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Baseline

Long-term water quality analysis reveals correlation between bacterial pollution and sea level rise in the northwestern Gulf of Mexico

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ABSTRACT

Long-term assessments are needed to identify water quality trends and their socio-environmental drivers for coastal management and watershed restoration. This study provides the first long-term assessment of fecal bacterial pollution in the northwestern Gulf of Mexico using enterococci data spanning the Texas coast from 2009 to 2020. The data were representative of 66 beaches, 169 stations, and over 75,000 samples. Findings demonstrate that 22 beaches are 'hotspots' of pollution and experienced enterococci levels that frequently exceeded the USEPA beach action value. Further, enterococci were correlated with time, population size, and sea level. Weak correlations detected in some counties highlight the multifactorial nature of water quality; additional factors are likely influencing enterococci levels. The correlation with sea level is concerning, as counties vulnerable to sea level rise frequently reported enterococci concentrations exceeding the beach action value. In consideration of sea level rise predictions, targeted studies are needed to pinpoint drivers of fecal pollution.

The quality of recreational water is commonly assessed by quantifying the abundance of fecal indicator bacteria (FIB), such as enterococci. Enterococci are Gram-positive cocci that belong to the *Enterococcus* genus and are often associated with fecal pollution originating from humans and other mammals (Byappanahalli et al., 2012). The enterococci are not presumed to be harmful; rather, the presence of elevated concentrations is viewed as a proxy for fecal pollution that could carry pathogenic disease-causing organisms (Boehm and Sassoubre, 2014). Numerous studies have demonstrated a positive correlation between elevated enterococci and the risk of gastrointestinal, respiratory, ear, eye, and skin-related illnesses among recreational bathers, lending to their utility in water quality assessments (e.g., Pruss, 1998; Wade et al., 2003; USEPA, 2012; Boehm and Sassoubre, 2014).

In US surface waters, outdoor recreational activities such as swimming, boating, and fishing account for approximately 4 billion recreational events annually (DeFlorio-Barker et al., 2018). These recreational events result in an estimated 90 million gastrointestinal, respiratory, ear, eye, or skin-related illnesses (DeFlorio-Barker et al., 2018). The primary etiologic agents responsible for these infections are water-borne fecal pathogens such as protozoa (e.g., *Cryptosporidium* and *Giardia*), bacteria (e.g., *Campylobacter* and *Salmonella*), and viruses (e.g., noroviruses and adenoviruses) (Korajkic et al., 2018). The economic burden of these illnesses costs $2.2–3.7 billion annually (DeFlorio-Barker et al., 2018). In Texas, bacterial pollution is the leading cause of Texas surface water impairments (TCEQ, 2020a). The health of recreational bathers is protected when beach advisories, warnings, and closures are publicly announced in response to elevated enterococci levels that exceed the US Environmental Protection Agency (USEPA) beach action value.

The Beaches Environmental Assessment and Coastal Health (BEACH) Act of 2000 required US states and territories to adopt water quality standards that are protective of human health (USEPA, 2000). The USEPA beach action value for marine recreational water quality is not more than 104 colony forming units (CFU) of enterococci per 100 mL (single-sample standard) or 35 CFU per 100 mL (geometric mean standard) (USEPA, 2012). The Texas General Land Office (TGLO) manages the Texas Beach Watch Program (TBWP), which is responsible for monitoring enterococci concentrations to assess marine recreational water quality. Since enterococci were adopted as Texas' standard for

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marine recreational water quality in 2004, the program has monitored enterococci concentrations through a network of 169 monitoring stations at 66 recreational beaches.

Characterizing long-term trends in coastal water quality is critical given the current and projected rates of population growth and climate change. Numerous previous studies have focused on short-term (i.e., diurnal, weekly, or monthly) assessments of water quality and its environmental drivers. For instance, rainfall, water temperature, sunlight and UV exposure, and tidal stage have been identified as short-term drivers of FIB (Parker et al., 2010; Mattioli et al., 2017; Boehm and Weisberg, 2005). Additional long-term factors, such as sea level rise, population size, urbanization and infrastructure expansion, and sewage and septic system conditions, have been implicated as drivers of longer-term changes (Elmir, 2018; Walters et al., 2011; Humphrey et al., 2018); however, significant knowledge gaps pertaining to yearly and decadal trends remain.

The purpose of this study was to characterize fecal bacteria pollution in the Texas coastal zone to gain insights and improve understanding of the water quality conditions. In this assessment, long-term trends of enterococci concentrations were predicted to change with population growth, land-use change (i.e., urbanization), weather and climate, and sea level rise. Conversely, short-term variability was predicted to be influenced by extreme rainfall events and sanitary sewer overflows (SSOs).

Enterococci data spanning 2009 to 2020 were provided by TGLO. Regular sampling was conducted on a weekly basis during 'peak' season (i.e., March and May through September) and a bi-weekly basis during 'off-peak' season; additional samples were obtained for a higher resolution temporal analysis when exceptionally high levels of FIB were detected. The TBWP quantified enterococci using the Enterolert test and the EPA 1600 membrane filtration method, under a USEPA-approved Quality Assurance Project Plan (QAPP) and reported the enterococci concentration as the most probable number (MPN) or CFU per 100 mL (Texas Beach Watch Program, 2015). The data encompassed 169 sampling stations, 66 beaches, and 10 coastal counties (coordinates available at www.texasbeachwatch.com). Data were inspected and corrected for anomalies and data entry errors. Samples that contained field replicates were averaged together, and a total of 75,380 samples were analyzed.

The mean, median, minimum, and maximum, as well as the number and percentage of exceedances above the USEPA beach action value (104 MPN/100 mL) and at the Enterolert test upper limit (24,196 MPN/100 mL) were calculated for each county (shown in Table 1) and all individual beaches (shown in Tables S1–S4). All beaches experienced minimum enterococci concentrations that were below the Enterolert test limit of detection (<10 MPN/100 mL), and the majority experienced median values equivalent to 10 or < 10 MPN/100 mL. However, 65 of the 66 beaches also experienced enterococci concentrations that exceeded the USEPA beach action value multiple times, 21 beaches experienced a mean enterococci value greater than 104 MPN/100 mL, and 19 beaches exceeded the upper limit of detection (24,196 MPN/100 mL) at least once.

The 10 counties and 66 beaches were ranked as having 'low', 'medium', 'high', and 'very high' levels of enterococci based on the percentage of samples that exceeded the USEPA beach action value. The ranks were chosen according to natural breakpoints in the data, as done in previous studies (Ferretti et al., 2011; Feng et al., 2016). County-specific trends are shown in Table 1 and Tables S1-S4 show beach-specific trends. Overall, Cameron and Jefferson were classified as having 'low' levels of enterococci, as they exceeded the USEPA beach action value less than 5% of the time. Galveston, Kleberg, and Aransas exceeded the USEPA beach action value 5–10% of the time and were classified as having 'medium' levels of enterococci. San Patricio, Nueces, and Brazoria exceeded the beach action value 10–20% of the time and were classified as having 'high' levels of enterococci. Matagorda and Harris were classified as having 'very high' levels of enterococci, as they exceeded the USEPA limit more than 20% of the time. The counties that exceeded the beach action value greater than 10% of the time were also considered to contain 'hotspots' of bacterial pollution (i.e., Harris, Matagorda, Brazoria, Nueces, and San Patricio).

Enterococci levels were investigated in the context of spatial and temporal trends. Due to the censored nature of the enterococci measurements (i.e., lower detection limit of <10 MPN and upper detection limit of >24,196 MPN/100 mL), the cenken and cendiff tests from the NADA package (Lee, 2020) in R were used to compute Kendall's tau correlation coefficient for the censored data (i.e., enterococci concentrations), and the cor.test in R was used to compute Kendall's tau correlation coefficient when non-censored data were analyzed (i.e., summary statistic data). In terms of spatial conditions, bayside stations ($N = 33$) representing low flushing environments and Gulfside locations ($N = 134$) representing higher flushing environments were compared to test the effect of local hydrodynamics. The bayside enterococci concentrations were significantly higher than the Gulfside stations location on the Gulf of Mexico (Fig. 1; cendiff test; $p < 0.001$).

The higher enterococci concentrations at bayside sites could be attributed to closer proximity to mainland population centers (e.g., Port Arthur, Houston, Port Lavaca, Corpus Christi, and Brownsville) and reduced dilution or flushing as multiple Texas bays and lagoons exhibit limited freshwater inflow and little exchange with the Gulf of Mexico (reviewed by Montagna et al., 2013). A previous long-term study along the Florida coast showed similar results, with geomorphology acting as a strong driver of FIB exceedances; beaches located on the bayside were four times more likely to exceed the EPA's beach action value than beaches located on the open coast (Donahue et al., 2017). Nearby rivers and canals were also associated with elevated FIB levels in that study, likely due to the transport of FIB from inland sources (Donahue et al., 2017). Another recent long-term data analysis at the German Baltic coast similarly revealed that bays and lagoons pose higher microbial risks compared to open-water areas (Buer et al., 2018). The authors of that study postulated that bacterial pollution in bayside sites was likely a multifactorial problem owing to the resuspension of bacteria from sediments in shallow water, prolonged bacterial survival in turbid water, and the heightened mainland impact of stormwater inflows.

A key finding from this study was that enterococci concentrations increased over time. The majority of beach action value exceedances (60% of the 6721 samples that exceeded the USEPA beach action value) were reported in the last six years, from 2015 to 2020 (Table 2). Similarly, 89% of the 92 samples that exceeded the upper limit of detection (24,196 MPN/100 mL) were reported since 2015 (Table 2). When the beaches were analyzed independently, the majority ($N = 41$) experienced increasing enterococci concentrations over the 11-year time span, whereas 20 of the beaches did not experience a significant correlation,

Table 1
Summary metrics for the 10 coastal counties. Based on the percentage of samples that exceeded the USEPA beach action value (104 MPN), water quality was classified as having 'low' (<5%; shown in green), 'medium' (5–10%; shown in yellow), 'high' (10–20%; shown in orange), or 'very high' (>20%; shown in red) levels of enterococci. Enterococci concentrations were measured as CFU or MPN/100 mL water. Minimum concentrations for every county were equivalent to 10 or < 10 MPN/100 mL.

County	Max.	Med.	Avg.	No. beaches	% exceedances	Category
Cameron	2,252.50	10	16.17	9	1.17	Low
Jefferson	1,723.00	10	32.12	2	3.44	Low
Galveston	24,196.00	10	68.16	23	7.09	Medium
Kleberg*	1,995.00	7	49.89	4	7.67	Medium
Aransas	19,863.00	10	107.46	1	8.27	Medium
San Patricio	4,611.00	10	61.98	1	10.55	High
Nueces	24,196.00	10	207.67	18	11.17	High
Brazoria	24,196.00	10	121.15	4	11.93	High
Matagorda	24,196.00	20	235.17	3	21.90	Very high
Harris	24,196.00	30	444.32	1	25.74	Very high

* Kleberg County samples were only recorded from 2009 to 2011.

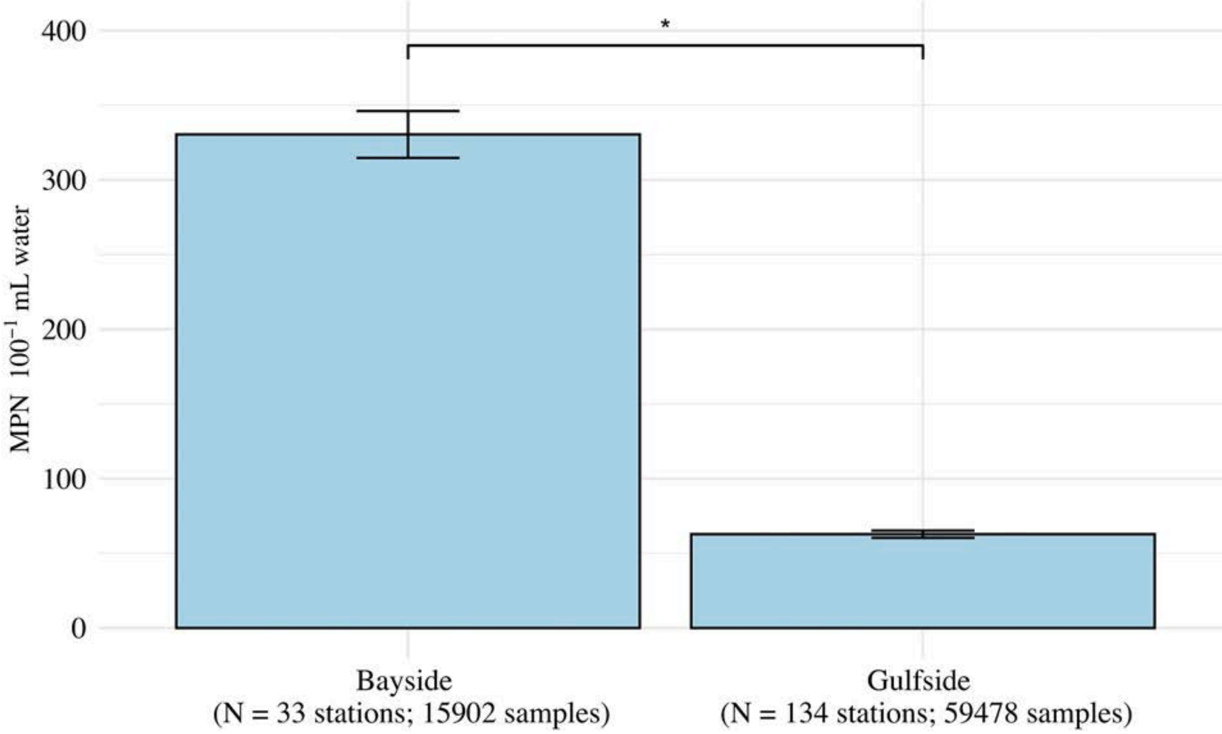

Fig. 1. Mean concentrations of enterococci in bayside versus Gulfside water samples. Error bars represent standard error of the mean. Enterococci were significantly higher in bayside sites (cendiff test; p < 0.001).

Table 2
Number and percentage of enterococci measurements above the beach action value (104 MPN) and the Enterolert test's upper limit of detection (24,196 MPN) each year. The majority of the exceedances of both values follow an increasing trend over time.

Year	No. and % of exceedances	
	104 MPN/100 mL	24,196 MPN/100 mL
2009	323 (5.13%)	1 (0.016%)
2010	507 (7.61%)	0 (0%)
2011	327 (4.95%)	0 (0%)
2012	581 (8.98%)	1 (0.015%)
2013	426 (6.77%)	5 (0.079%)
2014	495 (7.76%)	3 (0.047%)
2015	833 (12.31%)	26 (0.074%)
2016	602 (8.75%)	13 (0.189%)
2017	363 (5.74%)	0 (0%)
2018	593 (8.79%)	24 (0.36%)
2019	1461 (18.84%)	18 (0.23%)
2020[a]	210 (9.58%)	1 (0.046%)
Total	6721 (8.91%)	92 (0.122%)

[a] The data from 2020 only included enterococci concentrations from January through mid-May.

and five beaches had enterococci concentrations that were inversely correlated with time (Tables S1–S4). In general, the counties with poorer water quality had enterococci levels that were more strongly correlated with time (Table 3). Kendall's tau correlation was computed to test relationships between time and the percentage of samples that exceeded the beach action value (Fig. 2A; tau: 0.48, $p < 0.05$) and the percentage of samples exceeding the upper detection limit (Fig. 2B; tau: 0.42; $p < 0.1$). Additionally, a linear model was generated to show the relationship between the Kendall's tau correlation coefficients (between enterococci and time for each county) and the percentage of samples that exceeded the USEPA beach action value (Fig. 3A). Based on this model, counties that did not experience a significant correlation with time (i.e., Kendall's tau correlation coefficient = 0) exceeded the beach action value 5.36% of the time, whereas counties where tau = 0.2 exceeded the beach action value 20.42% of the time.

Table 3
Correlations between enterococci concentrations and time (2009–2020), population size (2010–2019), and sea level (2009–2020) in the 10 coastal counties (p < 0.05). NA = data not available; ns = not significant.

County	Time	Population size	Sea level
Cameron	−0.0314	−0.0421	0.0237
Jefferson	ns	0.0366	0.0630
Galveston	0.1238	0.1352	0.1294
Kleberg[a]	ns	NA	ns
Aransas	ns	ns	0.0752
San Patricio	0.0655	0.1025	0.1207
Nueces	0.0383	0.0447	0.0583
Brazoria	0.1581	0.1820	0.1303
Matagorda	0.1754	0.0247	0.1832
Harris	0.2048	0.2137	0.2168

[a] Data pertaining to Kleberg County was only available from 2009 to 2011.

Fig. 4 shows a combined temporal and spatial distribution of the total percentage of samples that exceeded the USEPA beach action value throughout the Texas coast. A total of 11 interpolated surfaces, one for each year, were generated to effectively visualize the spatial-temporal trends of fecal bacterial pollution in the coastal zone area. The formal delineation of the Texas Coastal Zone Boundary was obtained from TGLO (https://www.glo.texas.gov/land/land-management/gis/). The Inverse Distance Weighted technique (IDW) was used to generate a surface based on the value of the percentage of water samples that exceeded the USEPA's beach action value (>104 MPN/100 mL) for each year in each station. The interpolated surfaces for 2009–2019 were generated from the percentage values at all 169 stations. The stretch method, which spreads the interpolated values along a histogram from the minimum and maximum values, was used to display the interpolated surfaces in Fig. 4.

The relationships between enterococci and population size were also tested. Population size estimates were obtained from the United States

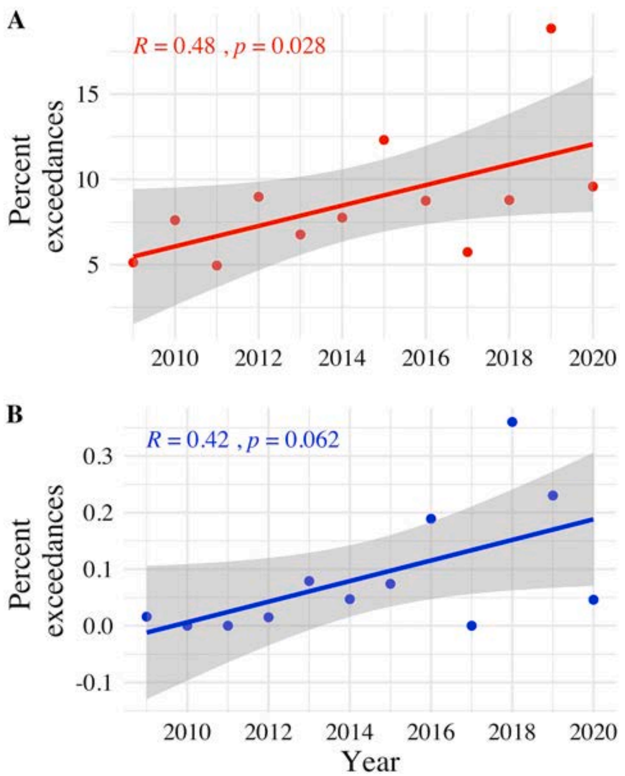

Fig. 2. Relationships (Kendall's tau correlation and significance) between (A) the percentage of samples that exceeded the beach action value (104 MPN) and time and (B) the percentage of samples that exceeded the Enterolert test's upper limit of detection (24,196 MPN) and time.

Census Bureau (https://www.census.gov/) for nine of the counties from 2010 to 2019. Kleberg County was excluded as water samples were only collected through 2011. In general, higher levels of enterococci were correlated with increasing population size in the majority of counties (Table 3). Aransas and Cameron Counties were exceptions, as the former did not experience a significant correlation, and the latter experienced an inverse relationship between the two variables. The correlations between enterococci and population size closely resembled the correlations between enterococci and time, which is unsurprising, given that the population size generally increased over time. A linear model was generated to show the relationship between the Kendall's tau correlation coefficients (between enterococci and population size for each county) and the percentage of samples that exceeded the USEPA beach action value (Fig. 3B). Based on this model, counties that did not experience a significant correlation with population size (tau = 0) can be expected to exceed the limit 7.35% of the time, whereas counties where tau = 0.2 can be expected to exceed the limit 17.42% of the time.

For the majority of counties, population size was directly correlated with enterococci concentrations. This result is consistent with findings of previous studies; for instance, an analysis of water quality in 14 California coastal sites revealed a direct correlation between FIB levels and urbanization (i.e., population size and impervious surface coverage) (Walters et al., 2011). Cameron was the only county where FIB levels were inversely correlated with time and population size; this county also had the least impaired water, with less than 2% of samples exceeding the USEPA beach action value. Two watershed protection plans in Cameron County (in Arroyo Colorado and the Lower Laguna Madre) could be contributing to the lower levels of fecal bacteria pollution in this region (TCEQ, 2020b; TCEQ, 2020c). Importantly, Texas' rapid coastal population growth may be predictive of future exceedances along nearly the entire coastline, given that coastal population size is predicted to increase dramatically by 2050 (TSDC, 2018).

Data pertaining to sea level were obtained from NOAA Tides &

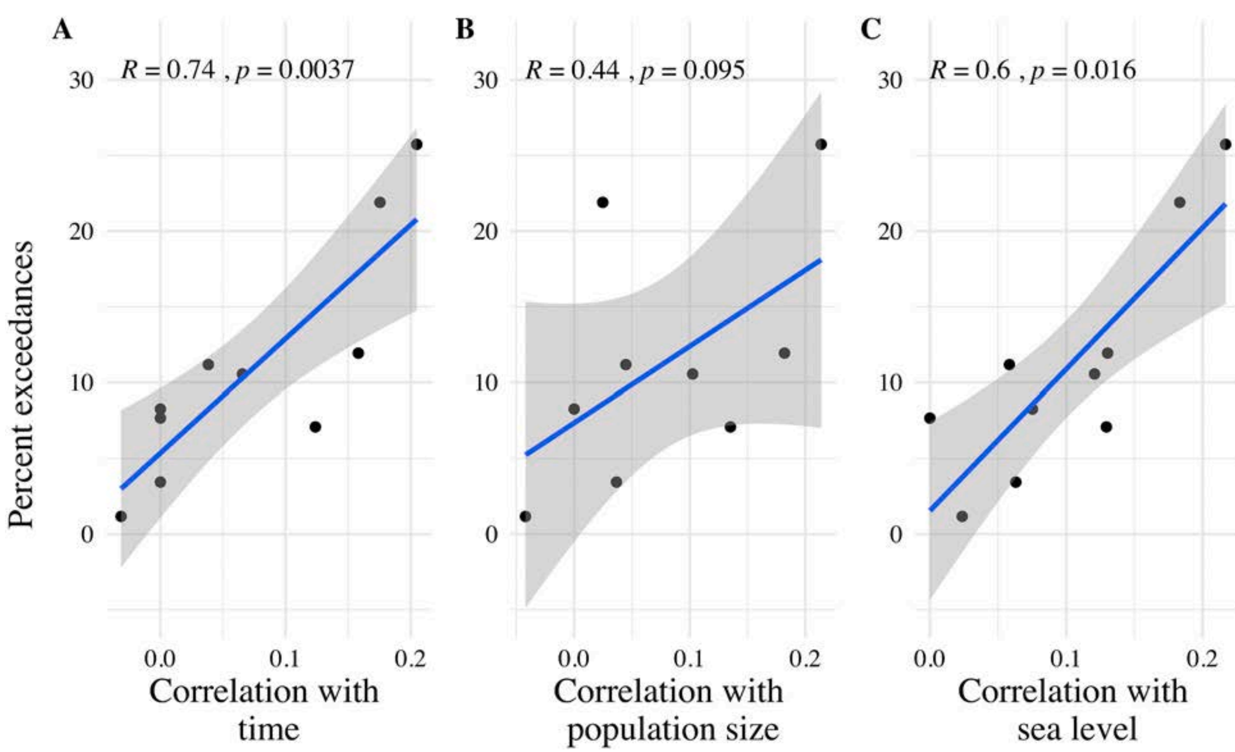

Fig. 3. Relationships between the percentage of samples in the 10 counties where enterococci exceeded the beach action value (104 MPN) and Kendall's tau correlation coefficients. Blue lines show the linear relationships between the values and 95% confidence intervals are shown in gray. A) Correlation with time; B) Correlation with population size; C) Correlation with sea level. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

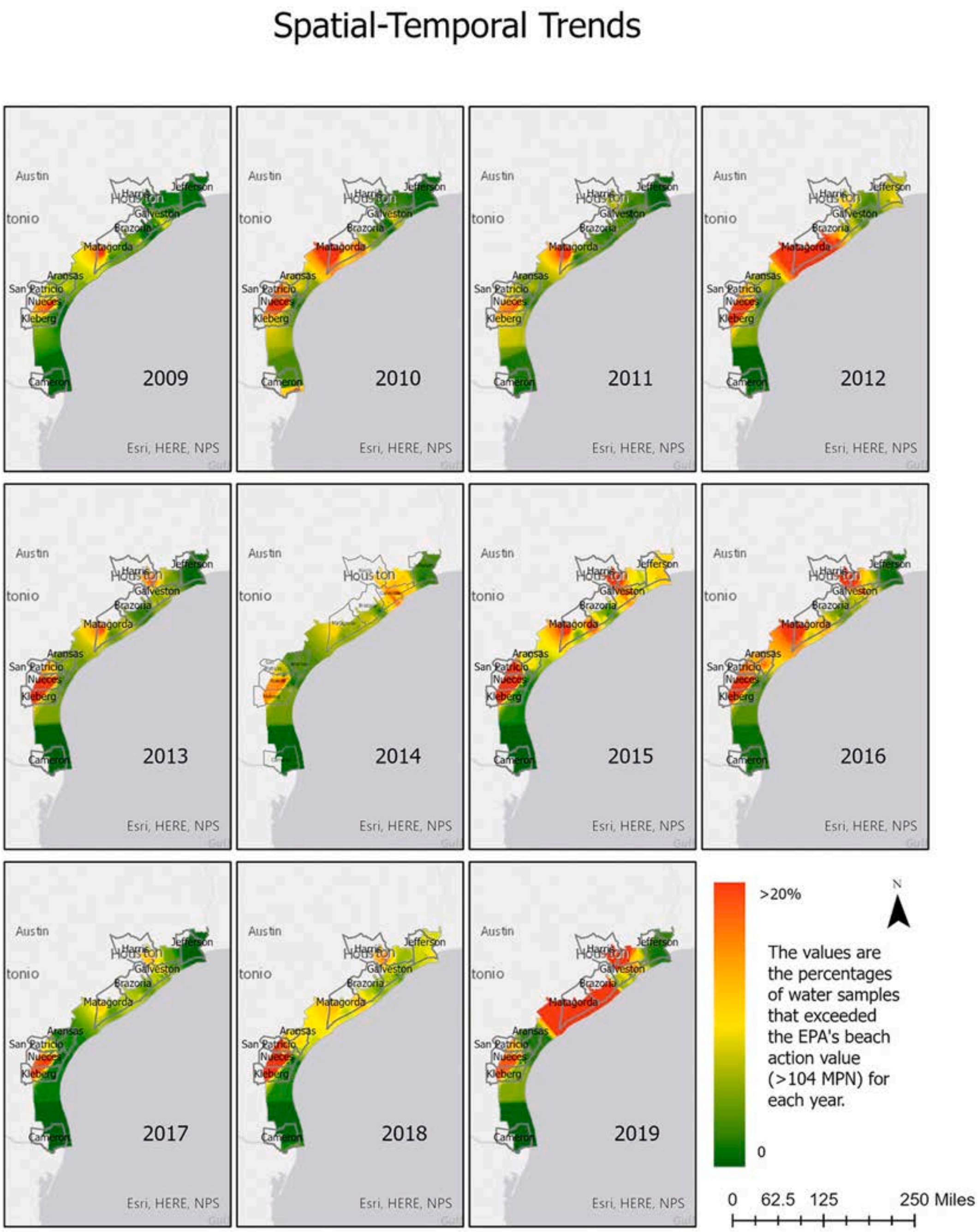

Fig. 4. Temporal and spatial trends of water samples that exceeded the beach action value across coastal Texas from 2009 to 2019.

Currents (https://tidesandcurrents.noaa.gov/) and the Texas Coastal Ocean Observation Network (https://tidesandcurrents.noaa.gov/tcoon.html). Sea level data were assessed based on monthly mean sea level from 2009 to 2020. Table 3 shows that nine of the 10 counties experienced significant correlations between enterococci concentrations and sea level. Importantly, the only county that did not have significant results was Kleberg County, which only contained data from 2009 to 2011. A linear model was generated to show the relationship between the Kendall's tau correlation coefficients (between enterococci and sea level for each county) and the percentage of samples that exceeded the USEPA beach action value (Fig. 3C). Based on this model, counties that do not experience a significant correlation with sea level (tau = 0) can be expected to exceed the limit 1.54% of the time, whereas counties where tau = 0.2 can be expected to exceed the limit 20.23% of the time.

Throughout the 11-year timespan of this study, enterococci concentrations in eight of the 10 counties were correlated with sea level. Brazoria, Matagorda, and Harris, in particular, exhibited a stronger relationship with sea level, and all three counties have been identified as vulnerable to coastal flooding and rising sea levels (Strauss et al., 2014). Harris County, one of the counties that comprises the Greater Houston region, experienced the strongest relationship between enterococci and sea level. This finding is particularly concerning since this region is also acutely vulnerable to catastrophic flooding and water damage, as evidenced by the recent impacts from Hurricane Harvey (Valle-Levinson et al., 2020). Furthermore, a recent study in South Florida revealed that thousands of septic systems, which are a potential source of fecal pollution (Humphrey et al., 2018), are malfunctioning and contributing to fecal pollution due to sea level rise (Elmir, 2018). The Fourth National Climate Assessment predicted sea level rise in the Gulf Coast will be above the global average (i.e., greater than 1–4 ft by 2100) (USGCRP, 2017); thus, future research should be focused on the distribution of septic systems in coastal Texas and the impact that rising sea levels have on their integrity.

The water quality in Brazoria, Matagorda, and Harris Counties was of particular concern due to 1) a history of elevated enterococci concentrations and 2) recent episodes of unusually high enterococci levels. During the summer of 2019, the episodes experienced in these counties were unique (i.e., statistical outliers) when compared with other counties across the 11-year dataset. The concentrations of enterococci in these three counties were significantly higher in 2019 compared to other years, particularly in four beaches (Quintana, Bryan, Sargent, and Palacios) (Table 4; cendiff test; $p < 0.001$). All of the beaches in these counties exceeded the beach action value more than 38% of the time, and several beaches (Sargent, Matagorda Jetty Park, Palacios, and Sylvan) exceeded the value more than 50% of the time (Table 4). The vast majority of the elevated enterococci levels were recorded in June, July, and August of 2019. Unusually high levels, approaching or exceeding the Enterolert test upper limit of detection (24,196 MPN/100 mL), were recorded at Follet's Island on 8/16/19, Surfside on 8/19/19, Bryan Beach on 8/21/19, Sargent Beach on 8/28/19, and Matagorda Jetty Park the following day.

The elevated concentrations of enterococci observed during 2019 were analyzed with respect to rainfall. Rainfall records corresponding to dates with elevated enterococci were obtained from the nearby weather monitoring stations in each county from the TexMesonet database (https://texmesonet.org/). Interestingly, a few occurrences of elevated concentrations in Brazoria County (recorded on 5/11/12, 4/13/15, 3/1/16, and 8/16/19) were preceded or followed by similar increases in neighboring Matagorda County (recorded on 5/23/12, 4/14/15, 3/15/16, and 8/28/19; Fig. 5). Three of the four increases in Brazoria were recorded after sporadic rainfall, with the exception of the increase on 3/1/16, whereas the increase recorded days later in Matagorda was not preceded by rainfall. Harris and Galveston Counties also experienced coinciding elevated enterococci levels on three recorded dates (6/02/2016, 9/12/2018, and 10/16/2019) that were preceded by sporadic rainfall.

That several beaches in Brazoria and Matagorda experienced similar temporal trends implies that a common set of conditions contributed to the elevated levels. For instance, sea level, water temperature, and precipitation in these counties were higher in June through August of 2019 than in previous years (NOAA; https://ncdc.noaa.gov/temp-and-precip/us-maps/). It is possible that one of these factors or some combination of them were driving these episodes; however, further study is needed to identify common conditions and drivers. In an attempt to explain the unusually high enterococci levels, episodes of elevated levels in Brazoria from 2018 to 2020 were compared with the partial list of reported SSOs. The USEPA Region 6 office (Robert Cook, personal communication) provided a partial record of known SSOs in Brazoria County from 2018 to 2020. However, this record did not include the estimated 205 failure points in the domestic wastewater collection system in the Village of Surfside Beach, Texas (TCEQ, 2019). Although some of the increases coincided with SSOs, the relationship between enterococci concentrations and SSOs was not significant (cendiff test; $p > 0.1$). It is therefore possible that SSOs contributed to these elevated FIB levels, but a more complete count of SSOs and their magnitude is needed to test this hypothesis.

Since 1960, the Gulf Coast region of the United States has experienced a rapid population increase that is more than double the rate of national population growth. Over the past two decades, coastal watersheds in Texas have also experienced significant human population growth. From 1997 to 2012, the population in Texas coastal counties increased by 29% (IRNR, 2014), and projections suggest that there will be an additional 34% population increase by 2050 (TSDC, 2018). In many other regions worldwide, a similar increasing human footprint has led to symptoms of water quality degradation, namely increasing bacterial pollution and symptoms of eutrophication (Cloern, 2001; Walters et al., 2011; Wu and Jackson, 2016). A recent study of multidecadal trends in the water quality of Texas estuaries found localized evidence of eutrophication, primarily in estuaries with highly urbanized watersheds (e.g., Galveston Bay and Oso Bay) as well as an estuary with a sparsely populated but agriculturally intensive watershed (i.e., Baffin Bay) (Bugica et al., 2020). However, that study did not assess patterns or quantify changes in fecal bacterial pollution, the presence of which can result in severe economic losses and cause serious health burdens in coastal regions across the globe (Malham et al., 2014).

This study provides the first comprehensive decadal assessment of fecal bacteria pollution across coastal Texas. Previous short-term bacteria analyses have targeted specific regions such as impaired segments in Corpus Christi Bay (Nicolau et al., 2011; Nicolau and Hill, 2013). Previous short-term studies have also investigated probable sources of

Table 4

Comparison of beaches in Brazoria, Matagorda, and Harris. Data is split by year; the 2019 rows contain data only from 2019, whereas the remaining rows contain data from 2009 to 2020 excluding 2019. The table shows mean, median, minimum, and maximum values of enterococci (MPN) and how often enterococci exceeded the beach action value (104 MPN). Follet's Island: $N = 5$ sampling stations; Surfside Beach: $N = 8$; Quintana Beach: $N = 2$; Bryan Beach: $N = 1$; Sargent Beach: $N = 3$; Matagorda Jetty Park: $N = 4$; Palacios Beach: $N = 2$; Sylvan Beach: $N = 2$. Enterococci concentrations in all three counties were significantly higher in 2019 compared to other years (cendiff test; $p < 0.001$).

County	Beach	Mean	Med.	Min.	Max.	% exceedances
Brazoria	Follet's Island	49.06	10	10	9,208	4.53
	Follet's Island (2019)	361.31	63	10	24,196	44.47
	Surfside Beach	73.33	10	10	24,196	4.87
	Surfside Beach (2019)	201.81	52	10	24,196	38.50
	Quintana Beach	161.09	20	10	24,196	17.99
	Quintana Beach (2019)	802.92	63	10	24,196	46.43
	Bryan Beach	64.94	10	10	3,436	10.60
	Bryan Beach (2019)	512.52	63	10	12,997	41.46
Matagorda	Sargent Beach	120.32	20	10	24,196	15.62
	Sargent Beach (2019)	755.48	164.5	10	24,196	58.93
	Matagorda Jetty Park	76.59	10	10	24,196	9.76
	Matagorda Jetty Park (2019)	826.19	115	10	24,196	51.75
	Palacios Beach	222.34	36	10	24,196	24.71
	Palacios Beach (2019)	744.01	124.5	10	19,860	53.85
Harris	Sylvan Beach	371.35	20	10	24,196	18.36
	Sylvan Beach (2019)	755.53	193	10	8,664	57.23

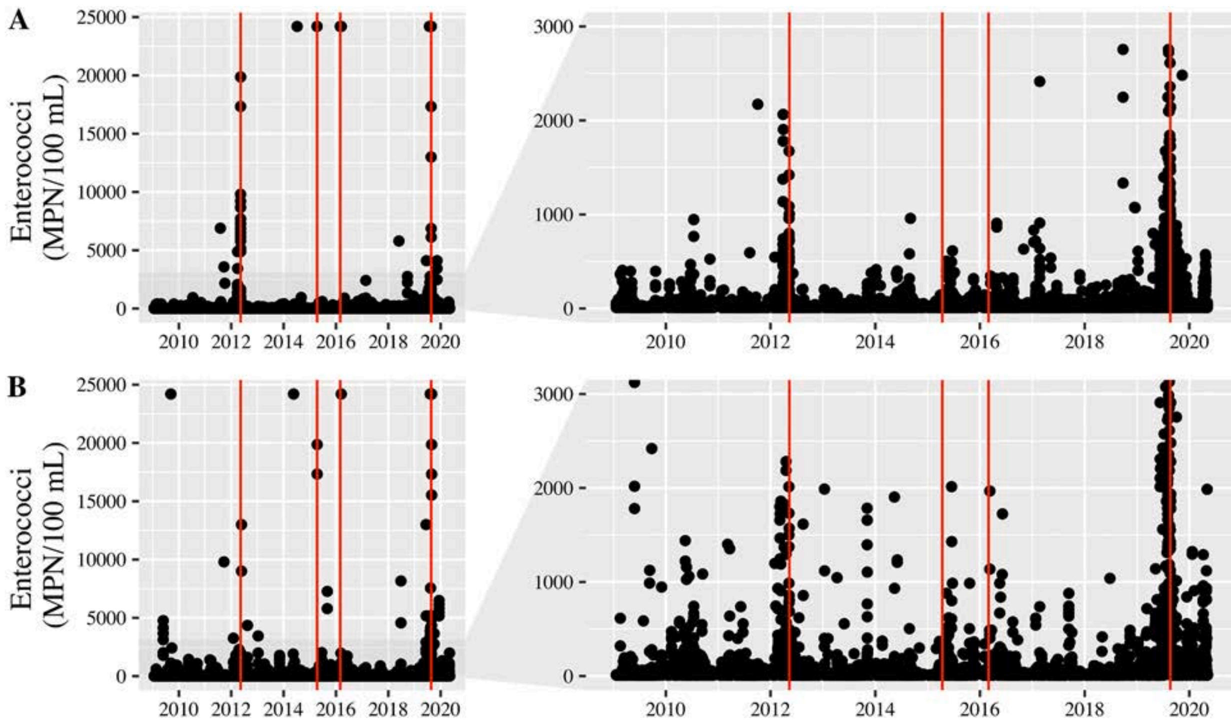

Fig. 5. Concentrations of enterococci in (A) Brazoria County and (B) Matagorda County from 2009 to 2020. The panels on the right show a closer look at concentrations that are under 3000 MPN/100 mL. Red lines coincide with major increases in enterococci. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

fecal pollution in impaired segments (Mott et al., 2010; Turner and Elledge, 2018; Turner et al., 2019; Powers et al., 2020). Long-term, coastwide data assessments, such as this study, are needed to identify the drivers of fecal bacteria contamination to guide proactive management and watershed restoration efforts. For instance, in south Florida, a 10-year analysis of 7422 historical data points revealed that exceedances were 2475 times more likely during high tide (Aranda et al., 2016). Another long-term study in California analyzed six years of historical water quality data and determined discharge from a local lagoon to be a significant source of fecal pollution (Riedel et al., 2015).

In this multi-year study, an analysis of 75,380 historical data points (spanning 11 years, 10 coastal counties, 66 beaches, and 169 sampling stations) clearly demonstrates that nearly one-third of Texas beaches ($N = 22$) and half of coastal Texas counties ($N = 5$) experienced USEPA beach action value exceedances on a regular basis (i.e., more than 10% of the time). The increase in enterococci detected over time coincided with temporal trends in two important broad-scale environmental drivers: population size and sea level, with beaches in Harris, Brazoria, and Matagorda exhibiting the strongest correlations. The links between these factors are an indication that seawater inflow and infiltration could be associated with the degradation and failure of sewage collection and treatment systems in this region. However, future evaluations of local sewage collection and treatment systems are needed to further explore this hypothesis.

The weak correlation values detected in some of the counties highlights the need to explore additional variables in the future, since water quality impairment is a multifactorial problem. For instance, additional geomorphic factors (i.e., proximity to rivers, canals, and other inland pollution sources) could shed light on water quality drivers, particularly in open coast sites (Donahue et al., 2017). Seeing that the most affected counties in this study (e.g., Harris, Brazoria, and Matagorda) are particularly vulnerable to future population growth and sea level rise, targeted studies are urgently needed to pinpoint the sources and drivers of fecal bacteria pollution. The findings from this study may be relevant in a global context, as sea level rise and population growth are not limited to the Gulf Coast. Policies in regions with impaired water quality may benefit from focusing on the maintenance and repair of coastal infrastructure that is susceptible to damage from urbanization and rising sea levels.

CRediT authorship contribution statement

Nicole C. Powers: Investigation, Formal analysis, Validation, Writing – original draft, Writing – review & editing, Visualization. **Jason Pinchback:** Conceptualization, Resources, Supervision, Funding acquisition, Writing – review & editing. **Lucy Flores:** Conceptualization, Resources, Data curation, Validation, Writing – review & editing. **Yuxia Huang:** Investigation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Michael S. Wetz:** Supervision, Project administration, Funding acquisition, Writing – original draft, Writing – review & editing. **Jeffrey W. Turner:** Supervision, Project administration, Funding acquisition, Writing – original draft, Writing – review & editing.

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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Appendix A. Supplementary data

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References

Aranda, A., Lopez, J.V., Solo-Gabriele, H.M., Fleisher, J.M., 2016. Using probabilities of enterococci exceedance and logistic regression to evaluate long term weekly beach monitoring data. J. Water Health 14, 81–89. https://doi.org/10.2166/wh.2015.030.

Boehm, A.B., Sassoubre, L.M., 2014. Enterococci as indicators of environmental fecal contamination. In: Gilmore, M.S., Clewell, D.B., Ike, Y., et al. (Eds.), Enterococci: From Commensals to Leading Causes of Drug Resistant Infections. Massachusetts Eye and Ear Infirmary, Boston, pp. 101–123. https://www.ncbi.nlm.nih.gov/sites/books/NBK190421/.

Boehm, A.B., Weisberg, S.B., 2005. Tidal forcing of enterococci at marine recreational beaches at fortnightly and semidiurnal frequencies. Environ. Sci. Technol. 39 (15), 5575–5583. https://doi.org/10.1021/es048175m.

Buer, A.L., Gyraite, G., Wegener, P., Lange, X., Katarzyte, M., Hauk, G., Schernewski, G., 2018. Long term development of bathing water quality at the German Baltic coast: spatial patterns, problems and model simulations. Mar. Pollut. Bull. 135, 1055–1066. https://doi.org/10.1016/j.marpolbul.2018.08.048.

Bugica, K., Sterba-Boatwright, B., Wetz, M.S., 2020. Water quality trends in Texas estuaries. Mar. Pollut. Bull. 152, 110903. https://doi.org/10.1016/j.marpolbul.2020.110903.

Byappanahalli, M.N., Nevers, M.B., Korajkic, A., Staley, Z.R., Harwood, V.J., 2012. Enterococci in the environment. Microbiol. Mol. Biol. Rev. 76, 685–706. https://doi.org/10.1128/MMBR.00023-12.

Cloern, J.E., 2001. Our evolving conceptual model of the coastal eutrophication problem. Mar. Ecol. Prog. Ser. 210, 223–253. https://doi.org/10.3354/meps210223.

DeFlorio-Barker, S., Wing, C., Jones, R.M., Dorevitch, S., 2018. Estimate of incidence and cost of recreational waterborne illness on United States surface waters. Environ. Health 17, 1–10. https://doi.org/10.1186/s12940-017-0347-9.

Donahue, A., Feng, Z., Kelly, E., Reniers, A., Solo-Gabriele, H.M., 2017. Significance of beach geomorphology on fecal indicator bacteria levels. Mar. Pollut. Bull. 121 (1–2), 160–167. https://doi.org/10.1016/j.marpolbul.2017.05.024.

Elmir, S., 2018. Septic Systems Vulnerable to Sea Level Rise. Miami-Dade County Water and Sewage Department, Florida Department of Health, Miami, FL, USA. https://www.miamidade.gov/green/library/vulnerability-septic-systems-sea-level-rise.pdf.

Feng, Z., Reniers, A., Haus, B.K., Solo-Gabriele, H.M., Kelly, E.A., 2016. Wave energy level and geographic setting correlate with Florida beach water quality. Mar. Pollut. Bull. 104 (1–2), 54–60. https://doi.org/10.1016/j.marpolbul.2016.02.011.

Ferretti, J.A., Tran, H.V., Cosgrove, E., Protonentis, J., Loftin, V., Conklin, C.S., Grant, R. N., 2011. Comparison of *Enterococcus* density estimates in marine beach and bay samples by real-time polymerase chain reaction, membrane filtration and defined substrate testing. Mar. Pollut. Bull. 62 (5), 1066–1072. https://doi.org/10.1016/j.marpolbul.2011.02.018.

Humphrey, C.P., Sanderford, C., Iverson, G., 2018. Concentrations and exports of fecal Indicator Bacteria in watersheds with varying densities of onsite wastewater systems. Water Air Soil Pollut. 229 (8), 277. https://doi.org/10.1007/s11270-018-3929-4.

IRNR, 2014. Status update and trends of Texas rural working lands. Texas A&M University Institute of Renewable Natural Resources (IRNR). Texas Land Trends 1, 16. https://nri.tamu.edu/media/1225/landtrends2014_1-1_web.pdf.

Korajkic, A., McMinn, B.R., Hardwood, V.J., 2018. Relationships between microbial indicators and pathogens in recreational water settings. Int. J. Environ. Res. Public Health 15, 2482. https://doi.org/10.3390/ijerph15122842.

Lee, L., 2020. NADA: nondetects and data analysis for environmental data. R package version 1 (6), 1. https://CRAN.R-project.org/package=NADA.

Malham, S.K., Rjko-Nenow, P., Howlett, E., Tuson, K.E., Perkins, T.L., Pallett, D.W., Wang, H., Jago, C.F., Jones, D.L., McDonald, J.E., 2014. The interaction of human microbial pathogens, particulate material and nutrients in estuarine environments and their impacts on recreational and shellfish waters. Environ Sci Process Impacts 16, 2145–2155. https://doi.org/10.1039/C4EM00031E.

Mattioli, M.C., Sassoubre, L.M., Russell, T.L., Boehm, A.B., 2017. Decay of sewage-sourced microbial source tracking markers and fecal indicator bacteria in marine waters. Water Res. 108, 106–114. https://doi.org/10.1016/j.watres.2016.10.066.

Montagna, P.A., Palmer, T.A., Beseres-Pollack, J., 2013. Hydrological Changes and Estuarine Dynamics. Springer Briefs in Environmental Science, New York.

Mott, J., Lindsey, M., Sealy, R., Smith, A., 2010. Bacteria monitoring and source tracking in Corpus Christi Bay at Cole and Ropes Parks. Coastal Bend Bays and Estuaries Program, Publication 67, Project 1010. https://www.cbbep.org/publications/publications.html.

Nicolau, B.A., Hill, E.M., 2013. TMDL investigation for bacteria in Corpus Christi Bay beaches interim data monitoring report: fiscal year 2011 (year-one) and fiscal year 2012 (year-two). Texas A&M University-Corpus Christi, Center for Coastal Studies Technical Report TAMU-CC-1202-CCS. Prepared for Texas Commission on Environmental Quality, Contract 582-11-90501. https://www.tceq.texas.gov/assets/public/waterquality/tmdl/97coastalbeaches/97-FY2012-interim-monitoring-report.pdf.

Nicolau, B.A., Hill, E.M., Baxter, A.S., Duke, R.F., 2011. Historical data review and site assessment on TMDL investigation for bacteria in Corpus Christi Bay beaches. Texas A&M University-Corpus Christi, Center for Coastal Studies Technical Report TAMU-CC-1104-CCS. Prepared for Texas Commission on Environmental Quality, Contract 582-11-90501.

Parker, J., McIntyre, D., Noble, R., 2010. Characterizing fecal contamination in stormwater runoff in coastal North Carolina, USA. Water Res. 44 (14), 4186–4194. https://doi.org/10.1016/j.watres.2010.05.018.

Powers, N.C., Wallgren, H.R., Marbach, S., Turner, J.W., 2020. Relationship between rainfall, fecal pollution, antimicrobial resistance, and microbial diversity in an urbanized bay. Appl. Environ. Microbiol. 86 https://doi.org/10.1128/AEM.01229-20 (e01229-20).

Pruss, A., 1998. Review of epidemiological studies on health effects from exposure to recreational water. Int. J. Epidemiol. 27, 1–9. https://doi.org/10.1093/ije/27.1.1.

Riedel, T.E., Thulsiraj, V., Zimmer-Faust, A.G., Dagit, R., Krug, J., Hanley, K.T., Adamek, K., Ebentier, D.L., Torres, R., Cobian, U., Peterson, S., 2015. Long-term monitoring of molecular markers can distinguish different seasonal patterns of fecal indicating bacteria sources. Water Res. 71, 227–243. https://doi.org/10.1016/j.watres.2014.12.037.

Strauss, B., Tebaldi, C., Kulp, S., Cutter, S., Emrich, C., Rizza, D., Yawitz, D., 2014. Texas and the Surging Sea: a vulnerability assessment with projections for sea level rise and coastal flood risk. Climate Central Research Report. 1–29. https://sealevel.climatecentral.org/uploads/ssrf/TX-Report.pdf.

TCEQ, 2019. Complaint Investigation Report: The Village of Surfside Beach Sanitary Collection System. Texas Commission on Environmental Quality.

TCEQ, 2020a. 2020 Integrated Report of Surface Water Quality for the Clean Water Act Sections 305(b) and 303(d). Texas Commission on Environmental Quality.

TCEQ, 2020b. Improving Water Quality in the Arroyo Colorado: A Watershed Protection Plan for Dissolved Oxygen. Texas Commission on Environmental Quality, Total Maximum Daily Load Program. https://www.tceq.texas.gov/assets/public/waterquality/tmdl/13arroyo/13-arroyowpp.pdf.

TCEQ, 2020c. Lower Laguna Madre/Brownsville Ship Channel Watershed Protection Plan Development. Texas Commission on Environmental Quality, Nonpoint Source Program. https://www.tceq.texas.gov/assets/public/waterquality/nps/projects/80206-10161-laguna-madre-brownsville-wpp.pdf.

Texas Beach Watch Program: Quality Assurance Project Plan. Texas General Land Office; Austin, Texas: 2015; https://cgis.glo.texas.gov/Beachwatch/docs/QAPP2016-2017.pdf.

TSDC, 2018. Texas State Data Center, http://txsdc.utsa.edu/Data/TPEPP/Projections/Index.aspx.

Turner, J.W., Elledge, N.C., 2018. A bacterial source tracking project to identify sources of fecal pollution at Cole and Ropes Parks: May 2017–May 2018. Coastal Bend Bays and Estuaries Program, Publication 124, Project 1705. https://www.cbbep.org/publications/publications.html.

Turner, J.W., Elledge, N.C., Wallgren, H.R., Amend, S.M., 2019. A bacterial source tracking project to identify sources of fecal pollution in Little Bay: May 2018–January 2019. Coastal Bend Bays and Estuaries Program, Publication 127, Project 1816. https://www.cbbep.org/publications/publications.html.

USEPA, 2000. Beaches Environmental Assessment and Coastal Health Act of 2000. Office of Water, United States Environmental Protection Agency, Washington, DC, USA. https://www.congress.gov/106/plaws/publ284/PLAW-106publ284.pdf.

USEPA, 2012. Recreational Water Quality Criteria. Office of Water, United States Environmental Protection Agency, Washington, DC, USA. https://www.epa.gov/sites/production/files/2015-10/documents/rwqc2012.pdf.

USGCRP, 2017. In: Wuebbles, D.J., Fahey, D.W., Hibbard, K.H., Dokken, D.J., Stewart, B. C., Maycock, T.K. (Eds.), Climate Science Special Report: Forth National Climate Assessment, Volume I. United States Global Change Research Program, Washington, DC, USA. https://science2017.globalchange.gov/downloads/CSSR2017_FullReport.pdf.

Valle-Levinson, A., Olabarrieta, M., Heilman, L., 2020. Compound flooding in Houston-Galveston Bay during hurricane Harvey. Sci. Total Environ. 747, 141272. https://doi.org/10.1016/j.scitotenv.2020.141272.

Wade, T.J., Pai, N., Eisenberg, N.S., Colford, J.M., 2003. Do U.S. Environmental Protection Agency water quality guidelines for recreational waters prevent gastrointestinal illness? A systematic review and meta-analysis. Environ. Health Perspect. 111, 1102–1109. https://doi.org/10.1289/ehp.6241.

Walters, S.P., Thebo, A.L., Boehm, A.B., 2011. Impact of urbanization and agriculture on the occurrence of bacterial pathogens and stx genes in coastal waterbodies of Central California. Water Res. 45 (4), 1752–1762. https://doi.org/10.1016/j.watres.2010.11.032.

Wu, J., Jackson, L., 2016. Association of land use and its change with beach closure in the United States, 2004–2013. Sci. Total Environ. 571, 67–76. https://doi.org/10.1016/j.scitotenv.2016.07.116.