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# Significance of Beach Geomorphology on Fecal Indicator Bacteria Levels

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## Abstract

Large databases of fecal indicator bacteria (FIB) measurements are available for coastal waters. With the assistance of satellite imagery, we illustrated the power of assessing data for many sites by evaluating beach features such as geomorphology, distance from rivers and canals, presence of piers and causeways, and degree of urbanization coupled with the enterococci FIB database for the state of Florida. We found that beach geomorphology was the primary characteristic associated with enterococci levels that exceeded regulatory guidelines. Beaches in close proximity to marshes or within bays had higher enterococci exceedances in comparison to open coast beaches. For open coast beaches, greater enterococci exceedances were associated with nearby rivers and higher levels of urbanization. Piers and causeways had a minimal contribution, as their effect was often overwhelmed by beach geomorphology. Results can be used to understand the potential causes of elevated enterococci levels and to promote public health.

## Graphical Abstract

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**Keywords**

enterococci; Florida; percent exceedance; beach characteristics; beach geomorphology; recreational water quality

## INTRODUCTION

Marine and freshwater beaches are a large part of the U.S. economy and economies worldwide. They influence travel and tourism sectors (Houston, 2008) as well as the well-being of local residents due to the availability of low-cost recreational areas (Ashbullby et al. 2013, Wheeler et al. 2012, White et al. 2016). In October 2000, the U.S. Environmental Protection Agency (EPA) established the Beaches Environmental Assessment and Coastal Health (BEACH) Act (U.S. EPA, 2000). This amendment to the Clean Water Act was made in response to potential beachgoer risks from waterborne bacterial pathogens and gastrointestinal illness(es) associated with unsafe water quality (Haile et al. 1999). The act provided funding for the creation of 35 statewide (including the U.S. territories and Great Lakes) recreational water-monitoring programs that test fecal indicator bacteria (FIB). As a result, more than 3,100 beaches nationwide have been monitored and millions of data points have been generated over the past 15 years (U.S. EPA 2016).

The datasets, at the state and national levels, are an unprecedented and incredible resource for comparing results throughout the U.S. Many prior studies that evaluated FIB data focused solely on individual beaches or small clusters of beaches. They have focused on evaluating measureable water quality and parameters such as temperature (Leight et al. 2016), rainfall (Farnham and Lall 2015), nutrient availability (Shelton et al. 2014), hydrodynamics (Feng et al., 2013, He et al., 2007, Ge et al. 2012, Rodrigues et al. 2016), and sediment (Solo-Gabriele et al. 2000, Desmarais et al. 2002, Frey et al. 2015). Some have been more comprehensive in evaluating beach water quality for the states of California (Dorsey 2010, Yamahara et al. 2007) and Florida (Feng et al. 2016). The prior study by Feng et al. (2016) evaluated historical measurements of FIB levels at 262 Florida beaches and demonstrated the associations of water quality exceedances with both wave energy level and geographic distribution in terms of the Atlantic versus the Gulf of Mexico coasts.

Although Feng et al. (2016) provided the first baseline water quality assessment in the state of Florida, the geomorphological and man-made features were not taken into account in that study. The objective of the present study was to evaluate whether geomorphological and man-made features observable through satellite imagery were correlated with enterococci bacterial exceedance levels amongst a large data set. To our knowledge, such an analysis based upon the use of satellite imagery has not been applied for the water quality evaluation.

## MATERIALS AND METHODS

For this study, we collected available data on beach bacteria levels for the state of Florida and converted this data to percent exceedances, evaluated beach features and structures through satellite imagery, and statistically evaluated whether beach characteristics were correlated with exceedances.

### Beach Bacteria Levels

Under the direction of the Florida Department of Health (FDOH), the Florida Healthy Beaches Program (FHBP) was initiated in August 2000 and is still in operation as of 2016. At the initiation of the program, samples were collected monthly for a subset of beaches and then after August 2002, sample collection increased to a weekly basis. From the beginning of the period of record, samples were analyzed for two fecal indicator bacteria, enterococci and fecal coliform. Due to budgetary restrictions, the fecal coliform measurements were dropped in June 2011. Also, some beach sampling sites were dropped and many sites located in the northern panhandle (n=57) began to collect samples only during warmer periods. Seasonal sampling did not significantly impact the results. Of the 57 beaches that collected seasonal samples after 2011, the vast majority (n=46) did not have statistically significant differences in percent exceedances between the times before and after seasonal sampling was initiated. Of the 11 that had statistically significant differences, 3 had significantly lower percent exceedances, and 8 had significantly higher values. Given the larger extent of the dataset, we chose to focus our analyses on enterococci for data available from August 2000 to December 2015. The enterococci data set was extensive and included 185,225 data points. There was a tendency throughout the period of record to initiate and abandon some sampling sites. To address this, we only included beach sites with a minimum of 120 data points for further analysis, resulting in a total of 316 beaches spanning 34 Florida counties.

For the data evaluated, the Florida Department of Health issued health warnings or advisories when fecal indicator bacteria levels exceeded a set threshold. These thresholds were based on either geometric mean or single sample measures. By far, the majority of the thresholds exceeded during the FHBP were the single sample maximums. In order to evaluate the dataset in terms of health concerns, the fecal bacteria levels were converted to percent exceedances. The percent exceedance is the percent of the time that the beach exceeded the single sample threshold level. From 2000 to 2015, the threshold levels were 104 colony forming units (CFU) per 100 ml for enterococci (U.S. EPA, 1986). Given the size of the dataset, the percent exceedance computations were conducted using Matlab software (Mathworks, Natick, MA). The resampled data points (outside of the regular monitoring schedule), which were conducted to confirm the initial exceedance of the threshold value, were excluded in the exceedance calculations. The elimination of the resamples removed the bias that would result from the more intense monitoring efforts that occur right after an exceedance was measured.

## Satellite Imagery

Using Google Earth satellite imagery, we performed a visual assessment on all 316 beaches. Beach sampling point locations were provided by the FDOH (David Polk, Beach Program Coordinator, personal communication). This information was presented in two forms: a spreadsheet of GPS coordinates linked to county and beach name, and a Google Earth kml file that also included the coordinates of the sampling points. The two sources were compared to reconcile beach locations and beach names within the available database. In addition, we confirmed beach sampling locations through contact with local beach managers. In the few instances where inconsistencies occurred, we deferred to the sampling point location as indicated by the beach managers. The Google Earth kml file is included in the supplemental text.

Beach perimeters were established in order to determine the area evaluated corresponding to each sampling point. The FDOH Google Earth kml file provided the coordinates for the perimeters of some beaches. However, there were a number of beaches that did not have specified beach perimeters on the kml file. For these beaches, we measured ±150 m from both sides of the sampling location in the direction parallel to the coastline using Google Earth's ruler tool. If the natural end of the beach landmass was within 2 times the 150 m distance (less than 300 m from the sampling location), the end of the beach perimeter would be defined at the end of the landmass. There were also several beaches that had formerly been one beach and subsequently divided into two beaches, north and south. The boundary between the split beaches was not given by the kml file, so we assigned the boundary at exactly half the distance between the corresponding sampling points.

From Google Earth imagery, we defined a sequence of characteristics for the 316 study beaches, including classification of beaches with respect to general geomorphological characteristics, identification of nearby rivers and canals, piers and causeways, and level of urbanization.

**Beach classification based upon geomorphology—**Upon review of the beach characteristics through Google Earth, Florida beaches were classified into 6 categories (Fig. 1). The majority of the Florida coastline is surrounded by barrier islands, which are narrow islands that run parallel to the mainland. Beaches on the Atlantic Ocean or on the Gulf of Mexico side of the barrier islands were considered as category 1, or open-coast beaches. These beaches are mostly dominated by surface gravity waves and wave-induced transport. Beaches behind the barrier islands or located within coastal bays, lagoons, sounds, intra-coastal waterways, or within upstream estuarine rivers were considered as category 2, or bay beaches. This type of beach typically has little to no wave action but may be influenced by tides. Some beaches were located along breaks in the barrier islands (within inlets and channels that separate barrier islands); these beaches were considered as category 3, inlet-channel-situated beaches. These beaches can have high mixing rates due to potentially strong tidal currents. Beaches defined as category 4 have significant structures placed around them that limit or obstruct water circulation. Due to the various degrees to which beaches may be obstructed, a subjective decision was made to define an obstruction as a structure whose length is longer than the beach itself. Piers are common obstructions that are often perpendicular to the coastline. Piers supported on columns that allow water to flow below the structure are not considered an obstruction. For category 5, we considered the parts of the Florida coast without barrier islands. The coastline along these areas is very marshy with densely vegetated delta regions. These beaches are predominantly located in the “Big Bend area” (Fig. 1). Category 6, or back reef beaches, corresponds to most beaches in the Florida Keys. The Florida Keys are an extension of the barrier island formations along the Florida southeastern coastline. They do not have a broad land mass behind them and are situated behind shallow coral reefs which dissipate wave energy onto the beaches. Within each category, beaches were further characterized in terms of the absence or presence of the following: rivers, canals, piers, and causeways. We also analyzed the degree of urbanization for areas adjacent to the beaches.

**River and Canals—**Rivers and canals were considered first together and then separately. Rivers were identified as winding, branching bodies of water, stemming from the inland areas and flowing towards the ocean. Typically, rivers that formed as smaller tributaries would join nearby tributaries as they flowed toward the ocean, forming increasingly larger bodies of water near beaches. Their location relative to the beach could potentially impact current flow and enterococci concentrations.

Canals are also a means through which water moves from inland areas towards the coast. These structures are characterized by their definitive, straight structure that reflects their man-made rigidity. These formations do not occur naturally and have the potential to affect water quality in surrounding beach waters, as canals are also typically associated with the transport of inland sources of contamination (Lu et al. 2004).

**Piers—**We examined the beaches for the presence or absence of pier(s). These man-made structures are easily visualized using satellite imagery and each pier’s shape, length, and number (where applicable) was noted. Within the study of piers, we looked for potential differences between those deemed “public” or “private.” Piers were considered public if they were built in a public access area. These piers tended to be larger in size with respect to their “private pier” counterparts. Some of the public piers had structures on them, such as restaurants and bathrooms. Private piers were linked to residential homes in private or remote areas; they are typically smaller in size and have no infrastructure built on top of them. Piers not only have potential to alter a beach’s water circulation with their structure (Saengsupavanich 2011), but they also have the ability to attract birds and people, as well as promote recreational activities.

**Causeways—**Causeways were investigated for reasons similar to piers. Man-made highways spanning a distance of water between two pieces of land are host to pollution from cars as well as other anthropogenic sources. The close proximity to bodies of water and their corresponding beaches raises concern over the pollution in run-off and its potential influence on FIB levels.

**Urbanization—**A beach's degree of urbanization was designated based on a two-part analysis: a) percentage of land developed and b) what was developed, i.e. parking lot versus hotel, or a small single-family house versus condominiums. Google Earth offers "elevation tool" that allows viewers to control the height above which they can view the area of interest, In order for our analysis to be consistent, we viewed the area with the sampling point centered in the screen and always from the same 600 m elevation vantage point.. The total area being viewed at 600 m elevation encompassed 336,800 $m^2$ (762 m by 442 m). The beaches were assigned a number from 1 to 5 based on our two criteria. Level 1 beaches were characterized by 0–20% of ground space developed with minimal infrastructure (i.e. a parking lot). Level 2 beaches displayed 20–40% of ground space covered with small developments (i.e. single family homes). Development of 40–60% of the ground space with major roadways and denser residences was indicative of a Level 3 beach. Level 4 beaches were defined as 60–80% land space developed with the presence of hotels or condominiums. Lastly, Level 5 beaches were 80–100% developed with high-rise buildings, major roads, and minimal visible open space.

### Statistical Analysis

We compared the percent exceedances and the features observed via satellite imagery for each beach using several different statistical methods offered through Microsoft Excel. Single Factor Analysis of Variance (ANOVA) model was used to evaluate groups of data (such as beach categorization and urbanization). Reported F values represent the ratio of variances between two sets of values. F critical corresponds to the ratio of variances that is significant at 95% confidence limits. If F is greater than F critical then the null hypothesis of equal variances is rejected and the variances of the populations are statistically different. In addition to ANOVA, heteroscedastic t-tests were conducted to compare percent exceedances among two specific data groups within various categories concerning beach classification, rivers, canals, piers, causeways and urbanization. Significant differences were assumed for $p$ values less than 0.05, assuming a two-tail distribution with unequal variance. Urbanization was also evaluated using regression analysis based upon a least squares approach.

## RESULTS

### Beach Classification

Results from the ANOVA indicate that there is a statistically significant difference between the various beach categories (F-critical = 2.2, F-value = 50, $p < 0.001$) (Fig. 2). Subsequent t-tests showed that open-coast beaches (category 1; $n = 212$), were statistically different than bay beaches (category 2; $n = 71$) ($p < 0.001$). The average exceedance for category 1 beaches was 1.7% (standard deviation, $\sigma = 1.7\%$). The average exceedance for category 2 beaches was 6.9% ($\sigma = 5.4\%$). Similarly, marsh beaches (category 5; $n = 17$) were found to be statistically different than all other beach types, with an average exceedance of 14.5% ($\sigma = 10.5\%$) ($p < 0.001$). The average exceedances of inlet-channel-situated beaches (3.5%; category 3; $n = 3$), manmade-structure-protected beaches (6.5%; category 4; $n = 5$), and back-reef beaches (3.5%; category 6; $n = 8$) were all greater than that of category 1 beaches, but less than that of category 5 beaches. It should also be noted that the low numbers of beaches within categories 3, 4, and 6 made it difficult to observe statistical differences for these data sets.

## Rivers and Canals

We first combined rivers and canals because of their similarity of water transport mechanisms from interior portions of the state towards the coastline. It should be noted that we included category 2, bay beaches within the “river-containing beach” data group under the simplified assumption that due to the nature of bay beaches, they are part of a river system whether as part of the Intracoastal Waterway located immediately behind the barrier islands, or their presence on the banks of a tributary to the Intracoastal. We compared 85 beaches that had river(s) and/or canal(s) within their formal perimeter boundaries against 231 beaches that did not have either characteristic within their perimeters. River and/or canal-containing beaches had higher exceedances (7.5%) in comparison to beaches that did not (2.3%, $p < 0.001$) (Table 1).

We then evaluated beaches that had river(s) and/or canal(s) including bay beaches within 600 m of the sampling point, independent of formal boundaries ($n = 89$). We compared them against beaches that did not have either characteristic within 600 m of the sampling point ($n = 227$). The beaches with rivers and/or canals demonstrated statistically significant exceedances (8.0%) in comparison to river and/or canal-lacking beaches (2.0%, $p < 0.001$). We then looked to evaluate rivers and canals separately to better understand their individual contributions.

**Rivers—**Beaches with rivers within their perimeters ($n = 79$) had statistically higher exceedances (7.3%) in comparison to those without river influence ($n = 237$, 2.5%, $p < 0.001$). To examine the effect, if any, of distance to rivers we then analyzed beaches where rivers were within 600 m of the sampling point versus beaches that did not have a river within 600 m – all independent of formal beach borders. Similarly, the beaches that had a river within 600 m of sampling point ($n = 84$) had statistically higher exceedances (8.1%) in comparison to those that did not ($n = 232$, 2.1%, $p < 0.001$).

Then, we performed a t-test in order to determine whether or not our assumption about bay beaches and river involvement was skewing the results. We did so by comparing beaches that had rivers explicitly within their perimeters (and excluding bay beaches on the Intracoastal Waterway away from river inputs) ($n = 15$), to beaches that did not have any rivers ($n = 301$). It should be noted that there were several bay beaches that did have definitive rivers within their perimeters; those beaches were still included within the river-containing data group as opposed to being excluded due to their bay categorization. The average exceedance for the former group was statistically higher (9.8 %) in comparison to the average exceedance in comparison to beaches that did not have rivers within their beach perimeter (3.4 %, $p = 0.02$).

Finally, we ran a similar t-test examining beaches with explicit rivers within 600 m of the sampling point ($n = 25$), excluding bay beaches on the Intracoastal, in contrast to beaches without rivers within 600 m of the sampling point ($n = 291$). Statistically higher exceedances were observed for the group of beaches with rivers within 600 m exceedance (11.8%) in comparison to the group of beaches without rivers (3.0%, $p < 0.001$).

**Canals—**We then examined beaches that had canals within borders versus beaches that did not have canals present. In this case, the exceedances for beaches that had canals within their borders ($n = 10$, 7.5%) were not statistically different than beaches that did not have canals within their borders ($n = 306$, 3.6%, $p = 0.2$); however, it is noted that the average exceedance was higher with canals than without which is consistent with the river analyses. The next analysis evaluated beaches that had canals within 600 m of the sampling point versus beaches that did not have canals present. Again, the differences were not statistically different, although the beaches with canals within 600 m of the sampling point (6.2%) had higher exceedances in comparison to canals that did not (3.6%, $p = 0.19$).

Overall, this analysis shows that the presence of rivers near beaches was found to be associated with higher percent exceedances and that rivers likely make a larger contribution to percent exceedance levels than canals do.

## Piers

We analyzed enterococci exceedance in the presence or absence of a pier within the boundaries of the beach perimeter. We found that the mean exceedance level for the 70 beaches with piers was 6.3% ($\sigma$ =7.5%). The mean exceedance level for the 246 beaches without a pier was 2.9% ($\sigma = 3.9\%$). The $p$-value for a two-tail test was less than 0.001, thus the enterococci exceedance levels between the two beach types were significantly different.

We then ran another analysis excluding the "Big Bend" marsh beaches ($n = 17$) to see if our data was still statistically significant. T-test analysis performed between beaches with piers ($n = 65$) and beaches without piers ($n = 234$) showed the mean exceedance level was 4.8% ($\sigma = 5.1\%$) for the beaches with piers and the mean exceedance was 2.6% ($\sigma = 3.2\%$) for the beaches without piers. The results were still significantly different ($p < 0.001$). Therefore, the marsh beaches in the "Big Bend" counties do not have a skewing effect on the data and support the results from the all-inclusive test.

Next, we examined enterococci exceedance of pier beaches between 56 "public" and 14 "private" piers. The results showed that the public piers had a mean exceedance level of 4.9% ($\sigma = 5.8\%$). As for the private piers, the mean exceedance was 11.6% ($\sigma = 10.6\%$). The $p$-value for a two-tail test was 0.04, thus the enterococci exceedance levels between the two pier types is significantly different.

Afterwards, we examined the open-coast (category 1) beaches that contained a pier within their boundaries versus those that did not. The t-test analysis found that the 30 pier-containing open coast beaches had an average exceedance value of 2.0% ($\sigma = 1.6\%$). The remaining 182 category-1 beaches with no piers had an average enterococci exceedance of 1.6% ($\sigma$ =1.8%). The $p$-value for a two-tail test was 0.18, indicating that the exceedance levels between category 1 pier-containing beaches and pier-lacking beaches are not statistically different.

We then conducted the same test amongst bay beaches (category 2). We found that bay beaches with piers ($n = 31$) had an average exceedance of 7.2% ($\sigma = 5.9\%$) and that the remaining bay beaches with no piers ($n = 40$) had an average enterococci exceedance of 6.7% ($\sigma = 4.9\%$). Similar to the prior analysis for open-coast beaches with piers and those without, the $p$-value for this two-tail test ($p = 0.70$) indicated no significant differences.

For further evaluation, we then compared the open-coast beaches with piers to the bay beaches with piers. The 30 pier-containing open-coast beaches had an average exceedance value of 2.0% ($\sigma = 1.6\%$). The 31 pier-containing bay beaches had an average exceedance value of 7.2% ($\sigma = 5.9\%$). The result is statistically significant ($p < 0.001$), which implies the effect of pier FIB contribution is likely secondary to the contribution of beach category.

Overall, beaches without piers (all beaches, non-marsh beaches, and open coast beaches only) had lower exceedances relative to beaches with piers. These differences were significant only when all beaches and beaches excluding marsh beaches were considered.

## Causeways

We ran a statistical analysis for exceedance of enterococci in the presence or absence of a causeway within the boundaries of the beach perimeter. We found that the mean exceedance level for 21 beaches with causeways was 5.5% ($\sigma = 4.2\%$). The mean exceedance level for the 295 beaches without a causeway was 3.6% ($\sigma = 5.1\%$). The $p$-value for a two-tail test was 0.056, suggesting that the enterococci exceedance levels of the beaches with causeways are not significantly different from those that do not have causeways within their perimeters, although the test for significance was close to the 0.05 value.

The next step in our analysis led us to examine the enterococci exceedance levels between causeway beaches and bay beaches. The 21 causeway beaches are beaches that contain a physical causeway structure within their beach perimeters, whereas bay beaches do not have a causeway but are located in the bay. It should be noted that there were 16 bay beaches that contained a causeway within their boundaries and were therefore analyzed in the "causeway" group, not the "bay" group. The causeway beaches had a mean exceedance level of 5.5% ($\sigma = 4.2\%$). The 55 bay beaches had a slightly higher exceedance level of 7.0% ($\sigma = 5.6\%$). The results ($p = 0.21$) were indicative that there is not a significant difference between these two types of beaches.

We then questioned if there was any difference in exceedance levels depending upon whether the causeway was inside or outside of a bay area. Out of the 23 causeway beaches, 15 were inside a bay area and 6 were not. The causeway beaches located within a bay had a mean exceedance level of 6.4% ($\sigma = 4.7\%$). The causeway beaches not located in a bay had a mean exceedance level of 3.3% ($\sigma = 1.1\%$). Given the resulting $p$-value for the two-tail test ($p = 0.03$), there was a statistically significant difference among causeway beaches, with those located in the bay showing relatively higher exceedances.

Lastly, we analyzed causeway-containing category 2 bay beaches versus category 2 bay beaches with no causeways, using a t-test. The former group ($n = 15$) had a mean exceedance level of 6.4% ($\sigma = 4.7\%$), while the latter group ($n = 55$) had an exceedance level of 7.0% ($\sigma = 5.6\%$). The results were statistically not different ($p = 0.65$). Thus, the presence of a causeway within a bay beach did not appear to be associated with enterococci levels.

Overall, our results suggest that the associations between causeways and elevated enterococci exceedances exist because causeway beaches are found predominantly within bays. When controlling for the bay category, statistical differences were not observed, suggesting that the influence of causeways is overwhelmed by the influence of their presence in bays.

### Urbanization

ANOVA analyses in FIB exceedance levels among the minimally developed level 1 beaches through the heavily urbanized level 5 beaches indicate that there is a statistically significant difference between the various beach types (F-critical = 2.40, F-value = 3.80, $p = 0.005$) (Table 2). Subsequent t-tests showed that there was statistical difference between level 3 and level 5 beaches ($p = 0.04$). Conversely, there was no statistical difference between level 1 beaches ($n = 99$) and level 3 beaches ($n = 66$, $p = 0.43$), or between level 1 beaches and level 5 beaches ($n = 32$) ($p = 0.11$). We performed a linear regression on the mean enterococci percent exceedances of all 316 beaches and their respective levels of urbanization (Fig. 3). A negative correlation ($r = -0.64$) was found despite being not statistically significant ($p = 0.24$).

Similar analyses were conducted for only category 1 (or open coast) beaches with respect to urbanization levels. The ANOVA test using this category showed that there was no statistically significant difference between the 5 levels of urbanization amongst category 1 beaches (F-critical = 2.4, F-value = 1.4, $p = 0.22$) (Table 2). T-tests between level 1 beaches and level 5 beaches ($n = 31$), as well as level 3 beaches and level 5 beaches, showed that exceedances were not different between these groups ($p = 0.057$ and $p = 0.062$ respectively). The t-test between category 1, level 1 beaches ($n = 54$) and category 1, level 3 ($n = 48$) beaches also did not demonstrate statistically different exceedances ($p = 0.63$). The linear regression on mean enterococci percent exceedances of category 1 beaches and corresponding urbanization levels resulted in a positive correlation ($r = 0.93$, $p = 0.02$) (Fig 3). This indicates a positive association between open coast beaches' increasing levels of urbanization and increasing levels of enterococci exceedance levels. Among the category 1 beaches, urbanization appears to be correlated with enterococci exceedance, indicating that the more urbanized the beach, the higher the exceedance, on average. This correlation was not observed when the data was analyzed as a whole, suggesting that the characteristics of bay and marsh beaches overwhelm the influence of urbanization.

## DISCUSSION

Results from the present study show that beach type is highly associated with exceedance levels, which is consistent with the prior study that found associations between wave energy and FIB exceedance levels (Feng et al. 2016). In this study, we categorized the beaches based on geomorphology and found that open coast beaches had the lowest average exceedance, whereas bay beaches had, on average, 4 times the exceedance relative to category 1 beaches. More significantly, marsh beaches were, on average, over 8 times the average of open coast beaches exceedances.

The significant differences between category 1, 2, and 5 beaches would suggest that specific characteristics or components pertaining to these beach types may contribute to and be ultimately responsible for these results. These characteristics can include limited water circulation (Byappanahalli et al. 2015) and wave action (Phillips et al. 2014), which are dictated by the hydrography and geomorphology of the beach. Bay beaches, located behind the barrier islands, are not directly exposed to gravity waves (particularly swell waves) generated and propagated in the Atlantic Ocean or the Gulf of Mexico. They also receive a considerable amount of river and canal input as water is brought to the ocean. Marsh beaches, although not behind barrier islands, are characterized by extremely shallow bottom slopes (Feng et al. 2016) and the presence of surrounding wetland areas. It is possible that marsh areas are characterized by different water chemistry and more highly organic coastal sediments that may play a role in the elevation of enterococci. For example, He et al. (2007) suggested that “pond-like” waters foster a more desirable environment for FIB to thrive, in contrast to the flowing water environments; this idea could support our findings of high percent exceedance in marsh beaches in contrast to open-coast beaches. Of interest is that the communities surrounding the marsh beaches were relatively small, so the influence of direct human sewage is limited due to the small populations in these areas. The large expanses of undeveloped land in the vicinity of marsh beaches suggests that if there is a source, it is likely natural, and potentially due to wildlife (Grant et al. 2001, Wright et al. 2011) coupled with the retention, persistence (Brooks et al. 2015), and possibly regrowth of bacteria within organic rich waters and coastal sediments (Desmarais et al. 2002, Lee et al. 2006).

Percent exceedances for the remaining beach categories were found to be between open-coast and marsh beaches, but were not consistently different from one another. Percent exceedances for category 3 inlet channel and category 6 back reef beaches were found to be between open coast and bay beaches, which is consistent with their geography. Inlet beaches are at breaks within the barrier islands and thus are located between open coast and bay beaches. The back reef beaches share some of the lower circulation features of bay beaches but are not completely blocked by barrier islands, thus illustrating exceedance levels between open coast and bay beaches. Category 4, manmade obstructed beaches demonstrated exceedance levels between the bay and marsh beaches. The obstruction of flow at manmade obstructed beaches can be severe, thereby greatly limiting dilution of the waters in these areas and further resulting in higher exceedances at manmade obstructed beaches relative to bay beaches.

Besides beach category, one of the more compelling geomorphological factors correlated with elevated enterococci levels in this study was the presence of rivers and canals in the vicinity of the beach. Multiple studies conducted have indicated that rivers and canals, in addition to inlets and marshes, are substantial sources of FIB (Grant et al. 2001, Sadowsky and Whitman 2011, Bradshaw et al. 2016, Templar et al. 2016). Our results strongly support these observations. In our study, the presence of rivers within 600 m is significantly related with higher exceedance levels despite the exact distance from the sampling point or bay contribution; thus, their effect is not overwhelmed by precise distance or beach classification. Canal presence was not significantly associated with exceedance levels; however, when comparing rivers and canals together, their combined significance despite distance from sampling point suggests an association with FIB contributions. Rivers and canals have potential to carry significant amounts of FIB from runoff accumulating from the inland areas (Nevers et al. 2007, Byappanahalli et al. 2010, Vergougstraete et al. 2015) This includes influences from agricultural and urban land-uses, both of which are associated with elevated FIB levels (Strauch et al. 2014, Walters et al. 2011). In addition to land use, studies have also shown that riverbank sediments carry and eventually release significant amounts of FIB from their banks (Desmarais et al. 2002, Brinkmeyer et al. 2015). If the goal is to minimize the possibility of elevated FIB levels, then in terms of siting beaches, if possible, rivers and canals should be avoided. If they cannot be avoided, then the contributing watersheds (Di’Donato et al. 2009, Gotkowska-Plachta et al. 2016) should be managed to minimize inputs of FIB, especially anthropogenic inputs (Dorsey 2010). However, as suggested for marsh beaches, there are other factors in addition to anthropogenic inputs that can result in larger FIB levels at beaches influenced by rivers and canals.

The data from the current study also indicates that beaches with piers have over twice the exceedance levels as non-pier beaches. Piers can attract birds, humans, and other animals (Boehm et al. 2003). Piers are shaded and can provide relief from sunlight for animals and can potentially serve as nesting places for birds (Wither et al. 2005). Fishing is a common activity at piers which in turn attracts animals, again, in particular, birds. Some piers have structures like bathrooms and restaurants – all of which, depending on degree of management, could be sources of FIB. Despite all of these FIB sources associated with piers, upon statistical testing, we conclude that the influence of pier on FIB can be observed, but the contribution is typically overshadowed by the beach category. This was particularly apparent when beaches with public versus private piers were compared. Beaches with private piers are found exclusively in marsh and bay beach areas, whereas public piers are found at open coast beaches as well as marsh and bay beaches. The inclusion of open coast beach data within the comparison resulted in statistically significant lower levels of enterococci at beaches with public piers in comparison to beaches with private piers.

Similar to piers, causeway beaches were found to have higher exceedances relative to beaches without causeways. However, the differences were not significant. The only statistical significance observed was for causeway beaches within bays versus those outside the bay. This difference is confounded by the geomorphological impacts of the bay as opposed to the actual presence of the causeway. The higher enterococci exceedances at causeway beaches, although not statistically higher, are also consistent with what is known about sources of runoff from impervious and highly trafficked surfaces (Dorsey 2010, Sadowsky and Whitman 2011).

When evaluating urbanization, variable results were observed depending upon whether all beaches or only open coast beaches were considered. When considered as a whole, beach type overwhelmed urbanization impacts. The beaches with the highest levels of enterococci exceedance were marsh beaches. However, marsh beaches are characterized by relatively low urbanization. This is in contrast to open coast beaches; this beach category has beaches at all levels of urbanization whereas marsh and bay beaches have urbanization levels of only 1, 2 and 3. It was not until the open coast beaches were evaluated separately that the associations with increased urbanization could be observed (Fig 3). By evaluating only category 1 beaches, the impact of beach type was removed. Under these conditions, a significant and positive correlation was observed between increasing urbanization and mean FIB exceedances. This correlation appears to be logical, as increased development and infrastructure would ideally equate to higher and denser anthropogenic use, and potentially higher contributions from various sources of FIB (as previously mentioned, human activities, sewage, and runoff pollutants) (Sadowsky and Whitman 2011, Dorsey 2010). These results would also further support the notion that rivers, inlets, and canals associated with marshes and bays are the critical contributing factors to the exceedance levels of nearby beaches instead of urbanization. It could also support the idea that urbanization plays a larger role for the open coast beach category.

Overall, beach geomorphology appears to be strongly associated with enterococci exceedance levels. Open coast beaches tend to have the best water quality (i.e., lowest exceedances), followed by bay beaches and, lastly, by marsh beaches. The presence of rivers and canals nearby (within 600 m) also appears to be associated with enterococci exceedance. Within open coast beaches, more urbanization is associated with higher FIB exceedances. Weak relationships were observed with the presence of piers and causeways. All of these results, with the exception of marsh beaches, are consistent with known FIB sources, from sources related to land use and from people. More research is needed to evaluate the influence of water and soil chemistry on the persistence of FIB in marsh areas.

## CONCLUSION

This study is the first of its kind to utilize a massive public database in conjunction with easily accessible satellite imagery at a state-wide level to evaluate associations between water quality and geomorphological features. The category-based approach utilized in this paper can be easily extended to evaluate beaches in other parts of the U.S. to serve as a model for future studies of coastal states nationwide. Of interest would be to evaluate whether the trends observed in Florida are consistent with beaches in other states. It is our aspiration that results from these types of analyses can be used to identify more vulnerable beaches from publicly available water quality data and aerial imagery. We believe that this information will help improve the process of siting beaches so that public health will be protected.

## Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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## Highlights

- Enterococci percent exceedance levels were compared to beach characteristics
- Beach geomorphology was the primary feature associated with exceedances
- Marsh and bay beaches were characterized by higher enterococci exceedances
- Statistical analysis using large database and satellite imagery is useful for identifying factors that may influence water quality

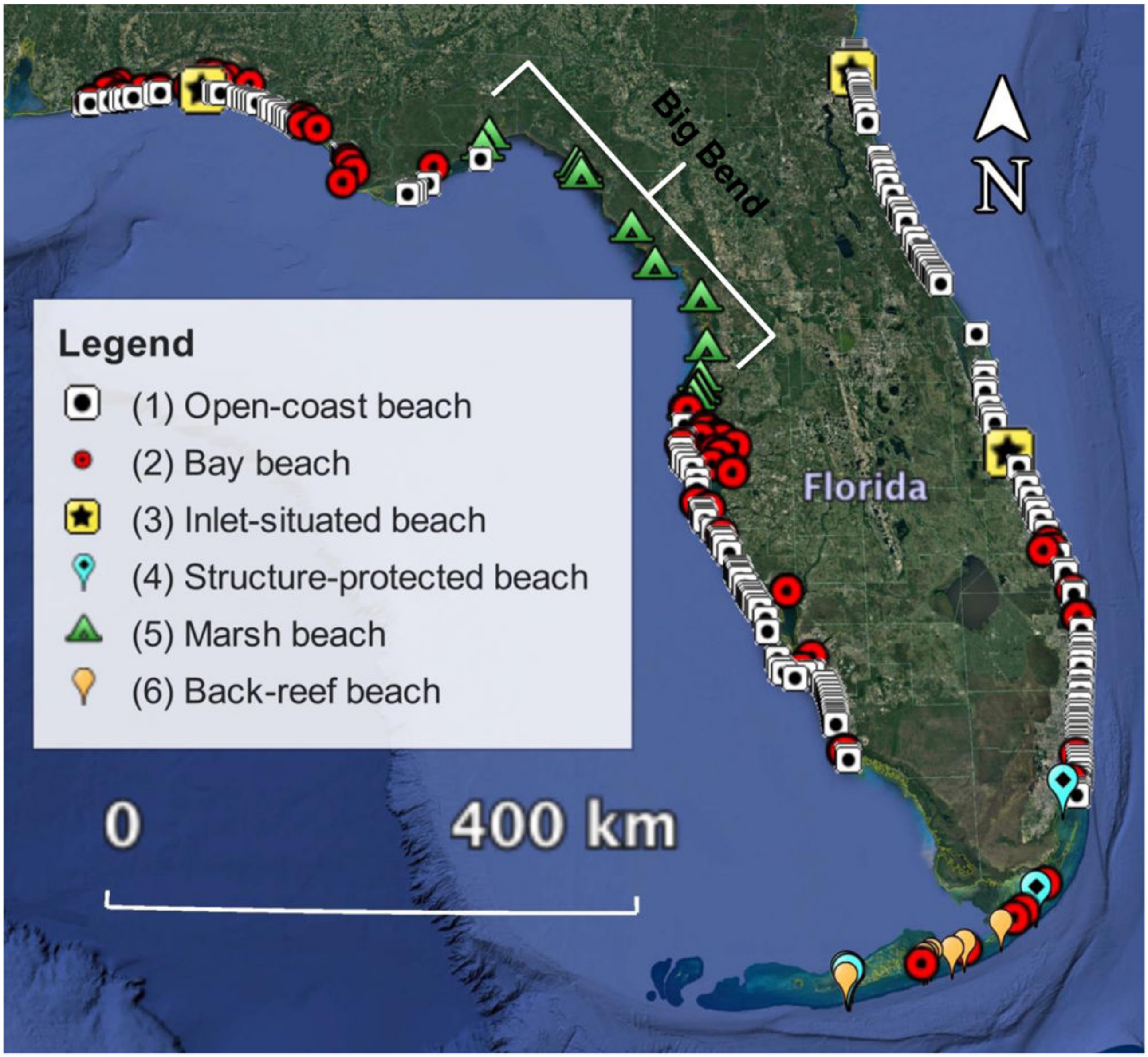

**Fig. 1.**

The geographic distribution and categorization of 316 recreational beaches in the study. The Big Bend area includes Pasco, Dixie, Taylor, Levy, Hernando, Citrus, and Wakulla counties.

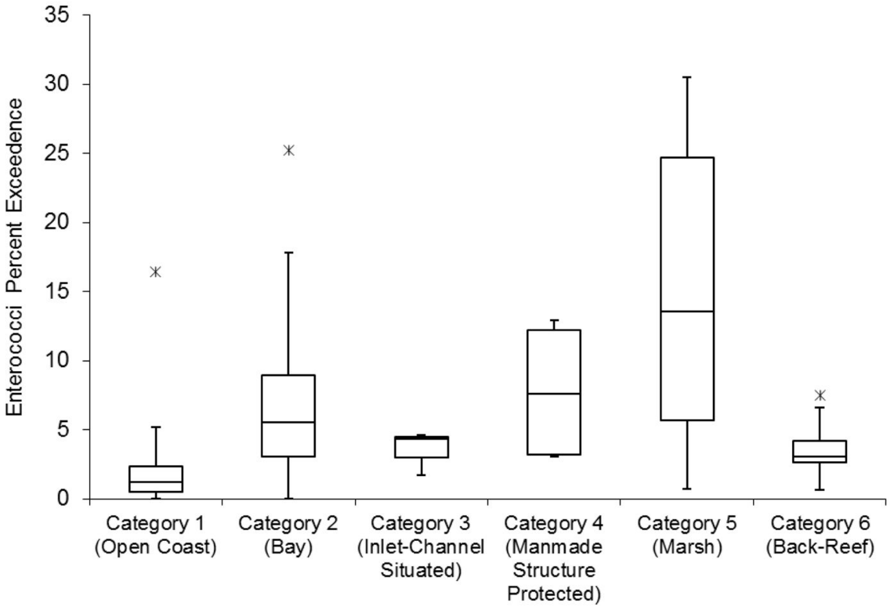

**Fig. 2.**

Box and Whisker Plot of Beach Categorization Data. The box edges represent the 25% and 75% ranges of the data with the line within the plot representing the median of the data. The ends of the whisker are set at 1.5 interquartile range (IQR) units above the third quartile and 1.5 IQR units below the first quartile. Values outside the whiskers are considered outliers.

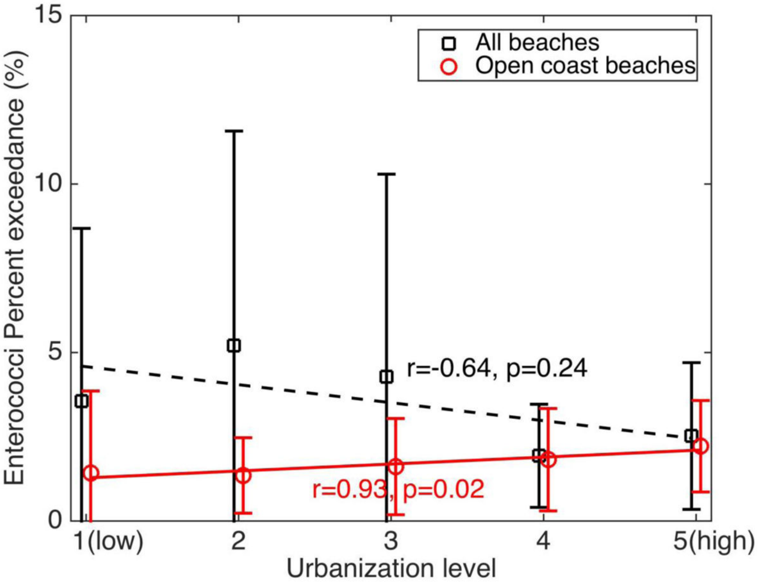

**Fig. 3.**

Mean enterococci percent exceedances in each urbanization level and linear fitted lines for all beaches versus open coast beaches. Error bars show standard deviations.

## Table 1

Results from the analysis of beaches with rivers and canals within their perimeters or within 600 meters. The categories compared (e.g., a versus b) are given in the first two columns. The columns to the right are patterned off of the first two columns with the statistics for category “a” are provided to the left and the statistics for category “b” are provided to the right

| **T-test comparison** | | **Number of Beaches** | | **Mean % exceedance and standard deviation**[*] | | **Range** | | **p-value** |
|---|---|---|---|---|---|---|---|---|
| Rivers within beach perimeter | No rivers | 79 | 237 | 7.32 (6.35) | 2.46 (3.94) | 0–30.5 | 0–30.1 | <0.001 |
| Rivers within 600 m | No rivers | 85 | 231 | 7.99 (7.35) | 2.09 (2.55) | 0–30.5 | 0–17.2 | <0.001 |
| Rivers (without bays) within beach perimeter | No rivers | 15 | 301 | 9.84 (9.86) | 3.39 (4.56) | 0.69–30.5 | 0–30.1 | 0.02 |
| Rivers (without bays) within 600m | No rivers | 25 | 291 | 11.8 (10.20) | 2.98 (3.69) | 0–30.5 | 0–25.2 | <0.001 |
| Canals within beach perimeter | No canals | 10 | 306 | 7.53 (9.05) | 3.55 (4.90) | 0–30.1 | 0–30.5 | 0.20 |
| Canals within 600 m | No canals | 15 | 301 | 6.24 (7.55) | 3.55 (4.94) | 0–30.1 | 0– 30.48 | 0.19 |
| Rivers and/or Canals within beach perimeter | No rivers or canals | 85 | 231 | 7.51 (6.71) | 2.26 (3.44) | 0–30.5 | 0–28.0 | <0.001 |
| Rivers and/or canals within 600 m | No rivers or canals | 89 | 227 | 7.96 (7.25) | 2.00 (2.41) | 0–30.5 | 0–17.2 | <0.001 |

[*] Standard deviation provided in parenthesis

## Table 2

Enterococci statistics for all beaches and open coast beaches when separated by degree of urbanization

| **Level of Urbanization amongst all beaches** | **Number of Beaches** | **Mean exceedance and standard deviation (%)**[*] | **Range (%)** | **Statistical significance**[**] |
|---|---|---|---|---|
| All Beaches | | | | |
| 1 (low) | 99 | 3.56 (5.12) | 0–29.6 | A |
| 2 | 66 | 5.20 (6.37) | 0–30.5 | B |
| 3 | 66 | 4.28 (6.01) | 0–30.1 | C |
| 4 | 53 | 1.93 (1.53) | 0–6.57 | A,B,C |
| 5 (high) | 32 | 2.52 (2.18) | 0.16–12.0 | B,C |
| Open Coast | | | | |
| 1 (low) | 54 | 1.42 (2.43) | 0–16.4 | A,B |
| 2 | 31 | 1.35 (1.12) | 0–4.76 | A |
| 3 | 48 | 1.61 (1.43) | 0–5.96 | A,B |
| 4 | 48 | 1.82 (1.52) | 0–6.57 | A,B |
| 5 (high) | 31 | 2.22 (1.36) | 0.16–5.23 | B |

[*] standard deviation provided in parenthesis

[**] Levels of urbanization sharing the same letter are statistically not different.

## Table 3

Table of factors associated with higher enterococci exceedances

| Factors of Influence | All Beaches | Subset of Data |
|---|---|---|
| Rivers and Canals * | Significant | Significant even when bay beaches without rivers/canals nearby were removed. |
| Rivers * | Significant | |
| Canals * | Not significant | |
| Piers | Significant | • Excluding Big Bend beaches - significant<br>• Private vs. Public – significant<br>• Category 1 beaches with and without piers – not significant<br>• Category 2 beaches with and without piers – not significant<br>• Category 1 vs. Category 2 - significant |
| Causeways | Not significant | • Causeway vs. Category 2 (bay) beaches –not significant<br>• Causeways in bay vs. Causeways not in a bay - significant<br>• Causeway-Category 2 vs. Category 2 without Causeways – not significant |
| Degree of Urbanization | (ANOVA) significant | Positive correlation within Category 1 beaches and increasing urbanization |

* within formal perimeters and within 600 m of water sampling point.