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Water quality trends in Texas estuaries

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ABSTRACT

Coastal watersheds in Texas have experienced significant human population growth over the past several decades, yet there have been no comprehensive assessments of water quality trends in Texas estuaries. Here, analysis of historical estuarine water quality data indicates regional "hot spots" of change. Galveston Bay and Oso Bay, which have highly urbanized watersheds, currently exhibit symptoms of eutrophication. Symptoms of eutrophication were also found in the Baffin Bay-Upper Laguna Madre complex, which has a sparsely populated but agriculturally-intensive watershed. Increasing salinity was observed in estuaries of the central Texas coast and are attributed to long-term decreases in freshwater inflow. Another artifact of decreasing freshwater inflow is a reduction in the delivery of carbonate minerals to estuaries, which manifests as decreases in pH. 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.

1. 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). In addition, population growth also affects freshwater inflows to, and ultimately salinity levels in estuaries through water usage and withdrawals (reviewed by Montagna et al., 2013). Studies in estuaries have noted deleterious effects on living resources and habitat 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 many of Texas' coastal communities, along with climatic changes that are occurring 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.

2. Materials & methods

2.1. Data sources

To quantify spatial patterns and 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 were newer than 2011

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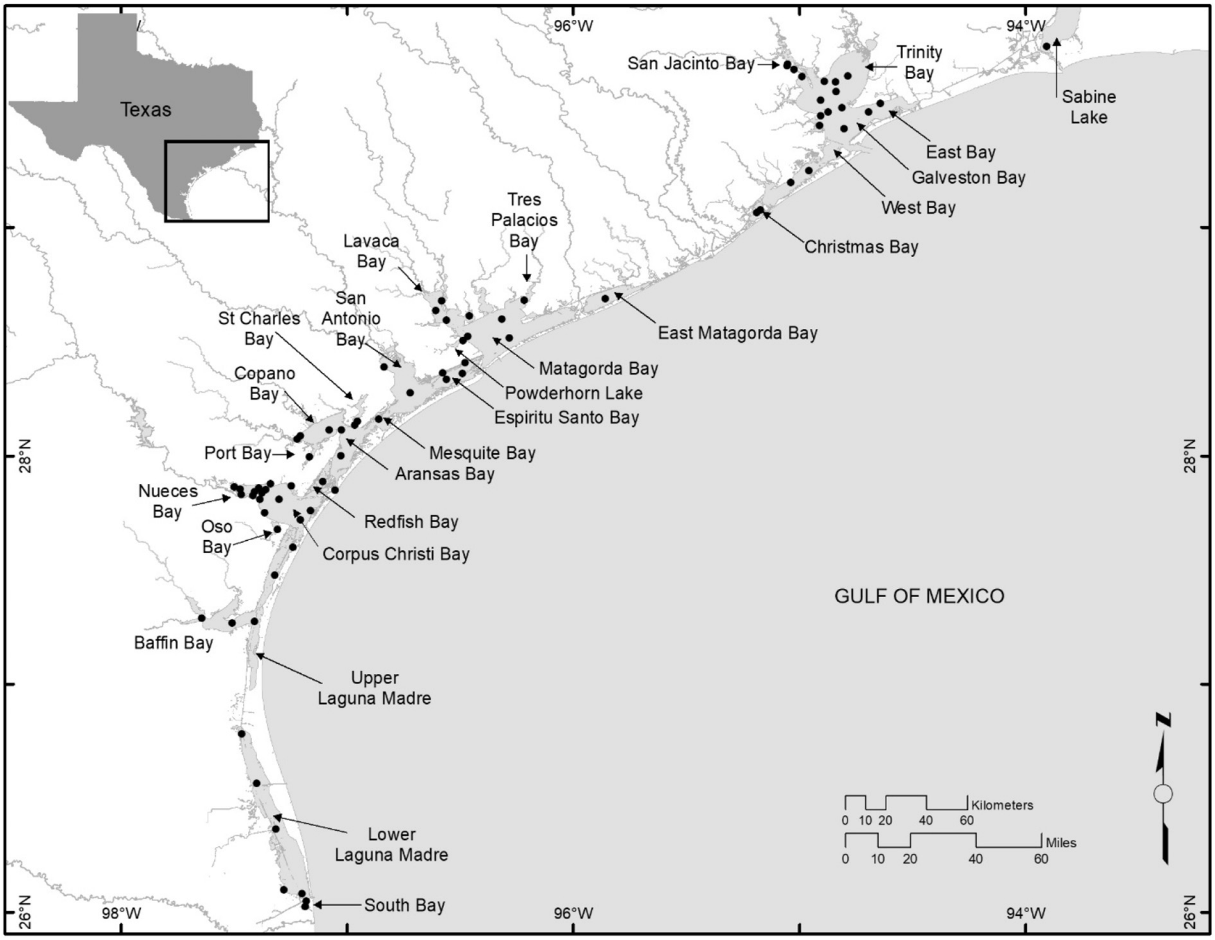

Fig. 1. Map of TCEQ SWQM sampling locations.

(Fig. 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) (Suppl. Table 1).

2.2. Statistical patterns and trend analysis

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 trends in a given season, 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).

3. Results

3.1. Spatial patterns

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

For nutrient related water quality variables where the state of Texas has designated "screening levels" for potential impairment, we report here sites/estuaries where those were exceeded in the 7-year average. Variables include total phosphorus (0.21 mg/l), orthophosphate (0.19 mg/l), nitrate (0.17 mg/l), ammonium (0.10 mg/l), and chlorophyll (11.6 μg/l). Total phosphorus (TP) concentrations > 0.21 mg/l were found at all three sites in San Jacinto Bay (0.34 ± 0.02 mg/l) and one site in Galveston Bay (0.25 mg/l) (Fig. 3a). Orthophosphate concentrations > 0.19 mg/l were only found at one site in San Jacinto Bay (0.22 mg/l). Most sites had orthophosphate concentrations ≤0.05 mg/l (Fig. 3b). Highest Total Kjeldahl Nitrogen (TKN) was found in upper San Antonio Bay (1.83 mg/l) and Oso Bay (1.83 mg/l) (Fig. 4a). Other locations with TKN averaging > 1 mg/l include two sites in each of the following locations: San Jacinto Bay (1.57–1.75 mg/l), Copano Bay (1.05–1.38 mg/l), Baffin Bay (1.35–1.40 mg/l), Upper Laguna Madre

Table 1
Magnitude of statistically significant ($p < 0.05$) long-term trends in select water quality variables. Units are °C yr^{-1} for temperature, yr^{-1} for salinity and pH, mg L^{-1} yr^{-1} for TP, PO_4^{3-}, TKN and D.O., and μg L^{-1} yr^{-1} for Chl *a*. Bays are organized based on location on the Texas coast for ease of comparison with the map on Fig. 1, from the northeast (Sabine Lake) to southwest (South Bay).

Bay	Station ID	Annual Temp.	Summer Temp.	Salinity	pH	TP	PO_4^{3-}	TKN	Chl a	D.O.
Sabine Lake	13300	NS	0.07	NS	NS	0.001	NS	0.01	NS	NS
Trinity	13315	NS	0.03	NS	NS	-0.004	-0.007	0.01	NS	NS
Galveston	13364	NS	NS	NS	NS	-0.005	-0.008	-0.02	NS	NS
Matagorda	13378	NS	0.03	0.31	-0.005	0.000	0.001	NS	NS	NS
Lavaca	13383	NS	NS	0.33	-0.006	0.001	0.002	0.01	NS	NS
Lavaca	13384	NS	0.03	0.21	-0.007	0.000	0.001	NS	NS	0.04
Lavaca	13563	NS	NS	0.52	NS	NS	NS	0.01	0.31	NS
Keller	13387	NS	NS	0.24	-0.005	NS	0.001	0.01	NS	-0.02
Espiritu Santo	13396	NS	0.04	NS	-0.006	NS	NS	NS	NS	NS
San Antonio	13397	NS	0.03	NS	-0.004	NS	NS	NS	NS	-0.03
San Antonio	14956	NS	NS	0.54	NS	-0.007	-0.023	NS	0.59	NS
Mesquite	13400	NS	NS	NS	NS	-0.001	NS	NS	NS	-0.06
Aransas	13402	NS	0.03	0.22	-0.004	NS	NS	NS	NS	NS
Copano	12945	NS	NS	NS	-0.004	NS	NS	-0.02	NS	NS
Copano	13404	NS	NS	0.30	-0.005	NS	NS	NS	NS	-0.04
Port	13405	NS	NS	NS	NS	NS	NS	NS	0.09	-0.11
Redfish	13426	NS	NS	NS	NS	NS	NS	NS	NS	NS
Corpus Christi	13407	NS	0.02	0.17	-0.006	NS	0.001	NS	NS	NS
Corpus Christi	13409	NS	NS	0.17	-0.003	NS	NS	-0.01	NS	0.03
Corpus Christi	13410	NS	NS	0.28	-0.004	-0.001	NS	NS	-0.08	NS
Corpus Christi	13411	NS	NS	0.20	NS	NS	NS	NS	NS	NS
Nueces	13420	NS	NS	1.03	-0.005	NS	0.002	NS	-0.41	NS
Nueces	13421	NS	NS	0.31	-0.004	NS	0.001	NS	NS	NS
Nueces	13422	NS	NS	0.30	NS	NS	0.002	NS	NS	NS
Nueces	13425	NS	NS	0.56	NS	NS	NS	NS	0.37	NS
Oso	13440	NS	NS	NS	NS	-0.002	NS	NS	0.42	NS
Upper Laguna Madre	13443	NS	NS	NS	NS	NS	0.002	-0.02	NS	-0.03
Upper Laguna Madre	13444	NS	0.03	NS	NS	0.001	0.002	NS	0.35	-0.02
Upper Laguna Madre	13445	NS	NS	0.22	NS	0.000	0.001	-0.02	0.35	NS
Baffin	13450	NS	NS	NS	NS	NS	0.002	-0.02	0.39	-0.03
Baffin	13452	NS	0.04	NS	NS	NS	0.002	-0.02	0.36	-0.02
Lower Laguna Madre	13446	NS	NS	NS	-0.006	NS	NS	0.01	NS	NS
Lower Laguna Madre	13447	NS	NS	NS	NS	NS	NS	NS	NS	NS
Lower Laguna Madre	13448	NS	0.03	NS	NS	0.000	0.001	NS	NS	NS
Lower Laguna Madre	13449	0.06	0.05	NS	NS	NS	0.001	NS	NS	NS
South	13459	NS	NS	NS	-0.005	NS	NS	NS	NS	NS

(1.01–1.33 mg/l), and Lower Laguna Madre (1.10–1.14 mg/l). TKN < 1 mg/l was found at all other locations. Using nitrate + nitrite (N + N) as a proxy for nitrate, concentrations > 0.17 mg/l were found at all three sites in San Jacinto Bay (0.92 ± 0.15 mg/l), three sites in Galveston Bay (0.34 ± 0.17 mg/l), one site in Trinity Bay (0.22 mg/l), and one site in Lower Laguna Madre adjacent to the Arroyo Colorado (0.52 mg/l) (Fig. 4b). Ammonium concentrations > 0.10 mg/l were found at all three sites in San Jacinto Bay (0.20 ± 0.03) and one site Galveston Bay (0.10 mg/l) (Fig. 4c). Highest chlorophyll *a* concentration was found at the two Baffin Bay sites (25.1–28.4 μg/l) (Fig. 5a). Other locations with chlorophyll *a* concentration > 11.6 μg/l include eight sites in Galveston Bay (n18.4 ± 3.1 μg/l), two sites in Upper Laguna Madre (15.1–21.2 μg/l), two sites in Lower Laguna Madre (12.8–21.9 μg/l), Oso Bay (23.3 μg/l), two sites in East Bay (13.3–19.3 μg/l), one site in San Antonio Bay (13.4 μg/l), and one site in Trinity Bay (15.2 μg/l) (Fig. 5a). All other sites on the Texas coast had chlorophyll < 11.6 μg/l. Highest average bottom dissolved oxygen (DO) values were seen in Galveston Bay and generally decreased moving south along the coast, corresponding with temperature and salinity gradients (Fig. 5b).

3.2. Temporal trends

Table 1 includes site-specific details on the magnitude of trends for each water quality variable of interest when statistically significant trends were observed. A statistically significant increase in annual water temperature was observed at a single site in the Upper Laguna Madre (Fig. 2a; Table 1), while no significant decreases were observed. Water temperature trends were often inconsistent in a given season except for summer, when 12 sites (33% of all sites with sufficient data for long-term trend analysis) showed temperature increases, and none showed decreases (Fig. 2b). Significant increases in summer temperature were observed at two sites in Lower Laguna Madre and one site in each of the following locations: Upper Laguna Madre, Baffin Bay, Matagorda Bay, Corpus Christi Bay, Aransas Bay, San Antonio Bay, Espiritu Santo Bay, Lavaca Bay, Trinity Bay, and Sabine Lake. Significant annual increases in salinity were observed at four sites in Corpus Christi Bay, four sites in Nueces Bay, three sites in Lavaca Bay, and one site in each of the following locations: Matagorda Bay, Copano Bay, Aransas Bay, Upper Laguna Madre, San Antonio Bay, and Keller Bay (Fig. 2c). Overall, 17 sites (61% of all sites with sufficient data) displayed a long-term salinity increase. Significant pH decreases were found at three sites in Corpus Christi Bay, two sites in Copano Bay, two sites in Lavaca Bay, two sites in Nueces Bay, and one site in each of the following locations: San Antonio Bay, Matagorda Bay, Aransas Bay, Keller Bay, Espiritu Santo Bay, Lower Laguna Madre, and South Bay (Fig. 2d). Overall, 16 sites (44% of all sites with sufficient data) saw decreases in pH.

A decrease in TP was observed at one site in each of the following locations: Trinity Bay, Galveston Bay, San Antonio Bay, Oso Bay, Corpus Christi Bay, and Mesquite Bay (Fig. 3a). In contrast, TP increased at two sites in Upper Laguna Madre and one site in each of the following locations: Matagorda Bay, Lavaca Bay, Keller Bay, Lower Laguna Madre, and Sabine Lake. Orthophosphate increased at three sites in Nueces Bay, three sites in Upper Laguna Madre, two sites in Lavaca Bay, two sites in Baffin Bay, two sites in Lower Laguna Madre,

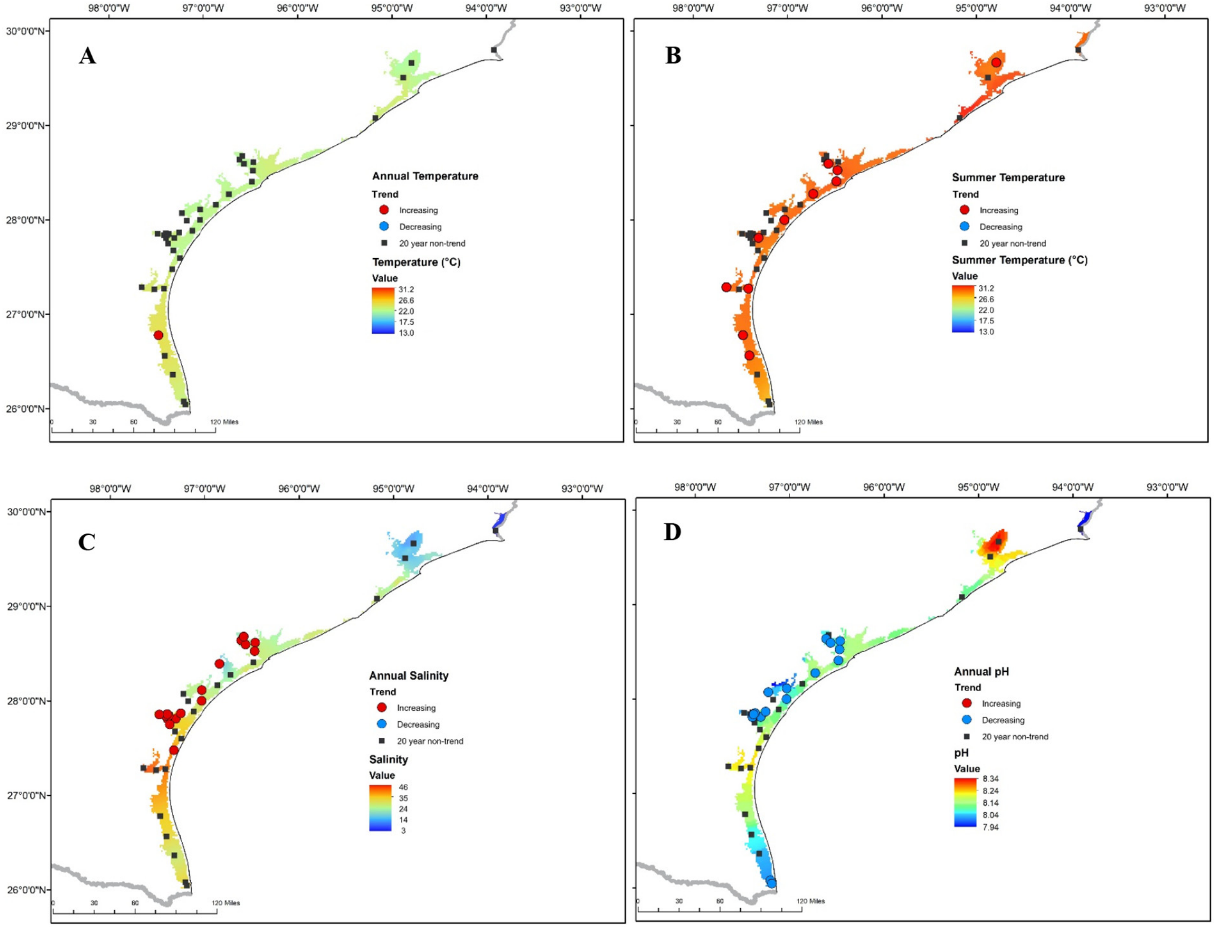

Fig. 2. Patterns and trends in annual water temperature (A), summer water temperature (B), annual salinity (C), and annual pH (D).

and one site in each of the following locations: Matagorda Bay, Keller Bay, and Corpus Christi Bay (Fig. 3b). In contrast, a decreasing trend was observed at one site in Trinity Bay, Galveston Bay, and San Antonio Bay. TKN decreased at two sites in Baffin Bay, two sites in Upper Laguna Madre, and one site in each of the following locations: Copano Bay, Corpus Christi Bay, and Galveston Bay (Fig. 4a). In contrast, TKN increased at two sites in Lavaca Bay, and one site in each of the following locations: Trinity Bay, Sabine Lake, Keller Bay, and Lower Laguna Madre. N + N and ammonium decreased over time at nearly every site along the coast (Figs. 4b,c), 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 chlorophyll *a* increases were found at two sites in Baffin Bay, two sites in Upper Laguna Madre, and one site in each of the following locations: Oso Bay, San Antonio Bay, Lavaca Bay, Port Bay, and Nueces Bay (Fig. 5a). Decreases in chlorophyll *a* were found at one site in Nueces Bay and Corpus Christi Bay. A significant decrease in DO was observed at two sites in Baffin Bay, two sites in Upper Laguna Madre, and one site in each of the following locations: San Antonio Bay, Keller Bay, Copano Bay, Port Bay and Mesquite Bay (Fig. 5b). In contrast, an increase in DO was observed at one site in Corpus Christi Bay and Lavaca Bay.

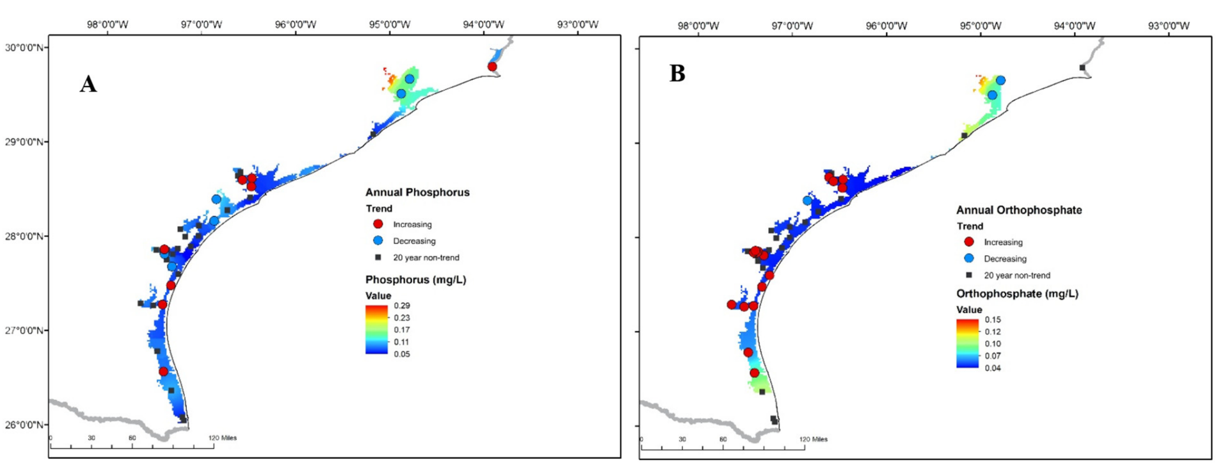

Fig. 3. Annual total phosphorus (A) and orthophosphate (B) patterns and trends.

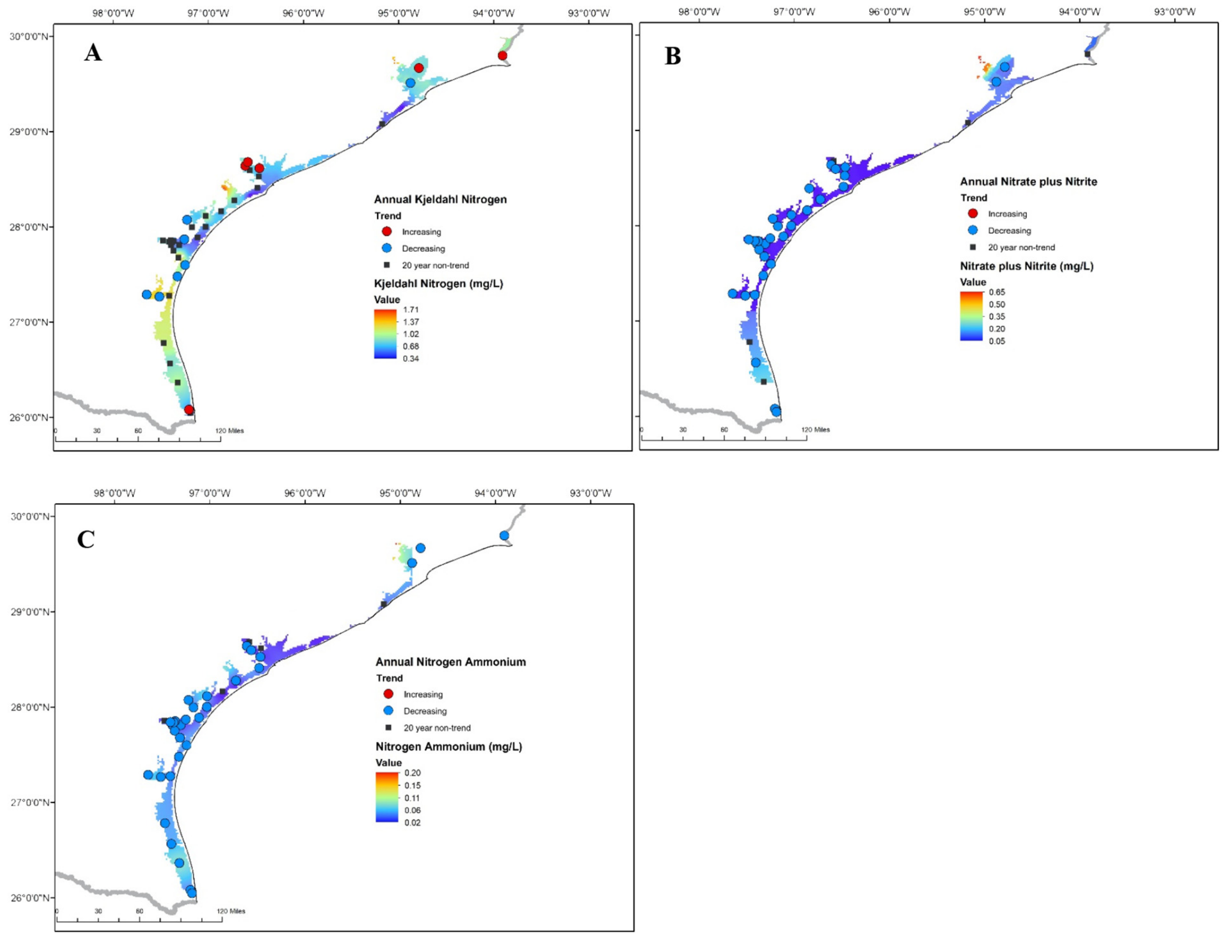

Fig. 4. Annual patterns and trends in TKN (A), N + N (B), and ammonium (C).

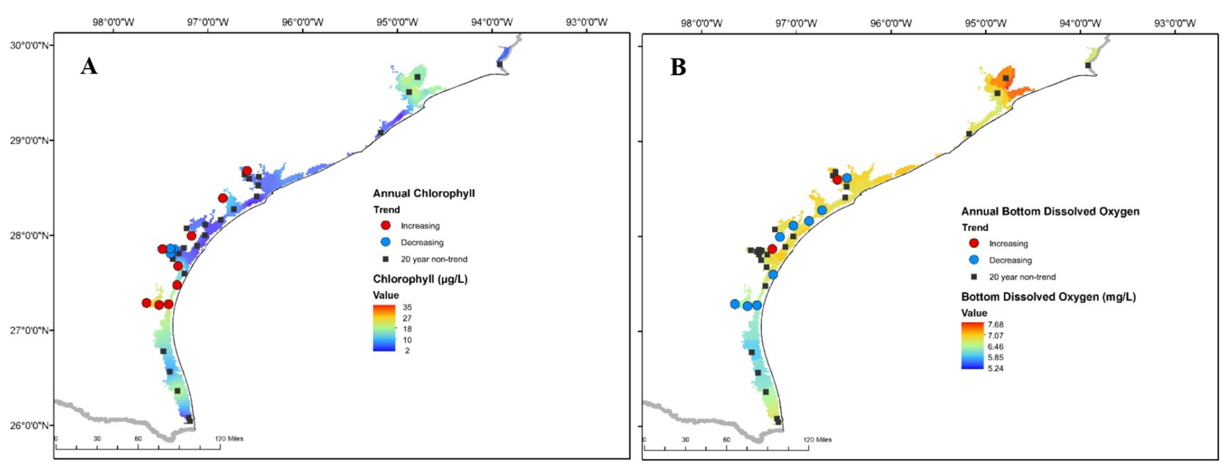

Fig. 5. Annual chlorophyll *a* (A) and annual bottom dissolved oxygen (B) pattern and trends.

4. 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. The eutrophication symptoms were observed in estuaries with a wide range of watershed characteristics, from highly urbanized watersheds with strong river influence (such as Galveston Bay) to sparsely populated but agriculturally-intensive watersheds with no major river inputs (such as Baffin Bay). In addition to nutrient-related water quality changes, other physico-chemical changes such as to salinity and pH were observed. For example, increasing salinity was observed in numerous estuaries of the central Texas coast. Decreasing pH (i.e., acidification) was found in numerous estuaries, primarily those where salinity increases were noted, suggestive of a common driver, namely decreasing freshwater inflows. 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, exhibit symptoms of eutrophication. In Galveston Bay and its tributaries, relatively high nutrient and chlorophyll concentrations were found. 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 densely populated, rapidly growing 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). Indeed, SPARROW model estimates suggest that 60% of nitrogen loads and 51% of phosphorus loads to Galveston Bay come from industrial and municipal point sources (Rebich et al., 2011). 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. Oso Bay, located largely within the city limits of Corpus Christi (pop. 327,000 in 2018) also had high nutrients as well as high and increasing chlorophyll. Oso Bay receives wastewater effluent from three 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 2018, the population of Corpus Christi grew from 257,000 to 327,000, 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 largest river in the watershed, 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 long-term decrease in riverine input and presumably nutrient loads 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).

Symptoms of eutrophication 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 observed in this study 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 a broader group of 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. The Baffin Bay-Upper Laguna Madre watershed is sparsely populated, with the largest cities being Kingsville (pop. 26,213) and Alice (pop. 19,576). Nonetheless, land use is dominated by agriculture (44%) (NOAA CCAP), which has been shown to contribute to eutrophication symptoms in many other estuarine environments (Jordan et al., 2003; Handler et al., 2006; Kaushal et al., 2008; Rothenberger et al., 2009). Indeed, SPARROW model output suggests that non-point source loadings from fertilizers and atmospheric deposition are the largest external nitrogen sources to Baffin Bay, followed by manure from pastures (Rebich et al., 2011). Aside from non-point source loadings, one stream that flows into Baffin Bay (San Fernando Creek) has 12 permitted wastewater facilities that discharge into it, and overall this stream has very high nutrient concentrations. Research is underway to further refine our understanding of load sources to the system to guide future reduction efforts. 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 (Montagna et al., 2013). This manifests as increasing salinity levels, which was observed in every major 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 estuaries 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 over the timeframe of data used in this study, 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).

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 exhibited a long-term decrease. Hu et al. (2015) attributed this 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).

5. 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 have a sparsely populated watershed. As such, they would not conform to traditional views of eutrophication that tend to focus on river-influenced systems. Nonetheless, with watersheds that still have a large influence from non-point and point-source load sources, and the estuaries themselves having long residence time due to general lack of flushing, 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. Surprisingly, the urbanized Nueces-Corpus Christi Bay system did not show signs of eutrophication, which we suspect is due to a long-term decrease in freshwater inflow and associated nutrient loadings. This decrease in freshwater inflow drives another major water quality concern affecting mid-coast estuaries in Texas, namely a long-term increase in the salinity. This 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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CRediT authorship contribution statement

Kalman Bugica:Formal analysis, Investigation, Data curation, Writing - original draft, Visualization.**Blair Sterba-Boatwright**:Methodology, Validation, Formal analysis, Writing - review & editing.**Michael S. Wetz**:Conceptualization, Validation, Resources, Writing - review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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