texas coast. SWQM sites chosen for spatial analysis had data that was newer than 2011 (Figure 1), while sites chosen for temporal analysis had active monitoring up to 2016, and also had at least 20 years of data (to 1996 or earlier).

Statistical analysis of long-term trends

Spatial patterns in water quality were calculated using averages of data collected between 2009 and 2016. A 7-year period was chosen to be consistent with methods employed in TCEQ's semiannual water quality assessments. Spatial analyses were done using the ordinary Kriging method with interpolations generated using an exponential semivariogram model (variable search radius of 6 points), a model popular in hydrological studies (Maidment 1993). Map figures were generated in ArcGIS 10.4. Kendall's τ_a regression was used to determine relationships between water quality variables and time (Kendall 1955). Rankings between two censored values were treated as ties, and rankings were treated as a tie between one censored and one uncensored value if no specific ranking could be calculated. The best-fit line for trends were computed using the Akritas-Theil-Sen nonparametric line (Akritas et al. 1995) with the Turnbull estimate for intercept (Turnbull 1976). Significant trends were identified using $\alpha = 0.05$. For analysis of long-term trends in a given season, SWQM data were averaged into respective seasons (Winter = DJF, Spring = MAM, Summer = JJA, Fall = SON). All calculations were made in R version 3.4.2 (R Core Team 2017), including use of the NADA package version 1.6-1 (Lee 2017) and EnvStats package version 2.3.1 (Millard 2013).

Results

Spatial patterns

Water temperature has a latitudinal gradient, with cooler temperatures generally found on the north-central coast and warmer temperatures found on the south coast (Figure 2). Salinity also follows a strong north-south gradient, with lowest salinities in Galveston Bay and higher salinities moving southward (Figure 3). The highest salinity values are found in Baffin Bay, exceeding >40 on average. High pH (>8.15) was seen in the Upper Laguna Madre, including Baffin Bay, as well as Galveston Bay (reaching 8.27) (Figure 4). Lower pH values (approaching 8.00) were found in the Lower Laguna Madre and upper reaches of both Copano Bay and Nueces Bay.

Site-specific total phosphorus (TP) concentrations >0.10 mg/l were found in Sabine Lake (n=1; 0.10 mg/l), San Jacinto Bay (n=3; 0.34 ± 0.02 mg/l), Galveston Bay (n=9; 0.16 ± 0.04 mg/l), Trinity Bay (n=2; 0.14-0.15 mg/l), East Bay (n=2; 0.14-0.15 mg/l), Lavaca Bay (n=1; 0.12 mg/l), Matagorda Bay (n=1; 0.11 mg/l), San Antonio Bay (n=2; 0.11-0.19 mg/l), Copano Bay (n=1; 0.13 mg/l), Nueces Bay (n=2; 0.11-0.15 mg/l), Oso Bay (n=1; 0.15 mg/l), Baffin Bay (n=1; 0.10 mg/l), and Lower Laguna Madre adjacent to the Arroyo Colorado (n=1; 0.18 mg/l) (Figure 5). Site-specific orthophosphate concentrations >0.10 mg/l were found in San Jacinto Bay (n=2; 0.15-0.22 mg/l), Galveston Bay (n=1; 0.12 mg/l), and Lower Laguna Madre adjacent to the Arroyo Colorado (n=1; 0.13 mg/l) (Figure 5). The majority of sites in Texas estuaries had orthophosphate concentrations ≤ 0.05 mg/l. Highest site-specific Total Kjeldahl Nitrogen (TKN) was found in upper San Antonio Bay (1.83 mg/l) and Oso Bay (1.83 mg/l) (Figure 6). Other locations with site-specific TKN averaging >1 mg/l include San Jacinto Bay (n=2; 1.57-1.75 mg/l), Copano Bay (n=2; 1.05-1.38 mg/l), Baffin Bay (n=2; 1.35-1.40 mg/l), Upper Laguna Madre (n=2; 1.01-1.33 mg/l), and Lower Laguna Madre (n=2; 1.10-1.14 mg/l). TKN <1 mg/l was found at all other locations. Site-specific nitrate+nitrite (N+N) concentrations >0.10 mg/l were found in Sabine Lake (n=1; 0.10 mg/l), San Jacinto Bay (n=3; 0.92 ± 0.15 mg/l), Galveston Bay (n=4; 0.28 ± 0.18 mg/l), Trinity Bay (n=1; 0.22 mg/l), Lavaca Bay (n=1; 0.10 mg/l), and Lower Laguna Madre adjacent to the Arroyo Colorado (n=1; 0.52 mg/l)(Figure 6). All other sites had N+N concentrations that were <0.10 mg/l on average. Site-specific ammonium concentrations >0.10 mg/l were only found in San Jacinto Bay (n=3; 0.20 ± 0.03) and Galveston Bay (n=1; 0.10 mg/l) (Figure 6).

Highest site-specific chlorophyll *a* concentration was found in Baffin Bay (n=2), where it averaged 25.1-28.4 µg/l (Figure 7). Other locations with site-specific chlorophyll *a* concentration >20 µg/l include Galveston Bay (n=2; 23.0-23.1 µg/l), Upper Laguna Madre (n=1; 21.2 µg/l), Lower Laguna Madre adjacent to the Arroyo Colorado (n=1; 21.9 µg/l), and Oso Bay (n=1; 23.3 µg/l). All other sites on the Texas coast had chlorophyll <20 µg/l. Highest average bottom dissolved oxygen (BDO) values were seen in Galveston Bay and generally decreased moving south along the coast, corresponding with temperature and salinity gradients (Figure 8).

Temporal trends

A statistically significant long-term increase in annual water temperature ($p < 0.05$; 0.06 °C/yr) was observed at a single site in the Upper Laguna Madre (Figure 2), while no significant decreases were observed. Water temperature trends were often inconsistent in a given season except for summer, when 12 sites (27 % of all sites with sufficient data for long-term trend analysis) showed temperature increases, and none showed decreases. Estuaries showing a long-term increase in summer temperature were Upper Laguna Madre (1 site; 0.03 °C/yr), Lower Laguna Madre (2 sites; 0.03-0.05 °C/yr), Baffin Bay (1 site; 0.04 °C/yr), Matagorda Bay (0.03 °C/yr), Corpus Christi Bay (1 site; 0.02 °C/yr), Aransas Bay (0.03 °C/yr), San Antonio Bay (1 site; 0.03 °C/yr), Espiritu Santo Bay (1 site; 0.04 °C/yr), Lavaca Bay (1 site; 0.03 °C/yr), Trinity Bay (0.03 °C/yr), and Sabine Lake (0.07 °C/yr). Significant annual increases in salinity were observed in multiple systems, including Corpus Christi Bay (4 sites; 0.20 ± 0.05/yr), Nueces Bay (5 sites; 0.50 ± 0.32/yr), Matagorda Bay (0.31/yr), Copano Bay (1 site; 0.30/yr), Aransas Bay (0.22/yr), Upper Laguna Madre (1 site; 0.22/yr), San Antonio Bay (1 site; 0.54/yr), Lavaca Bay (3 sites; 0.35 ± 0.15/yr), and Keller Bay (0.24/yr) (Figure 3). Overall, 22 sites (50% of all sites with sufficient data for long-term trend analysis) had a long-term salinity increase. This trend was primarily centered in the spring-summer months (data not shown). Significant long-term pH decreases were found in Corpus Christi Bay (3 sites; -0.004 ± 0.001/yr), Copano Bay (2 sites; -0.004--0.005/yr), San Antonio Bay (1 site; -0.004/yr), Matagorda Bay (-0.005/yr), Aransas Bay (-0.004/yr), Lavaca Bay (2 sites; -0.006--0.007/yr), Keller Bay (-0.005/yr), Espiritu Santo Bay (1 site; -0.006/yr), Nueces Bay (2 sites; -0.004--0.005/yr), Lower Laguna Madre (1 site; -0.006/yr), and South Bay (-0.005/yr)(Figure 4). Overall, 16 sites (36% of all sites with sufficient data for long-term trend analysis) saw decreases in pH.

A long-term decrease in TP was observed in Trinity Bay (-0.004 mg/l/yr), Galveston Bay (1 site; -0.005 mg/l/yr), San Antonio Bay (1 site; -0.007 mg/l/yr), Oso Bay (-0.002 mg/l/yr), Corpus Christi Bay (1 site; -0.001 mg/l/yr), and Mesquite Bay (-0.001 mg/l/yr)(Figure 5). In contrast, TP increased in Matagorda Bay (0.001 mg/l/yr), Lavaca Bay (1 site; 0.001 mg/l/yr), Keller Bay (0.001 mg/l/yr), Upper Laguna Madre (2 sites; 0.001 mg/l/yr), Nueces Bay (1 site; 0.003 mg/l/yr), Lower Laguna Madre (1 site; 0.001 mg/l/yr), and Sabine Lake (0.001 mg/l/yr). In the case of orthophosphate, an increasing trend was observed in Matagorda Bay (0.01 mg/l/yr), Lavaca Bay (2 sites; 0.001-0.002 mg/l/yr), Keller Bay (0.001 mg/l/yr), Corpus Christi Bay (1 site; 0.001 mg/l/yr), Nueces Bay (4 sites; 0.001-0.002 mg/l/yr), Upper Laguna Madre (3 sites; 0.001-0.002 mg/l/yr), Baffin Bay (2 sites; 0.002 mg/l/yr), and Lower Laguna Madre (2 sites; 0.001 mg/l/yr)(Figure 5), while a decreasing trend was observed in Trinity Bay (-0.007 mg/l/yr), Galveston Bay (1 site; -0.008 mg/l/yr), and San Antonio Bay (1 site; -0.02 mg/l/yr). TKN decreased in Copano Bay (1 site; -0.02 mg/l/yr), Baffin Bay (2 sites; -0.02 mg/l/yr), Upper Laguna Madre (2 sites; -0.02 mg/l/yr), Corpus Christi Bay (1 site; -0.01 mg/l/yr) and Galveston Bay (1 site; -0.02 mg/l/yr) (Figure 6). In contrast, TKN increased in Trinity Bay (0.01 mg/l/yr), Sabine Lake (0.01 mg/l/yr), Lavaca Bay (2 sites; 0.01 mg/l/yr), Keller Bay (0.01 mg/l/yr), and Lower Laguna Madre (1 site; 0.01 mg/l/yr). N+N and ammonium decreased over time at nearly every site along the coast (Figure 6), but this rate of change was very small compared to site averages and is likely an artifact of detection limits that have decreased over time.

Significant long-term chlorophyll *a* increases were found in Baffin Bay (2 sites; 0.36-0.39 µg/l/yr), Upper Laguna Madre (2 sites; 0.35 µg/l/yr), Oso Bay (0.42 µg/l/yr), San Antonio Bay (1 site; 0.59 µg/l/yr), Lavaca Bay (1 site; 0.31 µg/l/yr), Copano Bay (1 site; 0.09 µg/l/yr), and Nueces Bay (1 site; 0.37 µg/l/yr)(Figure 7). Long-term decreases in chlorophyll *a* were found in Nueces Bay (1 site; -0.19 µg/l/yr) and Corpus Christi Bay (1 site; -0.08 µg/l/yr). A significant decrease in BDO was observed in Baffin Bay (2 sites; -0.02--0.03 mg/l/yr), Upper Laguna Madre (2 sites; -0.02--0.03 mg/l/yr), Copano Bay (2 sites; -0.04--0.11 mg/l/yr), San Antonio Bay (1 site; -0.03 mg/l/yr), Keller Bay (-0.02 mg/l/yr), and Mesquite Bay (-0.06 mg/l/yr)(Figure 8). In contrast, a long-term increase was observed in Corpus Christi Bay (1 site; 0.03 mg/l/yr) and Lavaca Bay (1 site; 0.06 mg/l/yr).

Discussion

Coastal watersheds in Texas have experienced significant human population growth over the past two decades. In many other regions worldwide, this increasing human footprint has led to symptoms of water quality degradation, namely increasing pollutant loads, algal bloom proliferation, and fish kills (Paerl et al. 1998; Cloern 2001; Rabalais et al. 2009). Yet to date, there have been no comprehensive assessments of water quality trends on the Texas coast that could otherwise guide proactive management and/or watershed restoration efforts. In this study, analysis of long-term water quality data indicates regional “hot spots” of change in Texas estuaries. Examples of both eutrophication and oligotrophication were found. Increasing salinity was observed in numerous estuaries, while water temperature trends were inconsistent.

Decreasing pH (i.e., acidification) was found in numerous estuaries, primarily those where salinity increases were noted. These changes in water quality are occurring in estuaries with a wide range of watershed characteristics, from highly urbanized watersheds with strong river influence (such as Galveston Bay) to sparsely populated watersheds with no major river inputs (such as Baffin Bay). It is rare to have water quality datasets such as those used here that cover multiple decades and the aforementioned range of estuaries and watersheds. Thus, beyond understanding how Texas estuaries are changing from a water quality standpoint, results from this study are informative for understanding the broader watershed and estuary conditions that are susceptible to water quality degradation in estuaries worldwide.

Several Texas estuaries with highly urbanized watersheds, specifically Galveston Bay and Oso Bay, currently exhibit symptoms of eutrophication. In Galveston Bay, relatively high nutrient and chlorophyll concentrations were found, and a previous study found that fish kills, primarily from low dissolved oxygen, are pronounced in Galveston Bay compared to other estuaries in Texas (Thronson and Quigg 2008). Galveston Bay has a watershed that is over 62,000 km^2 and includes the major cities of Houston and Dallas-Fort Worth. Numerous studies have pointed to urbanization such as this as being a major contributor to the eutrophication of downstream coastal ecosystems (e.g., Peierls et al. 1991; Bowen and Valiela 2001; Rothenberger et al. 2009). One major challenge in the current study was an inability to firmly assess long-term trends in indicators such as chlorophyll in Galveston Bay because of the lack of sampling sites with 20 or more years of data. Efforts should be made to ensure continuity of sampling at strategic sites in the bay to ensure accurate assessment of trends as the watershed continues to urbanize. Another estuary, Oso Bay, also had high nutrients as well as high and increasing chlorophyll. Oso Bay receives wastewater effluent from a number of municipal treatment plants, and previous studies have demonstrated that this effluent is a major driver of eutrophication in the system (Wetz et al. 2016; Wang et al. 2018).

It was surprising that the larger Nueces Estuary complex, of which Oso Bay is a tributary, is not displaying similar symptoms of eutrophication given that the city of Corpus Christi (population 325,605 in 2017) lies adjacent to the bay. During the period of 1990 to 2001, the population of Corpus Christi grew from 257,000 to 305,000, resulting in a growing footprint of urbanization on land cover adjacent to the estuary. For example, between 1996 and 2010, the South Corpus Christi Bay watershed experienced a 10% increase in developed lands while the North Corpus Christi Bay watershed experienced a 19% increase in developed land (NOAA Coastal Change Analysis Program; https://coast.noaa.gov/ccapatlas/). However, most of the city's municipal wastewater effluent is routed through the Oso complex, which conceivably acts as a filter for the larger bay system. Furthermore, very little riverine input reaches Nueces and Corpus Christi Bays, which would otherwise contribute to nutrient loadings to the bay. In fact, discharge from the Nueces River, the larger river to the system, has decreased dramatically over the past half century due to damming and human water needs (Nueces River and Corpus Christi and Baffin Bays Basin and Bay Expert Science Team 2011). This may explain the decreasing chlorophyll trend observed at one site in lower Nueces Bay and one site in upper Corpus Christi Bay. Effects of this reduction in primary producer biomass on upper trophic levels are unknown, but studies in other systems have documented long-term declines in benthic and/or pelagic consumers as a result of decreasing primary productivity (e.g., Nixon 2003).

Along with the symptoms of eutrophication noted in two urbanized Texas estuaries (Galveston Bay, Oso Bay), symptoms were also found in two semi-arid, low inflow estuaries on the South Texas coast. In the Lower Laguna Madre, high nutrients and chlorophyll were observed at one location adjacent to the polluted Arroyo Colorado tributary. The watershed from which the Arroyo Colorado tributary originates has land cover that is dominated by agriculture (48% in 2010; NOAA CCAP, http://coast.noaa.gov/ccapatlas), but also has 25 active permitted wastewater discharge facilities. As a result of the poor water quality conditions in the Arroyo Colorado, a watershed protection plan has been implemented to reduce nutrient inputs to it and the Lower Laguna Madre. Baffin Bay and adjacent Upper Laguna Madre also have high and increasing chlorophyll levels, decreasing BDO levels, and high TKN concentrations, the majority of which is in organic form (Wetz et al. 2017). Episodic hypoxia, dense blooms of the "brown tide" harmful alga, *Aureoumbra lagunensis*, and fish kills have also been noted (reviewed by Wetz et al. 2017). The trend of increasing chlorophyll with decreasing TKN in Baffin Bay seems conflicted, given the importance of nitrogen for phytoplankton growth in the system (e.g., Wetz et al. 2017) and also that any increase in phytoplankton biomass would necessarily show up in the TKN pool. This trend also conflicts with findings from Wetz et al. (2017) and Montagna and Palmer (2012), who found an increasing TKN trend seasonally or annually when using data from additional sources that extended the time-series. Additional monitoring data is needed to assess whether the trend of decreasing TKN remains consistent or is an artifact of this dataset. Regardless, it is clear that Baffin Bay and Upper Laguna Madre are facing water quality challenges related to nutrient pollution, and stakeholder-led efforts are underway to address nutrient sources in the watershed. To the best of our knowledge, there have been few studies reporting on the eutrophication of estuaries like Baffin Bay-Upper Laguna Madre that are found in semi-arid regions and that lack defined river sources. Yet, as our findings show, these systems can still be susceptible to the process of eutrophication and its associated symptoms.

Aside from water quality issues related to nutrient pollution, the other major challenge facing Texas coastal ecosystems is a long-term decline in freshwater inflow. This manifests as increasing salinity levels, which was observed in every estuary from the Upper Laguna Madre to Matagorda Bay. When considering changes to freshwater inflow on the Texas coast, it is important to consider that there is strong interannual variability in precipitation that is linked to natural climate variability. Specifically, Tolan (2007) determined that periods of high rainfall on the Texas coast tend to occur during El Niño conditions. For each of the locations where a long-term increase in salinity was observed, we quantified concomitant trends in ENSO index during the same period as when the salinity data was collected to determine if the salinity trend could have been an artifact of natural variability (i.e., more La Niña events leading to less rainfall and higher salinities). The ENSO index only showed a statistically significant trend during the period of record corresponding with the salinity trend for San Antonio Bay (data not shown). However, the ENSO index during that time indicated a trend towards more frequent El Niño conditions, whereas the salinity trend showed increasing salinity, opposite what would be expected based on ENSO-rainfall linkages. Furthermore, in an analysis of monthly precipitation and evaporation data in a similar manner, obtained from the Texas Water Development Board (https://waterdatafortexas.org/lake-evaporation-rainfall), we found no significant trend in precipitation during the aforementioned timeframes, whereas decreasing evaporation trends were observed during several timeframes (data not shown). Again, the increasing salinity trend is opposite what would be expected with decreasing evaporation rates. Thus, we believe that the increasing salinity trends are likely not due to natural climate variability, but instead are symptomatic of other factors such as growing human water demand in watersheds. Adequate freshwater inflow and salinity levels are vital influences on estuarine ecosystem health

(Copeland 1966; Montagna et al. 2013), whereas prolonged increases in salinity above historical conditions can lead to deleterious declines in upper trophic level biomass and changes in diversity (Copeland 1966; Livingston et al. 1997; Palmer and Montagna 2015). In Texas, another artifact of decreasing freshwater inflow levels are changes to the carbonate chemistry system of estuaries. This study found numerous sites along the central Texas coast, often overlapping with sites of increasing salinity, where pH and alkalinity exhibited a long-term decrease. Hu et al. (2015) attributed these declines to reduced export of carbonate minerals from watersheds as a result of reduced freshwater inflow. Although differing in its cause from classic ocean acidification, the consequence for estuarine shell-forming organisms (e.g., oysters) is the same – namely, carbonate-reliant estuarine species may experience increased difficulty with growth and shell formation (reviewed by Gazeau et al. 2013).

Unlike coastal systems in other regions of the U.S. and elsewhere, there was no indication of widespread annual water temperature increases in this study. This was based on analysis of a water temperature record that began as early as 1969 in many locations, and in the 1970's at most other sites. On a seasonal basis, trends were inconsistent between and within estuaries, especially from fall-spring. In summer, when a significant trend was found, it was increasing. Overall, water temperature increased at 27% of sampling sites during summer in this study. It is important to note that the data record used in this study, by relying on quarterly data collections, misses other ecologically-relevant aspects of water temperature variability such as trends in nighttime lows, return period of freezes, etc., that can only be captured by higher frequency data. Thus, for more thorough examination of water temperature trends, it is clearly more appropriate to use datasets that have much higher frequency temporal coverage (such as those in the National Climatic Data Center).

Conclusions

Analysis of historical data on key water quality variables has identified localized areas of concern amongst Texas estuaries. For example, multiple indicators suggest that Baffin Bay and adjacent Upper Laguna Madre are undergoing eutrophication. These systems only receive freshwater input via episodic rainfall and flow from ephemeral streams, and thus would not conform to traditional views of eutrophication that tend to focus on river-influenced systems. But because of their long residence time, these systems can be especially susceptible to nutrient pollution and its associated symptoms (Bricker et al. 2008). The urbanized estuaries, Oso Bay and Galveston Bay, also display symptoms of eutrophication. Another major water quality concern is a long-term increase in the salinity of mid-coast estuaries from Upper Laguna Madre to Matagorda Bay. This is largely an artifact of increasing human freshwater demands in the watersheds of these estuaries, and has important implications for estuarine organisms that are sensitive to high salinities. With the findings from this study, targeted studies can now be directed at the estuaries that are experiencing water quality degradation in order to guide future management efforts.

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Figure Legends

Figure 1. Map of TCEQ SWQM sampling locations.

Figure 2. Patterns and trends in water temperature annually (A), and during summer (B).

Figure 3. Annual salinity pattern and trends.

Figure 4. Annual pH pattern and trends.

Figure 5. Annual total phosphorus (A) and orthophosphate (B) patterns and trends.

Figure 6. Annual patterns and trends in TKN (A), N+N (B), and ammonium (C).

Figure 7. Annual chlorophyll *a* pattern and trends.

Figure 8. Annual bottom dissolved oxygen pattern and trends.

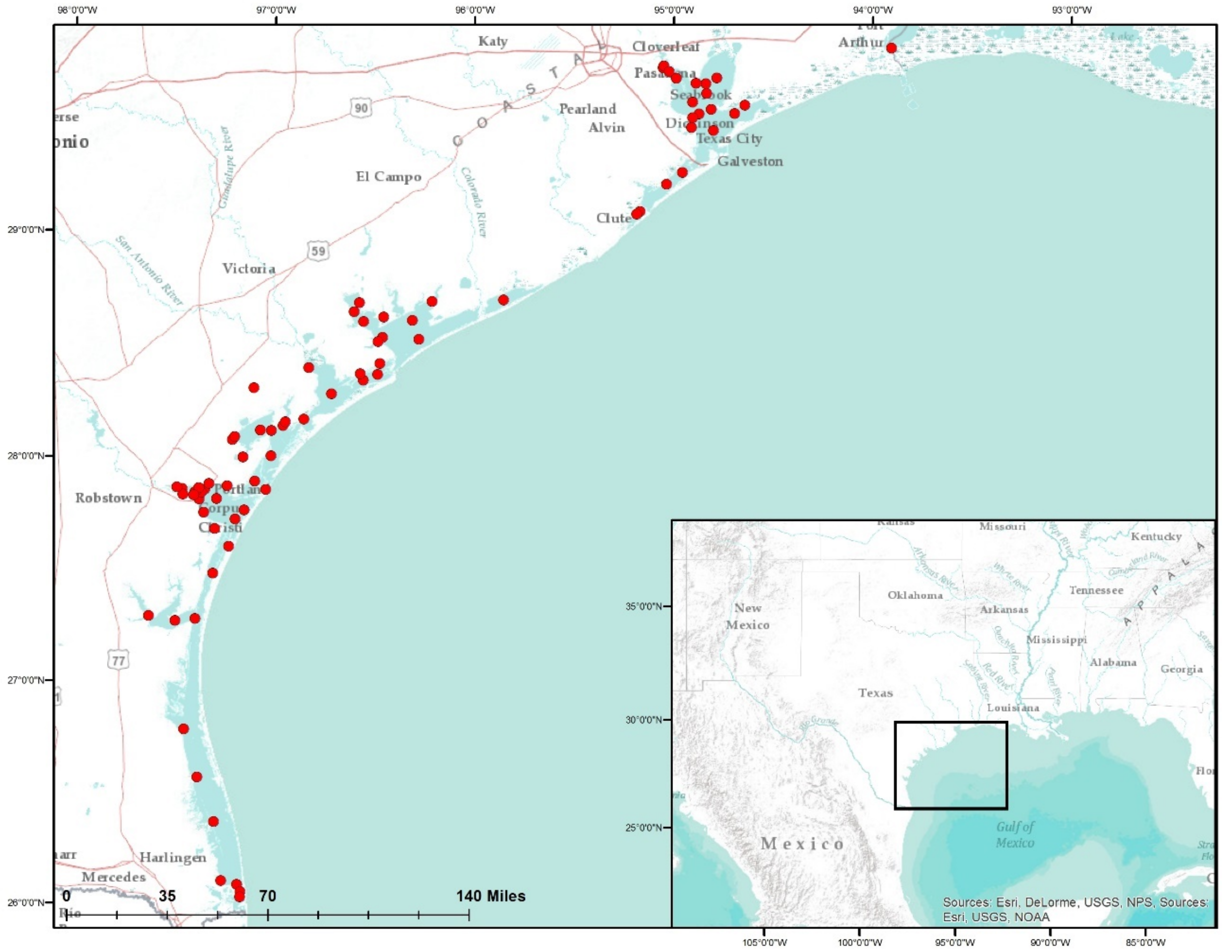
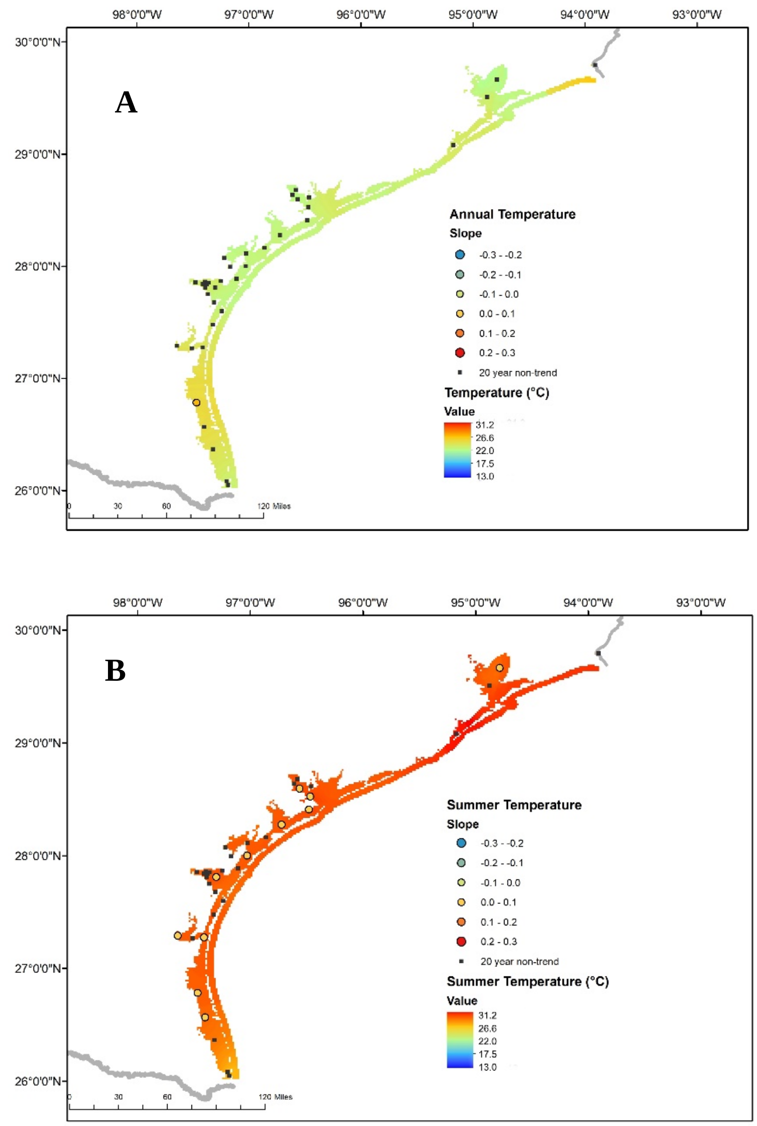


Figure 1.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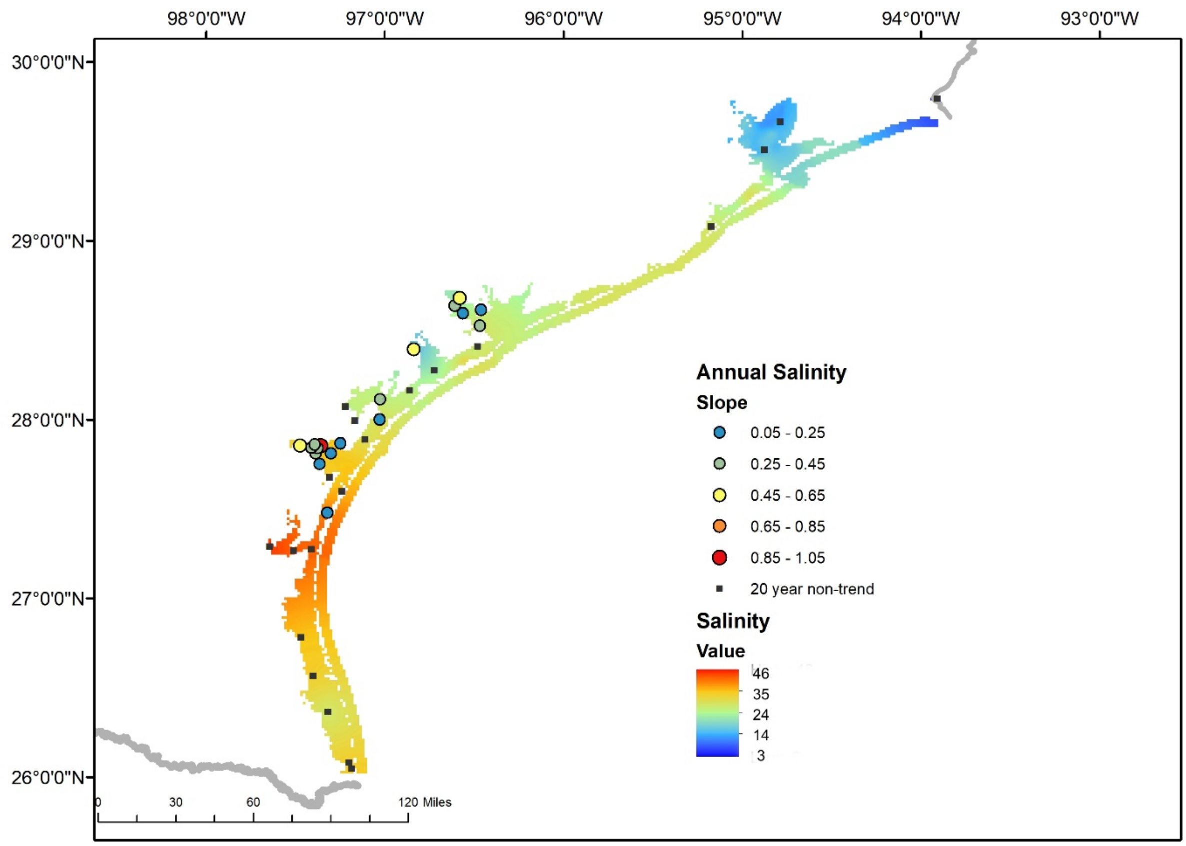
29°0'0"N
28°0'0"N
27°0'0"N
26°0'0"N
A
Annual Temperature
Slope
-0.3 - -0.2
-0.2 - -0.1
-0.1 - 0.0
0.0 - 0.1
0.1 - 0.2
0.2 - 0.3
20 year non-trend
Temperature (°C)
Value
31.2
26.6
22.0
17.5
13.0
0
30
60
120 Miles
B
Summer Temperature
Slope
-0.3 - -0.2
-0.2 - -0.1
-0.1 - 0.0
0.0 - 0.1
0.1 - 0.2
0.2 - 0.3
20 year non-trend
Summer Temperature (°C)
Value
31.2
26.6
22.0
17.5
13.0

Figure 2.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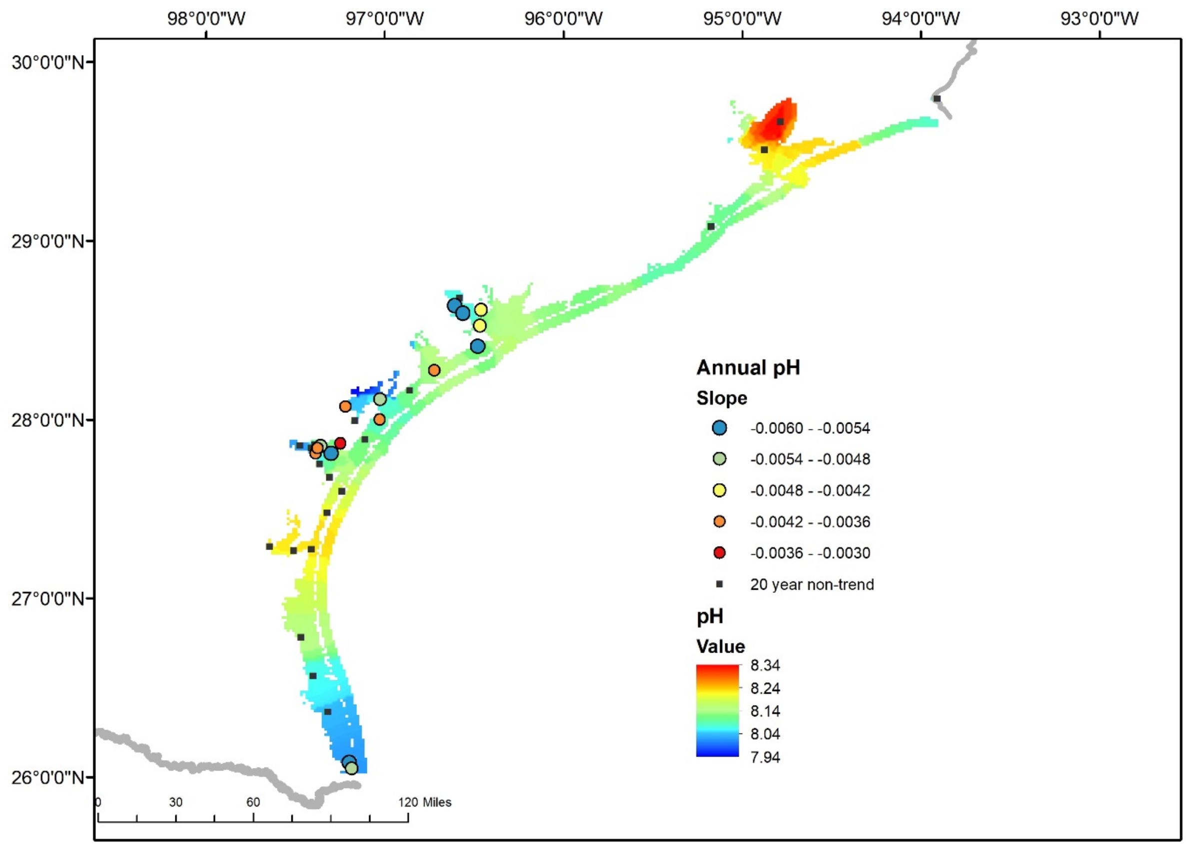
30°0'0"N
29°0'0"N
28°0'0"N
27°0'0"N
26°0'0"N
Annual Salinity
Slope
0.05 - 0.25
0.25 - 0.45
0.45 - 0.65
0.65 - 0.85
0.85 - 1.05
20 year non-trend
Salinity
Value
46
35
24
14
3
0
30
60
120 Miles

Figure 3.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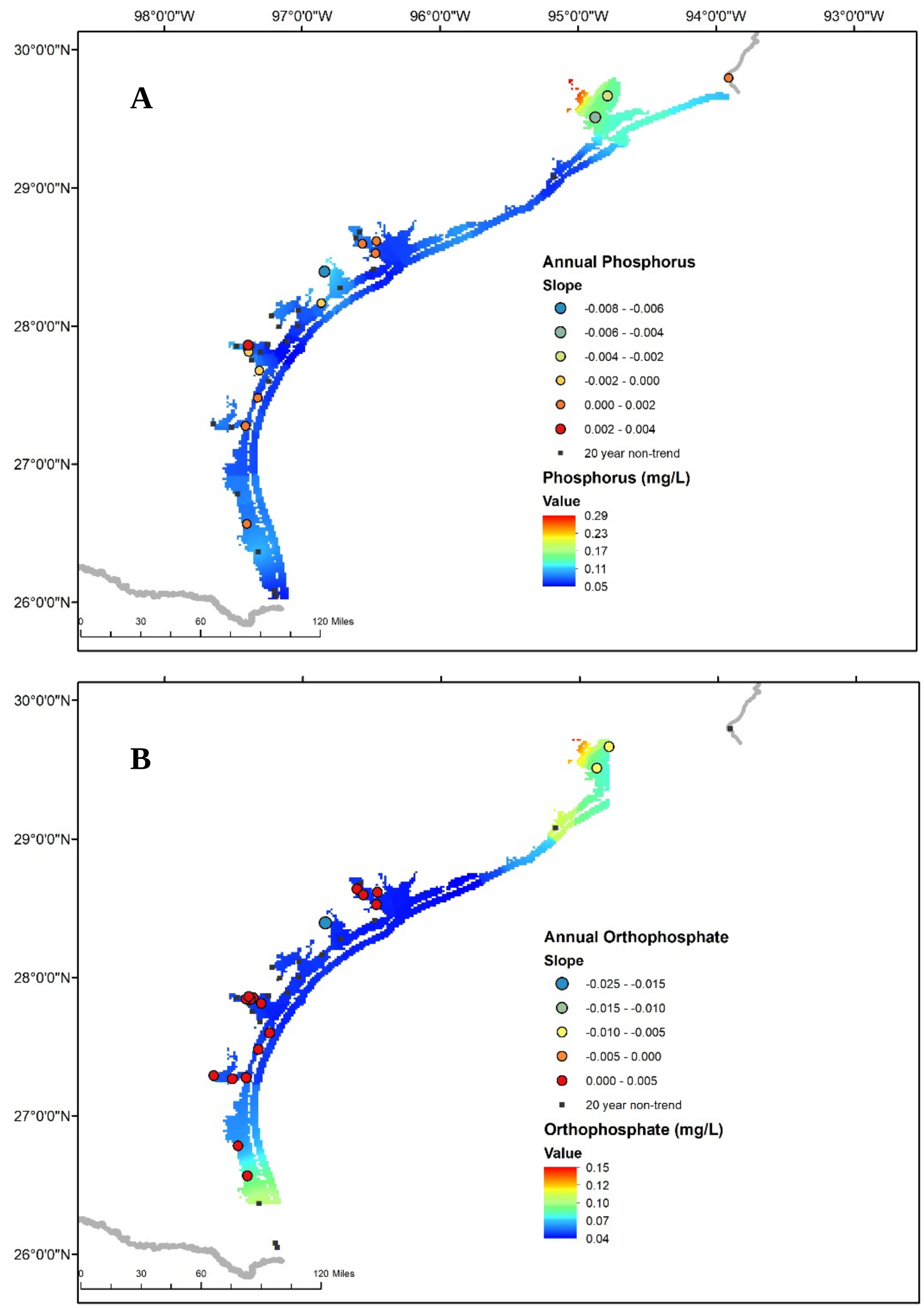
30°0'0"N
29°0'0"N
28°0'0"N
27°0'0"N
26°0'0"N
Annual pH
Slope
-0.0060 - -0.0054
-0.0054 - -0.0048
-0.0048 - -0.0042
-0.0042 - -0.0036
-0.0036 - -0.0030
20 year non-trend
pH
Value
8.34
8.24
8.14
8.04
7.94
0
30
60
120 Miles

Figure 4.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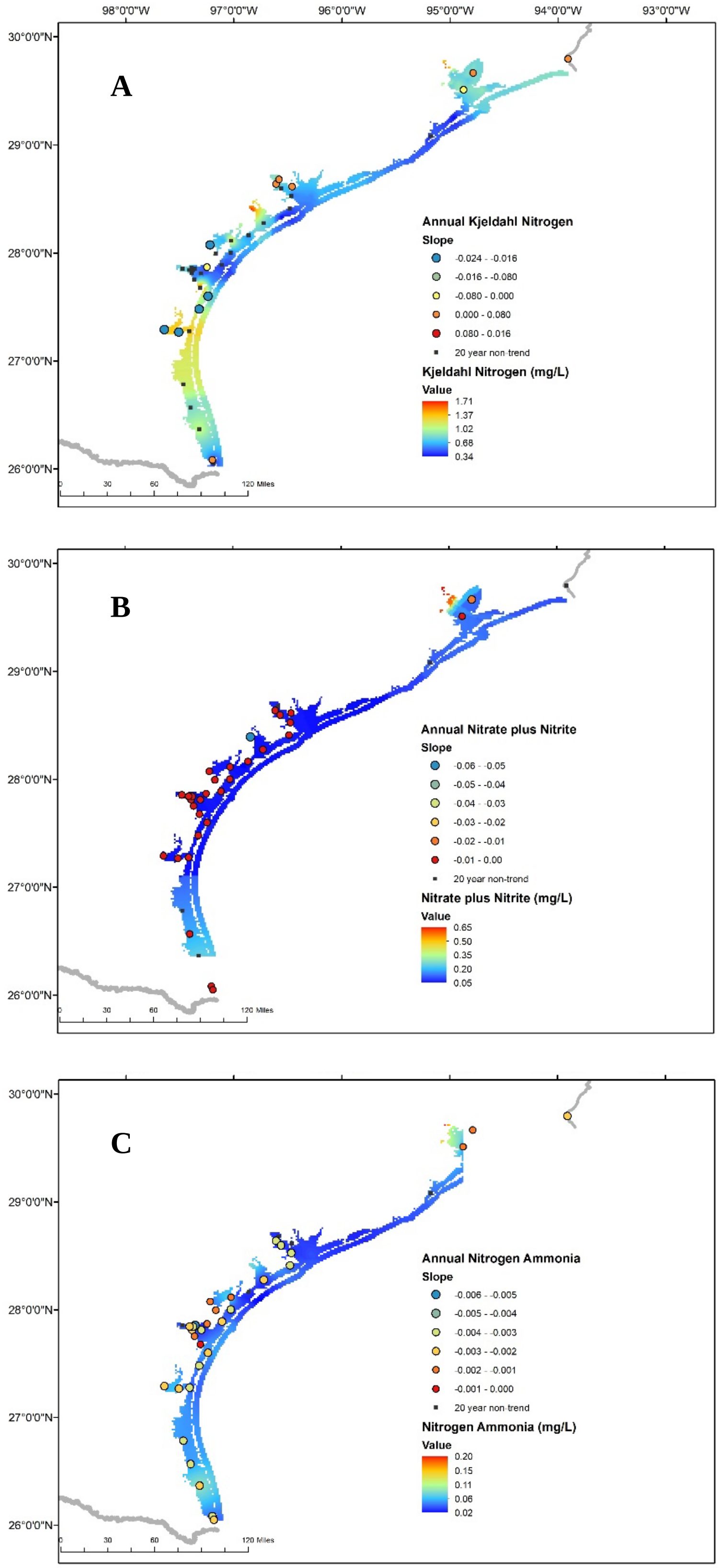
29°0'0"N
28°0'0"N
27°0'0"N
26°0'0"N
A
Annual Phosphorus
Slope
-0.008 - -0.006
-0.006 - -0.004
-0.004 - -0.002
-0.002 - 0.000
0.000 - 0.002
0.002 - 0.004
20 year non-trend
Phosphorus (mg/L)
Value
0.29
0.23
0.17
0.11
0.05
0
30
60
120 Miles
B
Annual Orthophosphate
Slope
-0.025 - -0.015
-0.015 - -0.010
-0.010 - -0.005
-0.005 - 0.000
0.000 - 0.005
20 year non-trend
Orthophosphate (mg/L)
Value
0.15
0.12
0.10
0.07
0.04

Figure 5.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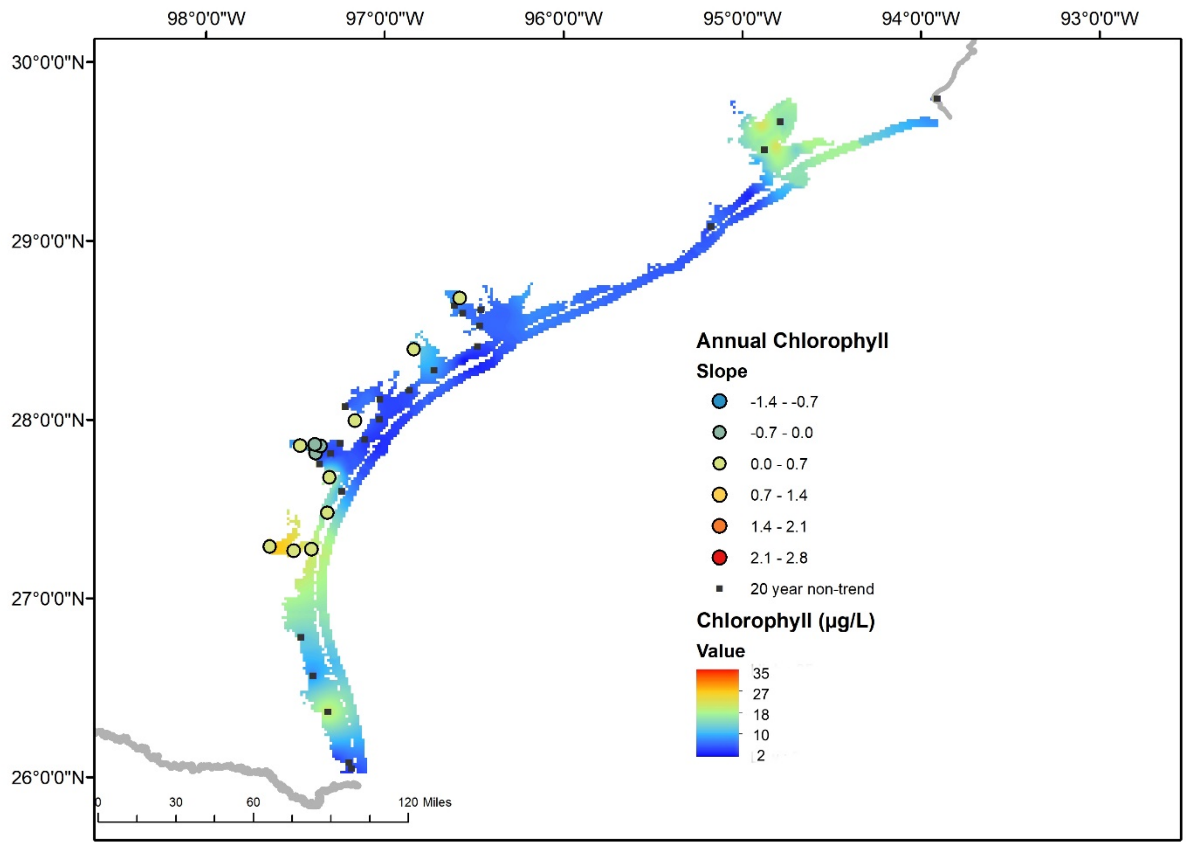
30°0'0"N
29°0'0"N
28°0'0"N
27°0'0"N
26°0'0"N
A
Annual Kjeldahl Nitrogen
Slope
-0.024 - -0.016
-0.016 - -0.080
-0.080 - 0.000
0.000 - 0.080
0.080 - 0.016
20 year non-trend
Kjeldahl Nitrogen (mg/L)
Value
1.71
1.37
1.02
0.68
0.34
0 30 60 120 Miles
B
Annual Nitrate plus Nitrite
Slope
-0.06 - -0.05
-0.05 - -0.04
-0.04 - -0.03
-0.03 - -0.02
-0.02 - -0.01
-0.01 - 0.00
20 year non-trend
Nitrate plus Nitrite (mg/L)
Value
0.65
0.50
0.35
0.20
0.05
C
Annual Nitrogen Ammonia
Slope
-0.006 - -0.005
-0.005 - -0.004
-0.004 - -0.003
-0.003 - -0.002
-0.002 - -0.001
-0.001 - 0.000
20 year non-trend
Nitrogen Ammonia (mg/L)
Value
0.20
0.15
0.11
0.06
0.02

Figure 6.



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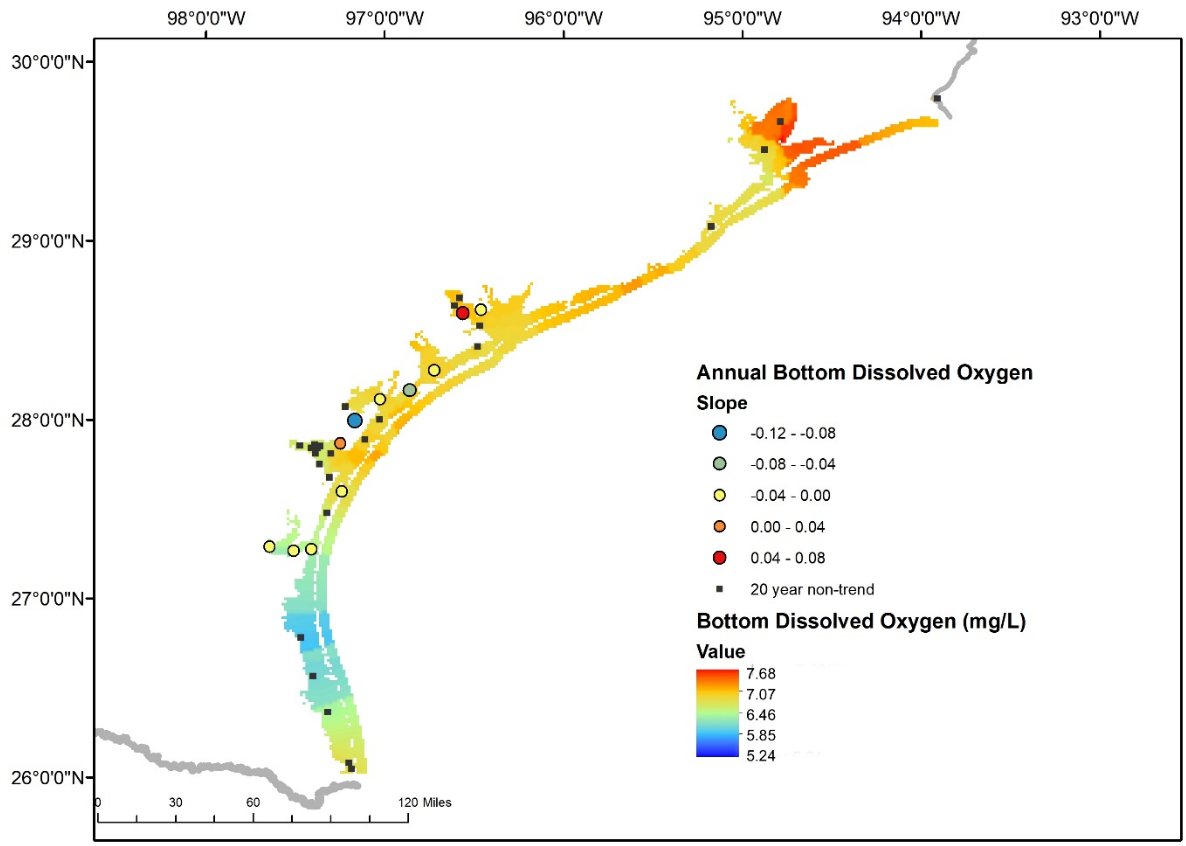
94°0'0"W
93°0'0"W
30°0'0"N
29°0'0"N
28°0'0"N
27°0'0"N
26°0'0"N
Annual Chlorophyll
Slope
-1.4 - -0.7
-0.7 - 0.0
0.0 - 0.7
0.7 - 1.4
1.4 - 2.1
2.1 - 2.8
20 year non-trend
Chlorophyll (µg/L)
Value
35
27
18
10
2
0
30
60
120 Miles

Figure 7.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93°0'0"W
30°0'0"N
29°0'0"N
28°0'0"N
27°0'0"N
26°0'0"N
Annual Bottom Dissolved Oxygen
Slope
-0.12 - -0.08
-0.08 - -0.04
-0.04 - 0.00
0.00 - 0.04
0.04 - 0.08
20 year non-trend
Bottom Dissolved Oxygen (mg/L)
Value
7.68
7.07
6.46
5.85
5.24
0
30
60
120 Miles

Figure 8.

Supplemental Table 1. List of sampling locations used in spatial analysis. Station ID corresponds to designation used in the Texas Commission on Environmental Quality's SWQM program. Italicized stations are those used in the trend analysis with at least 20 years of data.

Station.ID	Estuary	Latitude	Longitude
13402	*ARANSAS BAY*	*28.001*	*-97.028*
16492	ARANSAS BAY	27.851	-97.054
13450	*BAFFIN BAY*	*27.268*	*-97.510*
13452	*BAFFIN BAY*	*27.290*	*-97.643*
13351	*CHRISTMAS BAY*	*29.079*	*-95.173*
15931	CHRISTMAS BAY	29.068	-95.190
12945	*COPANO BAY*	*28.074*	*-97.221*
13404	*COPANO BAY*	*28.114*	*-97.026*
14783	COPANO BAY	28.088	-97.209
17724	COPANO BAY	28.116	-97.081
13407	*CORPUS CHRISTI BAY*	*27.811*	*-97.301*
13409	*CORPUS CHRISTI BAY*	*27.869*	*-97.248*
13410	*CORPUS CHRISTI BAY*	*27.810*	*-97.388*
13411	*CORPUS CHRISTI BAY*	*27.751*	*-97.365*
14355	CORPUS CHRISTI BAY	27.761	-97.162
17791	CORPUS CHRISTI BAY	27.721	-97.208
15229	*EAST BAY*	*29.546*	*-94.644*
16216	EAST BAY	29.509	-94.696
18378	EAST MATAGORDA BAY	28.690	-95.859
13396	*ESPIRITU SANTO BAY*	*28.410*	*-96.479*
14732	ESPIRITU SANTO BAY	28.362	-96.492
14733	ESPIRITU SANTO BAY	28.337	-96.563
14951	*ESPIRITU SANTO BAY*	*28.365*	*-96.578*
13364	*GALVESTON BAY*	*29.509*	*-94.875*
15224	*GALVESTON BAY*	*29.449*	*-94.913*
16517	GALVESTON BAY	29.527	-94.814
16519	GALVESTON BAY	29.491	-94.907
16523	GALVESTON BAY	29.435	-94.804
15242	*GALVESTON BAY*	*29.598*	*-94.838*
15244	*GALVESTON BAY*	*29.663*	*-94.990*
15903	GALVESTON BAY	29.642	-94.891
16512	GALVESTON BAY	29.559	-94.908
13387	*KELLER BAY*	*28.615*	*-96.461*
13443	*UPPER LAGUNA MADRE*	*27.600*	*-97.240*
13444	*UPPER LAGUNA MADRE*	*27.276*	*-97.410*

13445	*UPPER LAGUNA MADRE*	*27.479*	*-97.321*
13446	*LOWER LAGUNA MADRE*	*26.083*	*-97.200*
13447	*LOWER LAGUNA MADRE*	*26.367*	*-97.317*
13448	*LOWER LAGUNA MADRE*	*26.567*	*-97.400*
13449	*LOWER LAGUNA MADRE*	*26.783*	*-97.467*
14870	LOWER LAGUNA MADRE	26.100	-97.281
13383	*LAVACA BAY*	*28.639*	*-96.609*
13384	*LAVACA BAY*	*28.596*	*-96.563*
13563	*LAVACA BAY*	*28.680*	*-96.582*
13378	*MATAGORDA BAY*	*28.526*	*-96.467*
18395	MATAGORDA BAY	28.600	-96.317
18397	MATAGORDA BAY	28.517	-96.283
13400	*MESQUITE BAY*	*28.163*	*-96.862*
13420	*NUECES BAY*	*27.853*	*-97.360*
13421	*NUECES BAY*	*27.840*	*-97.377*
13422	*NUECES BAY*	*27.843*	*-97.410*
13423	*NUECES BAY*	*27.861*	*-97.391*
13425	*NUECES BAY*	*27.856*	*-97.474*
14832	NUECES BAY	27.879	-97.339
14833	NUECES BAY	27.827	-97.417
18365	NUECES BAY	27.831	-97.470
18866	NUECES BAY	27.864	-97.500
13440	*OSO BAY*	*27.679*	*-97.310*
13405	*PORT BAY*	*27.996*	*-97.168*
14726	POWDERHORN LAKE	28.506	-96.489
13426	*RED FISH*	*27.889*	*-97.110*
13300	*SABINE LAKE*	*29.796*	*-93.908*
13397	*SAN ANTONIO BAY*	*28.277*	*-96.723*
14956	*SAN ANTONIO BAY*	*28.392*	*-96.838*
16499	SAN JACINTO BAY	29.710	-95.055
17923	SAN JACINTO BAY	29.719	-95.053
17924	SAN JACINTO BAY	29.694	-95.025
13459	*SOUTH BAY*	*26.050*	*-97.183*
14865	SOUTH BAY	26.026	-97.186
17692	ST CHARLES BAY	28.136	-96.967
18222	ST CHARLES BAY	28.152	-96.955
18398	TRES PALACIOS BAY	28.683	-96.217
13315	*TRINITY BAY*	*29.665*	*-94.787*
16505	TRINITY BAY	29.640	-94.842
15226	*WEST BAY*	*29.252*	*-94.959*

15928	WEST BAY	29.200	-95.038