# Effect of beach management policies on recreational water quality

Kelly, Elizabeth A.; Feng, Zhixuan; Gidley, Maribeth L.; Sinigalliano, Christopher D.; Kumar, Naresh; Donahue, Allison G.; Reniers, Adrianus J.H.M.; Solo-Gabriele, Helena M.

**DOI**
10.1016/j.jenvman.2018.02.012

**Publication date**
2018

**Document Version**
Final published version

**Published in**
Journal of Environmental Management

Journal of Environmental Management 212 (2018) 266–277

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

# Effect of beach management policies on recreational water quality

Elizabeth A. Kelly [a, b, c, 1], Zhixuan Feng [b, d, 2], Maribeth L. Gidley [b, e, f, 3], Christopher D. Sinigalliano [b, f, 4], Naresh Kumar [g, 5], Allison G. Donahue [b, h, 6], Adrianus J.H.M. Reniers [b, i, 7], Helena M. Solo-Gabriele [a, b, c, *]

[a] University of Miami, Leonard and Jayne Abess Center for Ecosystem Science and Policy, Coral Gables, FL, USA
[b] NSF NIEHS Oceans and Human Health Center, Rosenstiel School of Marine and Atmospheric Science, University of Miami, Key Biscayne, FL, USA
[c] University of Miami, College of Engineering, Department of Civil, Architectural, and Environmental Engineering, USA
[d] Woods Hole Oceanographic Institution, Woods Hole, MA, USA
[e] University of Miami Cooperative Institute for Marine and Atmospheric Studies, Key Biscayne, FL, USA
[f] NOAA Atlantic Oceanographic and Meteorological Laboratory, Key Biscayne, FL, USA
[g] University of Miami Department of Public Health Sciences, Division of Environment & Public Health, Miami, FL, USA
[h] University of Miami, Department of Biology, Coral Gables, FL, USA
[i] Delft University of Technology, Department of Hydraulic Engineering, Delft, The Netherlands

ARTICLE INFO

*Article history:*
Received 9 August 2017
Received in revised form
19 November 2017
Accepted 2 February 2018
Available online 22 February 2018

*Keywords:*
Beach management
Water quality
Fecal indicator bacteria
Beach use
Fecal coliform
Enterococci

ABSTRACT

When beach water monitoring programs identify poor water quality, the causes are frequently unknown. We hypothesize that management policies play an important role in the frequency of fecal indicator bacteria (FIB) exceedances (enterococci and fecal coliform) at recreational beaches. To test this hypothesis we implemented an innovative approach utilizing large amounts of monitoring data ($n > 150{,}000$ measurements per FIB) to determine associations between the frequency of contaminant exceedances and beach management practices. The large FIB database was augmented with results from a survey designed to assess management policies for 316 beaches throughout the state of Florida. The FIB and survey data were analyzed using t-tests, ANOVA, factor analysis, and linear regression. Results show that beach geomorphology (beach type) was highly associated with exceedance of regulatory standards. Low enterococci exceedances were associated with open coast beaches ($n = 211$) that have sparse human densities, no homeless populations, low densities of dogs and birds, bird management policies, low densities of seaweed, beach renourishment, charge access fees, employ lifeguards, without nearby marinas, and those that manage storm water. Factor analysis and a linear regression confirmed beach type as the predominant factor with secondary influences from grooming activities (including seaweed densities and beach renourishment) and beach access (including charging fees, employing lifeguards, and without nearby marinas). Our results were observable primarily because of the very large public FIB database available for analyses; similar approaches can be adopted at other beaches. The findings of this research have important policy implications because the selected beach management practices that were associated with low levels of FIB can be implemented in other parts of the US and around the world to improve recreational beach water quality.



* Corresponding author. Present address: 1251 Memorial Drive, McArthur Engineering Building, Room 252, Coral Gables, FL 33146, USA.
*E-mail address:* hmsolo@miami.edu (H.M. Solo-Gabriele).
[1] Present/permanent address: 1365 Memorial Drive, Ungar Building, 2nd Floor, Suite 230F, Coral Gables, FL 33146, USA.
[2] Present/permanent address: Biology Department, Woods Hole Oceanographic Institution, MS #33, Redfield 2-44, Woods Hole, MA 02543, USA.
[3] Present/permanent address: University of Miami Cooperative Institute for Marine and Atmospheric Studies, 4600 Rickenbacker Causeway, Miami, FL 33149 USA.
[4] Present/permanent address: NOAA Atlantic Oceanographic and Meteorological Laboratory, Ocean Chemistry and Ecosystems Division, 4301 Rickenbacker Causeway, Miami, Florida 33149 USA.
[5] Present/permanent address: University of Miami Department of Public Health Sciences, Division of Environment & Public Health # 1063, Clinical Research Building, 1120 NW 14th, St., Miami, FL 33136 USA.
[6] Present/permanent address: University of Miami, The Rosenstiel School of Marine and Atmospheric Science, 1365 Memorial Drive, 210 Ungar Building, Coral Gables, FL 33146 USA.
[7] Present/permanent address: Delft University of Technology, Civil Engineering and Geosciences, Delft University of Technology, Delft, 2628CN, The Netherlands.

https://doi.org/10.1016/j.jenvman.2018.02.012
0301-4797/

## 1. Introduction

Beach water quality monitoring programs include sample collection and laboratory analysis to evaluate levels of fecal indicator bacteria (FIB). When the levels of FIB exceed a set threshold, beach advisories or closures are issued, as these exceedances could indicate a threat to public health. As a result of these programs, a database of long-term FIB monitoring data is created. These databases tend to grow over time resulting in an untapped resource for analysis.

One common goal of these monitoring programs is a desire to reduce the number of beach advisories by identifying and reducing FIB contributions. These sources of FIB to beaches include point sources, such as leaks from sanitary sewers and effluent from wastewater treatment plants. Non-point sources such as storm water runoff (Molina et al., 2014), and humans and animals that frequent beaches (Wright et al., 2009; Elmir et al. 2007, 2009; Converse et al., 2012; Sinigalliano et al., 2013) also contribute FIBs. One of the hypotheses underlying this study is that these sources of FIB, in particular non-point sources, can be controlled through beach management practices, thereby resulting in a reduction of beach advisories. Beach management is defined here as infrastructure and a sequence of policies that are implemented to maintain the recreational and ecological value of a beach.

The state of knowledge related to beach management practices and their influences on recreational water quality includes many major gaps. Studies such as Rippy et al. (2013), Russell et al. (2014), Wu and Jackson, 2016, Feng et al. (2016), and Donahue et al. (2017) have examined some of these issues, but focused on relationships between microbial water quality and physical, chemical, biological, and geomorphological factors. The influence of beach management practices and policies on water quality has not been comprehensively addressed.

Beach grooming studies are underrepresented (Nevers et al., 2016; Whitman et al., 2014; Kinzelman et al., 2003; Verhougstraete and Rose, 2014; Russell et al., 2014); studies that most closely relate to beach grooming, focus on sand erosion and issues of coastal zone management (Sutton-Grier et al., 2015). Studies of birds (Sinigalliano et al., 2013) and some on humans and dogs (Elmir et al., 2009; Wright et al., 2009) have been conducted, but the impact of wildlife and other domesticated animals on recreational water quality is unknown. FIB studies on vehicular traffic; facilities like restrooms and showers; concession stands; solid waste management; and fees to access the beach are not found in the literature. This represents many major gaps in knowledge. The issue of anthropogenic impact, modifications or uses that allow FIBs and pathogens to be introduced into the beach environments, and transport to the beach environment, has also not been well studied.

The primary objective of this study is to evaluate whether beaches characterized by a set of management policies are associated with lower FIB levels. This work is unique in that it evaluates the understudied areas to fill in some of the gaps and indicates areas of future work. It is innovative by classifying beaches based upon major geomorphological characteristics and then evaluating within these characteristics whether specific conditions and policies used to manage a beach were associated with improved water quality. Since beach management policies are in place for long periods of time, on the order of 10–20 years or more, this study used the entire period of record (15 years) to define a beach's overall average exceedance rate (percentage of time the beach FIB exceeds the regulatory thresholds). This study builds on the work of Feng et al. (2016) and Donahue et al. (2017), by examining the anthropogenic impact on beach water quality due to beach management practices. Earlier studies examined natural and man-made features. This study also evaluated the interaction of these features with new data on beach management practices.

## 2. Methods

To evaluate beach management policies, a large FIB database was consolidated, corresponding to the entire state of Florida as documented through the Florida Healthy Beaches Program (FHBP). Analysis included the establishment of inclusion criteria, which resulted in 316 beaches for evaluation. Beach type was identified based upon the method of Donahue et al. (2017). The FIB data for each beach were converted to a percent exceedance value to track the fraction of times that the beaches exceeded regulatory guidelines. A beach management survey was developed to collect data on management policies. The results were then compared to FIB data to determine which management condition corresponded to lower bacteria levels. The observed influence of beach morphology determined how each of the responses in the beach management survey were analyzed. For each question within the various categories, the data were analyzed in four groups, 1) all beaches for enterococci, 2) open coast beaches for enterococci, 3) all beaches for fecal coliform, and 4) open coast beaches for fecal coliform. Open coast beaches represented the vast majority of the beach types in Florida ($n = 211$). We also included questions about human and animal densities on a typical Sunday noon and Wednesday noon. Only the results for Sunday are discussed in this paper.

### 2.1. Analysis of data from the Florida Healthy Beaches Program (FHBP)

The FHBP (Florida Department of Health, 2016) was originally established in August 2000. Through this program FIB data have been collected and reported to the Florida Department of Health (FDOH), which is responsible for maintaining a statewide database. The total number of samples collected through the FHBP for the July 31, 2000 to December 31, 2015 period of record was 189,640 for enterococci and 153,805 for fecal coliform. For a beach to be included for analysis within the current study, the site had to have been included in the FHBP with a minimum of 120 samples during the 15-year period of record (2000-2015). The threshold of 120 was chosen after evaluating the continuity of the records for the beaches in the 100 to 400 sample range, and by also considering input from beach managers concerning their views about the permanency of sites in this range.

A total of 316 beaches from all 34 coastal counties (Fig. 1) met the criteria for inclusion. There were over 50 other sites with fewer than 120 samples and these data were excluded from our analyses. In some cases, extra exploratory samples were collected following a sample that exceeded the “poor” water quality threshold. In our study, we excluded these exploratory samples from the analysis to minimize bias due to extra sampling conducted during periods of high bacteria levels. After excluding the exploratory samples and data for sites with less than 120 samples, the total number of beach monitoring data points utilized for the analysis was 185,225 for enterococci and 151,000 for fecal coliform.

When issuing advisories, both the geometric mean and single sample maximums are considered. From 2000 until 2015, the FDOH has issued beach advisories or closures when single samples exceeded 104 colony forming units (CFU) per 100 ml for enterococci (See supplemental Table S1). Fecal coliform was also measured for beaches in Florida during the majority of the period of study. Fecal coliforms were recommended earlier by the EPA for both freshwater and saltwater (EPA, 2017). From August 2000 through June 2002, closures were issued at 800 CFU/100 mL. This was adjusted to 400 CFU/100 mL, which was in effect from July 2002 until June 2011. After June 2011, fecal coliform was dropped from sampling.

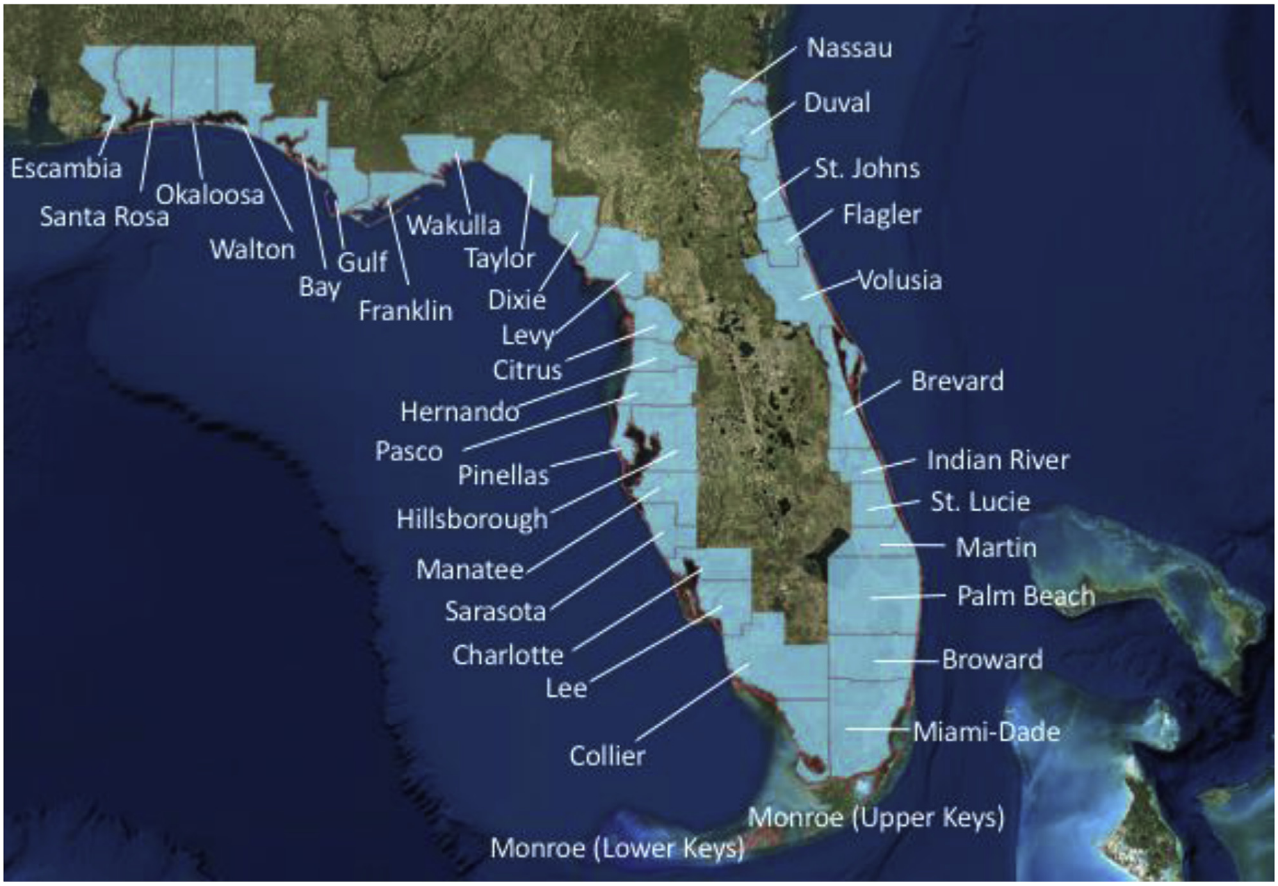


**Fig. 1.** Coastal Counties Participating in Florida Department of Health's Florida Healthy Beaches Program prior to 2011.

To obtain a measure of the frequency with which beaches are closed due to potential health risks, we converted the numerical measurements of colony forming units to percent exceedance based on the single-sample thresholds for issuing beach advisories. A threshold value of 104 CFU/100 ml was used for enterococci, which is consistent with the threshold value used by Florida beach managers throughout the 2000 to 2015 period of record evaluated in this study. A threshold value of 400 CFU/100 ml was used for fecal coliform which corresponded to the time period when the majority of the sample collection took place for these bacteria. For analyzing data on a county-by-county basis, the percent exceedance value for that entire county was aggregated using a weighted average based upon the number of samples collected at each beach within the county to compute a percent exceedance value for that county. On a beach basis, percent exceedance was computed for the entire period of record, providing one value per beach. The aggregation of the beach monitoring data was considered important for averaging out short-term and seasonal variabilities in FIB measures.

### 2.2. Beach management survey

The survey (copy in supplemental text) was designed with two parts. Part I focused on county-level information including sample collection, sample transportation, and laboratory analysis protocol. Part I was sent to the offices of all 34 Florida County Health Departments that participated in the FHBP during the period of record (2000-2015). During the process of distributing the survey, the team learned that sample collection was handled by various entities in Monroe County and as we received responses from both the Upper Keys and the Lower Keys in Monroe County, these responses were classified separately, giving a total of 35 counties surveys instead of 34 (Fig. 1). For county-level analyses, both the Upper and Lower Keys values were analyzed using the weighted average FIB data for Monroe County as a whole.

Part II covered items that were specific to each beach. The questions included in Part II addressed six categories. These categories included three that addressed sources of fecal indicators within the beach environment (e.g., human use, animal densities and control, and solid waste management). Additional categories included "grooming," focused on aspects that would alter the sediment distribution at the beach (such as seaweed densities, beach grooming policies, and beach renourishment), "beach access," focused on policies concerning fees charged and how the beach can be used (e.g., concessions at beach), and "drainage" which focused on impacts from sources outside the beach environment through storm water drainage and the sanitary infrastructure.

Upon receipt of the responses from the beach managers, they were entered into a master database. Of 316 beaches surveyed, responses were received for 301 beaches. For beaches that did not provide responses and were no farther than an hour's drive (4 beaches), members of the University of Miami team visited the beaches and recorded the responses that could be observed from field visits. This led to a total of 305 beaches with surveys completed (97%). Survey data were consolidated on a county-by-county basis and then sent back to the beach managers for that county asking that they review the responses for the entire county. Corrections to the responses were made in accordance to the second round of responses received from the beach managers.

### 2.3. Comparison of FIB data and beach survey results

FIB data were first evaluated spatially by plotting the data in ArcGIS. Once standardized, the survey data were then analyzed against the percent exceedance for enterococci and fecal coliform levels from the FHBP using the statistical analysis suite Statistical Analysis System (SAS)(SAS 9.4, SAS Institute, Cary, North Carolina). The survey responses were standardized into categories, usually "yes", "no," and "no answer" (indicating that the respondent left the response blank), although the open-ended questions required additional categories. For questions that could be divided into two groups, such as "yes" or "no," T-tests were performed, using the Satterthwaite method as the equality of variances is unknown and assumed to be unequal for our groups. For the open-ended questions, each answer was evaluated and assigned a code, an abbreviated version of the answer provided. Once these codes were developed for all responses to a question, some of the codes that were, for all intents and purposes, the same, were hybridized under new codes that reflected all of the similar answers. These questions were analyzed through ANOVA; the F-values are included in the tables and the p-values are in the text and in the tables. Similar to the way that a T-test indicates whether or not a single variable is statistically different, an F-test such as ANOVA indicates whether a group of variables are statistically different. The F-statistic approaches 1 when where there is no difference in variances among the groups; F-values closer to 1 tend to be accompanied by lower p-values. In this study, F-values greater than 1 and p-values less than 0.05 were considered significant.

### 2.4. Factor analysis and linear regression

Responses to the questions in the beach survey were analyzed within the six categories (human use, animal policies and control, solid waste management, grooming, beach access, and drainage). ANOVA and T-tests were performed, and the questions that demonstrated a significant effect on FIB levels were selected for further analysis. In each category, the responses to selected questions were assigned a numerical score based on whether the answer would be consistent with an increase or decrease in FIB. The responses were given a negative one if the practice would lower FIB levels, a zero if there was no response and the effect is not known, or a positive one if the practice described would increase FIB levels. These numbers were then averaged for the questions in each category. Once these categories were analyzed, all six scores plus a beach type score were analyzed together through SAS factor analysis to evaluate which had the greatest effect on enterococci and on fecal coliform. Since the identified six measures of beach management practices were autocorrelated, these measures cannot be assumed independent in the regression analysis. Therefore, factor analysis was conducted to collapse these beach measures into two factors, which accounted for most of the variance across these measures. Using linear regression, the effects of these factors was examined on both enterococci and fecal coliform. The coefficient of multiple determination ($R^2$) was evaluated to determine the proportion of variance in the exceedances explained by the model. The p-values were also used to determine which of the factors was the most significant.

## 3. Results

Results were organized into 1) beach-specific results, the beach type plus the six categories included in the surveys (human use, animal densities and control, solid waste management, grooming, beach access, and drainage), and 2) county-level results, which focused on sample collection, sample transport and laboratory methods. In order to consolidate the information presented, only the questions that had significant associations as determined from the factor analysis and regression are discussed in the main text of this paper. See the supplementary section for discussions about the remaining questions.

### 3.1. Beach classification

The spatial distribution of enterococci and fecal coliform percent exceedances for the period of record at each of the 316 beaches shows lower levels of FIB along the northeast coast of Florida and higher levels in bays (Fig. 2). With respect to the "Big Bend" area (Wakulla, Dixie, Levy, Citrus, Hernando, Taylor, and Pasco Counties), enterococci levels frequently exceeded the regulatory threshold. However, this same trend was not as emphasized when evaluating fecal coliform.

This spatial distribution is consistent with the beach classification scheme as described in Donahue et al., (2017), which defined six beach types in Florida based upon their geomorphology as observed from Google Earth imagery and given the wave energy designations of Tanner (1960) and Feng et al. (2016). These beach types included open coast, bay, inlet-channel situated, manmade-structure-protected, marsh surrounded, and back-reef beaches (See supplemental Figure S1 for categorization of beaches).

When the beach classifications were compared to the percent exceedances, certain beach types seemed to be associated with lower exceedance levels (Table 1). Enterococci percent exceedances for open coast beaches were statistically lower than for bay beaches, which in turn were statistically lower than marsh beaches. For fecal coliform, open coast beaches were statistically lower than marsh beaches, which, in turn, were statistically lower than man-made protected beaches. These results indicate that although open coast beaches are lowest in enterococci and fecal coliform exceedance, the relative exceedance between other types of beaches depends upon which FIB is chosen. Marsh beaches tend to fare worse under the enterococci threshold, whereas man-made-structure-protected beaches fare worse under the fecal coliform threshold.

### 3.2. Human use

Human use was examined through questions about the densities of visitors and presence of homeless populations. For enterococci, when considering all results, (Table 2), the "dense" category had the lowest exceedances, followed by "medium", "sparse," and then "zero" categories, which is the opposite of what would be expected if humans are considered sources. The observed trend, when considering all beaches, may be due to the fact that marsh beaches are more remote and tend to have lower human densities. The open coast beaches, as a whole, tend to have lower FIB levels, but have higher human densities on average, with beach managers at open coast beaches mostly reported dense or medium populations (240/267). Thirteen of 15 beach managers at marsh beaches reported medium to zero (6 medium, 6 sparse, 1 zero.)

To remove the impacts of geomorphologic factors (marsh beaches and bays), the associations of human densities were evaluated for "open coast" beaches only ($n = 211$). In this case, the expected trend was observed. The enterococci results in this case show that the "sparse" category had the lowest FIB exceedances (0.64%), followed by "medium" (1.34%) and "dense" (1.73%) category. The exceedances for open coast beaches were statistically different for "sparse" human density beaches relative to "dense" human density beaches ($p = 0.0011$). In this case, when the impacts of beach geomorphological features were removed by considering only open coast beaches, the impacts of human density were observable with

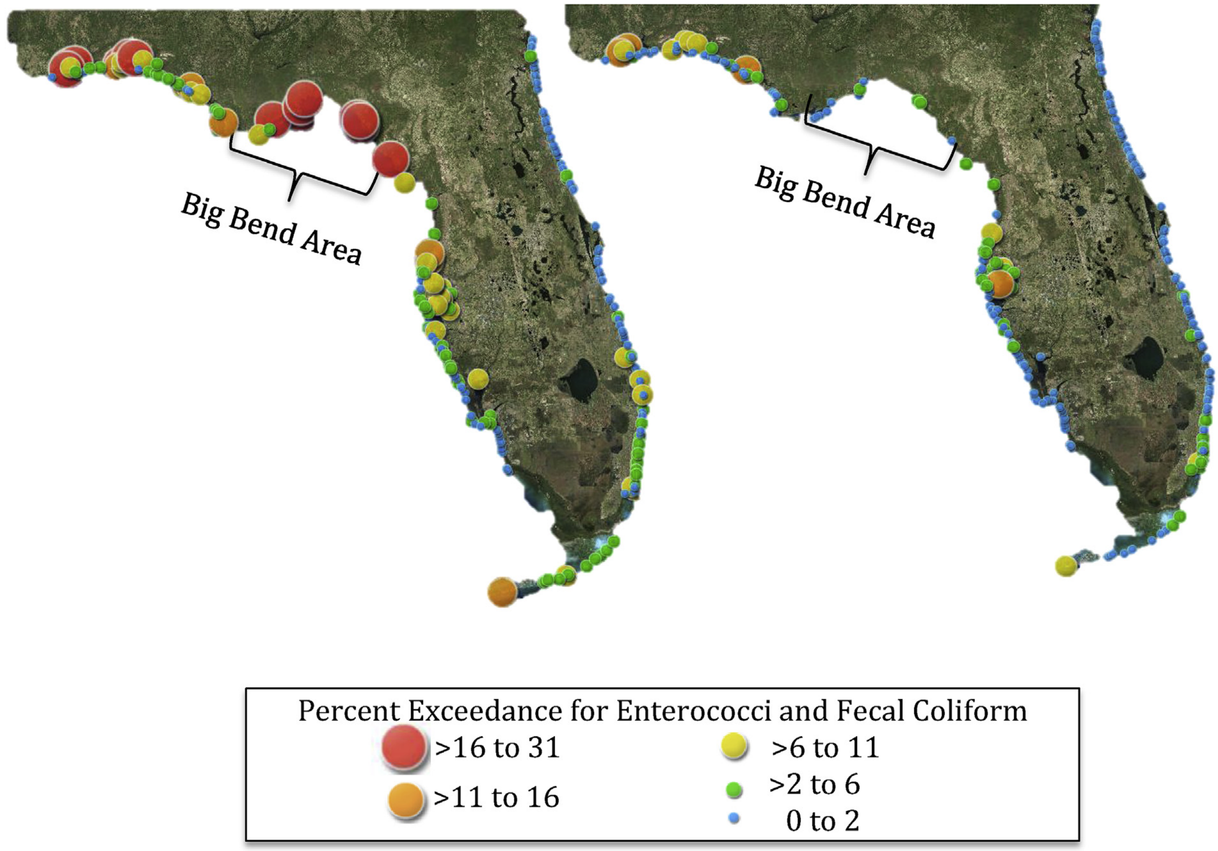


**Fig. 2.** (Left) Percent enterococci exceedances throughout Florida, 2000-2015; (Right) percent fecal coliform exceedances throughout Florida 2000–2011.

**Table 1**
Enterococci and fecal coliform percent exceedance statistics by beach type.

| Beach Type | ENT | | | | COL | | | |
|---|---|---|---|---|---|---|---|---|
| | Mean % Exceed. | Standard Dev | Range | Statistical Significance[a] | Mean % Exceed. | Standard Dev | Range | Statistical Significance[a] |
| Type 1, Open coast (n = 211) | 1.65 | 1.72 | 0.0–16.4 (16.4) | A | 0.64 | 1.03 | 0.00–5.25 (5.25) | A |
| Type 2, Bay (n = 72) | 6.87 | 5.33 | 0.0–25.2 (25.2) | B | 3.84 | 4.04 | 0.00–18.2 (18.2) | B, C, E |
| Type 3, Inlet-channel-situated (n = 3) | 3.54 | 1.60 | 1.69–4.59 (2.9) | A, B | 1.43 | 1.43 | 0.60–3.09 (2.49) | A, B, D |
| Type 4, Manmade-structure-protected (n = 5) | 6.46 | 5.52 | 1.17–12.9 (11.8) | B | 6.09 | 3.64 | 3.01–10.75 (7.74) | C, E |
| Type 5, Marsh-surrounded (n = 17) | 14.5 | 10.5 | 0.69–30.5 (29.8) | C | 2.94 | 1.60 | 1.00–7.14 (6.14) | D, E |
| Type 6, Back-reef (n = 8) | 3.50 | 2.02 | 0.65–7.51 (6.86) | A,B | 1.08 | 0.90 | 0.00–2.81 (2.81) | A, D |

[a] Beach types sharing the same letter are statistically not different.

beaches characterized by sparse human densities with lower enterococci exceedances relative to beaches with dense human densities.

For fecal coliform, similar trends were observed as for enterococci when evaluating all of the results, with lower percent exceedances for "dense" human densities and higher for "zero" human densities (Table 2). When evaluating open coast beaches only, the results showed a similar trend as for the enterococci, with lower fecal coliform exceedances for "sparse" beaches.

For the presence of homeless populations at the beach (Table 3), results for all groups (all responses, open coast, enterococci and fecal coliform), demonstrate that beaches that reported no homeless populations had lower FIB than those that had homeless populations. The difference in FIB levels was significant for 3 of the groups: fecal coliform in the "all responses" group, and both enterococci and fecal coliform in the "open coast" group (Table 3).

Overall, results suggested that the lack of humans is generally associated with lower FIB levels. This was evident for beaches that reported no homeless populations. With respect to beach visitors, the impact of human densities was observed only when evaluating open coast beaches. Beach geomorphology appears to overwhelm the influence of human densities such that these trends were only observed when disaggregating the data by beach type. For open coast beaches, enterococci exceedances were lower for beaches

**Table 2**
Statistics of enterococci and fecal coliform percent exceedances survey responses for questions related to density of humans, dogs, birds, and seaweed. ALL = all responses; OC = open coast beaches only.

| Question | Mean % Exceed | | Mean % Exceed | | Mean % Exceed | | Mean % Exceed | | Mean % Exceed | | Statistics |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Dense | n | Medium | n | Sparse | n | Zero | n | No Response | n | |
| **Human Density at Noon Sunday** | | | | | | | | | | | |
| Enterococci | | | | | | | | | | | |
| ALL | 2.07 | 104 | 3.94 | 136 | 7.54 | 26 | 9.46 | 1 | 4.18 | 49 | F = 7.40 p=<0.001 |
| OC | 1.73 | 89 | 1.34 | 77 | 0.64 | 14 | N/A | 0 | 2.19 | 31 | F = 5.58 p = 0.0011 |
| Fecal coliform | | | | | | | | | | | |
| ALL | 0.90 | 104 | 1.89 | 136 | 1.35 | 26 | 2.45 | 1 | 2.40 | 49 | F = 3.59 p = 0.007 |
| OC | 0.79 | 89 | 0.45 | 77 | 0.18 | 14 | 0.00 | 0 | 0.93 | 31 | F = 3.36 p = 0.020 |
| **Dog Density** | | | | | | | | | | | |
| Enterococci | | | | | | | | | | | |
| ALL | 7.51 | 1 | 4.00 | 54 | 4.96 | 81 | 2.77 | 147 | 3.91 | 33 | F = 2.72 p = 0.030 |
| OC | 0.00 | 0 | 1.85 | 34 | 1.31 | 50 | 1.58 | 107 | 1.82 | 20 | F = 1.25 p = 0.291 |
| Fecal coliform | | | | | | | | | | | |
| ALL | 2.01 | 1 | 1.90 | 54 | 1.52 | 81 | 1.44 | 147 | 2.04 | 33 | F = 0.57 p = 0.681 |
| OC | 0.00 | 0 | 0.66 | 34 | 0.46 | 50 | 0.76 | 107 | 0.47 | 20 | F = 1.21 p = 0.309 |
| **Bird Density** | | | | | | | | | | | |
| Enterococci | | | | | | | | | | | |
| ALL | 3.94 | 55 | 3.53 | 127 | 3.24 | 86 | 1.61 | 2 | 4.68 | 46 | F = 0.74 p = 0.564 |
| OC | 2.50 | 39 | 1.34 | 91 | 1.31 | 54 | 0.20 | 1 | 2.25 | 26 | F = 0.82 p = 0.514 |
| Fecal coliform | | | | | | | | | | | |
| ALL | 1.20 | 55 | 1.29 | 127 | 1.91 | 86 | 1.64 | 2 | 2.36 | 46 | F = 2.02 p = 0.091 |
| OC | 0.48 | 39 | 0.59 | 91 | 0.76 | 54 | 0.20 | 1 | 0.86 | 26 | F = 0.82 p = 0.514 |
| **Seaweed Density** | | | | | | | | | | | |
| Enterococci | | | | | | | | | | | |
| ALL | 7.35 | 44 | 2.95 | 118 | 3.08 | 84 | 3.22 | 31 | 3.39 | 39 | F = 7.19 p=<0.0001 |
| OC | 3.76 | 20 | 1.54 | 85 | 1.80 | 57 | 0.43 | 25 | 1.22 | 24 | F = 13.98 p=<0.0001 |
| Fecal coliform | | | | | | | | | | | |
| ALL | 2.26 | 44 | 1.48 | 118 | 1.37 | 84 | 1.60 | 31 | 1.74 | 39 | F = 2.97 p = 0.0205 |
| OC | 0.91 | 20 | 0.78 | 85 | 0.65 | 57 | 0.05 | 25 | 0.53 | 24 | F = 2.97 p = 0.0205 |

with sparse human densities relative to beaches with high human densities.

### 3.3. Animal densities and control

Animal densities were evaluated in separate categories determined by the type of animal (dogs, other domestic animals, birds, and wildlife other than birds). From these categories, the densities were evaluated in much the same way as human use. In subsequent sections, an emphasis is placed on discussing the results concerning dog and bird densities and policies for control.

#### 3.3.1. Dogs

The first question in this series asked if dogs were allowed at the beach. Survey results indicated that among the responses 68% of the beaches do not allow dogs to visit. Results (Table 3) show statistically lower levels of FIBs (3.19% not allowed; 4.71% where allowed) for enterococci for beaches that do not allow dogs when all beaches were considered ($p = 0.037$). No statistical differences were observed for the other categories.

For dog densities, results (Table 2) show that the enterococci percent exceedance for “all responses” demonstrated that the “zero” category had the lowest (2.77%) and increased with “sparse” (4.96%) “medium” (4.00%) and “dense” (7.51%) dog densities. Only the sparse and zero categories were statistically different (“sparse” 4.96%, “zero” 2.77%, $p = 0.030$). For the 211 open coast beaches, none of the responses for open coast beaches were statistically different for enterococci.

For fecal coliform, the “all responses” sections were very similar to the enterococci, with “zero” as the lowest, then “sparse”, “medium”, and then “dense” as the highest percent exceedance. However, due to the very low levels of exceedances for fecal coliform limiting the range in values, none of the fecal coliform percent exceedances were statistically different.

We then followed up with questions on the policies for dogs at the beach and how this was addressed. There were questions on signage, and whether or not bags were provided. Of these questions, only one (signage and enterococci levels at open-coast beaches) showed statistical differences in FIB exceedances (Table 3) between beaches with and without signage.

Overall, results showed consistently that lower dog densities appear to be associated with lower FIB exceedances, and that policies that address dog waste (address/do not address, signage for dog waste disposal, availability of dog waste bags) are also associated with lower FIB exceedances. However, the FIB exceedances among the different categories evaluated were not always statistically significant. These results provide some evidence of the benefits of minimizing dog waste, although the evidence can be considered weak due to lack of statistical differences among the various groupings.

#### 3.3.2. Birds

Survey results indicate that a vast majority of the beaches in Florida (99%) are visited by birds. Statistical differences were observed between beaches with birds versus those without bird visits only when all responses were considered for enterococci. Here beaches where birds visit ($n = 285$) had statistically significantly higher percent exceedances (3.63%) relative to beaches that did not ($n = 3$, 3.34%) (Table 3). The birds observed at the beaches were most commonly gulls. More details about the distribution of bird species is provided in the supplemental text. With respect to the density of birds, open coast beaches (Table 2) demonstrated decreased percent exceedances for enterococci where there were fewer birds.

We then asked if the birds gather in specific areas of the beach. Results (Table 3) show that when all beaches were considered both enterococci and fecal coliform exceedances were statistically different for beaches where birds gather (1.97% for enterococci and

**Table 3**
Statistics for enterococci and fecal coliform percent exceedances for select survey questions associated with human use and animal density and control questions.

| Question | All Responses | | | | | Open Coast | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Yes | n | No | n | p value | Yes | n | No | n | p value |
| **Human Use** | | | | | | | | | | |
| Homeless Present | | | | | | | | | | |
| Enterococci | 4.21 | 39 | 3.45 | 239 | 0.237 | 2.35 | 23 | 1.49 | 165 | 0.036 |
| Fecal coliform | 2.58 | 39 | 1.26 | 239 | 0.007 | 1.22 | 23 | 0.49 | 165 | 0.027 |
| **Animal Densities and Control** | | | | | | | | | | |
| Dogs Allowed | | | | | | | | | | |
| Enterococci | 4.71 | 94 | 3.19 | 198 | 0.037 | 2.09 | 61 | 1.58 | 137 | 0.123 |
| Fecal coliform | 1.64 | 94 | 1.53 | 198 | 0.723 | 0.54 | 61 | 0.74 | 137 | 0.174 |
| Dogs Visit Anyway | | | | | | | | | | |
| Enterococci | 3.43 | 120 | 3.29 | 88 | 0.817 | 1.85 | 83 | 1.51 | 61 | 0.167 |
| Fecal coliform | 1.65 | 120 | 1.83 | 88 | 0.640 | 0.96 | 83 | 0.67 | 61 | 0.150 |
| Dog Policies/Address Dogs | | | | | | | | | | |
| Enterococci | 2.57 | 155 | 4.11 | 25 | 0.055 | 1.65 | 119 | 2.14 | 13 | 0.258 |
| Fecal coliform | 1.17 | 155 | 2.31 | 25 | 0.098 | 0.69 | 119 | 1.28 | 13 | 0.127 |
| Dog Signage | | | | | | | | | | |
| Enterococci | 3.75 | 125 | 4.15 | 85 | 0.632 | 1.98 | 82 | 1.25 | 55 | 0.018 |
| Fecal coliform | 1.73 | 125 | 1.37 | 85 | 0.248 | 0.65 | 82 | 0.73 | 55 | 0.695 |
| Bags Available | | | | | | | | | | |
| Enterococci | 4.24 | 98 | 3.58 | 109 | 0.386 | 2.05 | 56 | 1.40 | 78 | 0.074 |
| Fecal coliform | 1.87 | 98 | 1.24 | 109 | 0.058 | 0.63 | 56 | 0.67 | 78 | 0.812 |
| Birds Visit | | | | | | | | | | |
| Enterococci | 3.63 | 285 | 3.34 | 3 | 0.0319 | 1.63 | 194 | 2.23 | 3 | 0.2511 |
| Fecal coliform | 1.54 | 285 | 1.14 | 3 | 0.1274 | 0.66 | 194 | 1.14 | 3 | 0.0871 |
| Birds Gather In Specific Areas | | | | | | | | | | |
| Enterococci | 1.97 | 127 | 5.40 | 55 | <0.001 | 1.17 | 103 | 2.25 | 29 | 0.080 |
| Fecal coliform | 0.89 | 127 | 2.32 | 55 | 0.009 | 0.38 | 103 | 0.42 | 29 | 0.761 |
| Bird Policies | | | | | | | | | | |
| Enterococci | 2.07 | 59 | 4.12 | 211 | <0.001 | 0.90 | 41 | 1.69 | 138 | <0.001 |
| Fecal coliform | 0.74 | 59 | 1.72 | 211 | <0.001 | 0.25 | 41 | 1.62 | 138 | <0.001 |

0.89% for fecal coliform) versus beaches where they do not (5.40% for enterococci (ENT) and 2.32% for fecal coliform (COL)) (p=<0.001 ENT; 0.009 COL).

We then asked if there were policies for management of birds at the beaches. There was a significant difference between beaches that have policies in comparison to those that do not, for all four categories evaluated. Those with policies were characterized by statistically lower FIB exceedances (Table 3) in comparison to those that do not have policies for managing birds (p =< 0.002 for all categories).

Overall, results showed that lower enterococci exceedances are associated with lower numbers of birds. The answers to our open-ended questions provide interesting insight into how birds behave at the beach, and the sorts of policies designed around birds at the beach. For example, while survey respondents stated that birds may contribute to FIB levels at their specific beaches, most policies are designed to protect the birds, without consideration of FIB levels. Low exceedances are associated with beaches that have policies that address birds regardless of whether the policies address nuisance birds or the protection of birds.

### 3.4. Solid waste management

Among the 301 responses to our question on whether or not trash cans are available to visitors, the vast majority reported trash cans on the beach (96%), with smaller proportions reporting trash cans nearby (2%) or reporting no trash cans (2%). Results show that beaches with solid waste disposal facilities had statistically higher exceedances for enterococci (3.34%) than those that did not (0.68%, p=<0.001). Fecal coliform results were similar, and the open coast beach results also followed this pattern. No statistical differences were observed between beaches reporting covered trash cans ($n = 150$) versus beaches reporting uncovered trash cans ($n = 126$) (Table 4).

Most beaches have trash cans. The availability of trash cans appears to be associated with FIB; beaches that have trash cans have higher FIB levels. About half of the trash cans at beaches are covered and the other half are uncovered. Distinct trends were not observed with the frequency of trash collection.

### 3.5. Grooming

This section addresses seaweed, beach grooming, and renourishment policies. The first series of questions focused on seaweed. We asked about the density of the seaweed present at the beaches. Among the respondents, 11% reported zero seaweed, 30% reported sparse, 43% reported medium, and 16% reported dense. Significant differences were seen for enterococci when all beaches and open coast beaches were considered. For “all responses” enterococci, statistical differences in exceedance were observed between the “dense” category (7.35%) and all of the others (<3.4%, $p < 0.001$). The “open coast” enterococci also showed significant differences between “dense” (3.76%) and all of the other groups (<1.8%, $p < 0.001$), as well as between “sparse” and “zero,” and “medium” and “zero.” For fecal coliform, the “all responses” data showed no significant differences. The open coast fecal coliform data showed significant differences between the “medium” and “zero” categories (Table 2). This, along with the general trend of lower exceedances toward the sparse/zero end and higher exceedances in the dense/medium end, suggests an association between the amount of seaweed on the beaches and FIB levels in the water, with enterococci showing a stronger response relative to fecal coliform.

We then asked if part of the grooming protocol is designed to address seaweed (Table 4). There were no significant differences among any of the “all responses” categories. In the “open coast” section, both the enterococci (“yes” 2.14%; “no” 0.97%, p=<0.001) and the fecal coliform (“yes” 1.15%; “no” 0.21%, p=<0.001) means were statistically different, demonstrating that the “no” group was

**Table 4**
Statistics of enterococci and fecal coliform percent exceedances when compared to beach management survey responses for solid waste management and grooming questions.

| Question | All Responses | | | | | Open Coast | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Yes | n | No | n | p value | Yes | n | No | n | p value |
| With Trash Cans | | | | | | | | | | |
| Enterococci | 3.34 | 290 | 0.68 | 5 | <0.001 | 1.71 | 200 | 0.43 | 4 | <0.001 |
| Fecal coliform | 1.56 | 290 | 0.48 | 5 | 0.001 | 0.66 | 200 | 0.31 | 4 | 0.071 |
| Covered Trash Cans | | | | | | | | | | |
| Enterococci | 3.55 | 150 | 3.56 | 126 | 0.984 | 1.99 | 93 | 1.57 | 96 | 0.106 |
| Fecal coliform | 1.69 | 150 | 1.44 | 126 | 0.431 | 0.64 | 93 | 0.74 | 96 | 0.524 |
| Grooming Protocol Addresses Seaweed | | | | | | | | | | |
| Enterococci | 3.53 | 114 | 4.02 | 106 | .517 | 2.14 | 76 | 0.97 | 73 | <.0001 |
| Fecal coliform | 1.95 | 114 | 1.27 | 106 | .048 | 1.15 | 76 | 0.21 | 73 | <.0001 |
| Sand Renourished | | | | | | | | | | |
| Enterococci | 2.86 | 163 | 4.76 | 101 | 0.011 | 1.29 | 120 | 1.39 | 53 | 0.618 |
| Fecal coliform | 1.35 | 163 | 1.99 | 101 | 0.079 | 0.51 | 120 | 0.59 | 53 | 0.583 |

the lowest (Table 4). This could possibly indicate that disturbing the seaweed causes an increase in FIB levels. Future work would be very beneficial in understanding the relationship between FIBs in the water and beach grooming policies involving seaweed.

Our next question focused on beach renourishment, the addition of sand to the beach. We first asked if the beaches have been renourished. In all cases, the "no" category had higher FIB exceedances. There was a significant difference ($p = 0.011$) between "yes" (2.86%) and "no" (4.76%) in the "all results" enterococci section, but none in the fecal coliform section ($p = 0.079$), as seen in the t-tests (Table 4).

Overall, results showed that amounts of seaweed, grooming, and renourishment have an association with FIB exceedances. Beaches with naturally lower amounts of seaweed had lower instances of FIB exceedances, while removal of seaweed at beaches was associated with an increase in FIB exceedances. Beaches that were renourished demonstrate lower FIB exceedances.

### 3.6. Beach access and use

This section considered beach access, and the ways in which the beaches are used. Policies concerning beach use included 1) maintenance vehicles on the beach, 2) fees to access the beach, 3) lifeguards, and 4) marinas near the beach. All of the factors listed here are related to economics: if an agency that manages the beach charges fees for access, that agency then has funding to pay for lifeguards and maintenance vehicles. Funding can also be provided through amenities such as concession stands and marinas.

We examined whether or not vehicles for maintenance purposes are permitted on the beach (Table 5). The "all responses" enterococci section showed significantly lower FIB exceedances for the "yes" category, (2.95%) but the "open coast" group had lower FIB exceedances in the "no" category (1.30%) ($p = 0.181$). Overall, mixed results were obtained for this question.

We asked if there was a fee that visitors must pay to access the beach (Table 5). Among the respondents, 31% of the beaches require fees. In all of the categories, beaches where visitors had to pay for access (all responses 2.47% ENT, 0.98% COL; open coast 1.29% ENT; 0.49% COL) were associated with lower FIB levels in comparison to those without fees (all responses 4.11% ENT, 1.76% COL; open coast 1.86% ENT; 0.72% COL) (Table 5). Significant differences were seen in three of the four categories evaluated ($p = 0.001$ all responses ENT; 0.002 all responses COL; 0.012 open coast ENT) with the exception of fecal coliform at open coast beaches ($p = 0.115$).

We then asked if there are lifeguards at the beach. Among the respondents, 53% reported lifeguards. Significant differences were seen between "yes" and "no" responses for three of four categories evaluated with both FIB in the all responses category showing statistically lower FIB for beaches with lifeguards ($p < 0.003$) and for enterococci in the open coast group ($p = 0.02$).

We then asked if there are marinas near the beaches. On average, the percent exceedance for the "no" category was lower than the "yes" category in every group (Table 5). These differences were statistically significant for three of the four categories (all responses ENT $p = 0.0007$, all responses COL $p = < 0.0001$, open coast COL $p = 0.017$).

These responses revealed many different policies for beach use and access. These policies varied by beach; some of them have greater impact on the beach environment than others, especially those associated with funding, such as fees for access. These fees allow for the presence of lifeguards, which is generally associated with lower FIB. Nearby marinas, although a source of funding, appear to be associated with higher levels of FIB.

### 3.7. Drainage and sanitary infrastructure

This section considers the associations between storm drainage and sanitary infrastructure and FIB levels (Table 6). Our first question asked how storm water is managed at the beaches. We divided the answers into two categories, one where storm water was managed by transporting it away from the beach, retaining it, use of subsurface disposal, or avoiding paved areas at the beach, and another where there is no attempt to manage storm water. For enterococci, results show that the "yes" group was associated with lower exceedances (2.97%) relative to the "no" category (5.15%) in the "all responses" group ($p < 0.038$); for fecal coliform exceedances were lower as well (2.47% for "yes" and 3.13% for "no", $p = 0.281$), but the differences were not statistically significant. Differences were not statistically significant when evaluating the storm water management at "open coast" beaches ($p = 0.81$ ENT and $p = 0.94$ COL).

The next series of questions focused on potential sources of sewage. The first question in this group asked whether or not there were public restroom facilities at the beaches. The only significant differences (Table 6) were observed among the fecal coliform data, with the "yes" category showing lower fecal coliform percent exceedance (1.38% for all responses and 0.56% for open coast) in comparison to the "no" category (2.62%, $p = 0.057$ for all responses, 1.30%, $p = 0.012$ for open coast beaches). Of interest was that enterococci percent exceedances were not associated with the presence of public restrooms, suggesting that fecal coliform may respond more strongly to the presence of restroom facilities in comparison to enterococci.

We then asked if the restroom facilities are open overnight. There were significant differences in all of the categories, with the "yes" response lower than "no" in three of the four analyses. Here,

**Table 5**
Statistics for enterococci and fecal coliform percent exceedances for select survey questions associated with beach access and use.

| Question | All Responses | | | | | Open Coast | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Yes | n | No | n | p value | Yes | n | No | n | p value |
| Maintenance Vehicles on Beach | | | | | | | | | | |
| Enterococci | 2.95 | 251 | 7.10 | 47 | 0.005 | 1.73 | 183 | 1.30 | 20 | 0.181 |
| Fecal coliform | 1.43 | 251 | 2.03 | 47 | 0.251 | 0.69 | 183 | 0.36 | 20 | 0.049 |
| Charge Fees | | | | | | | | | | |
| Enterococci | 2.47 | 92 | 4.11 | 206 | 0.001 | 1.29 | 64 | 1.86 | 139 | 0.012 |
| Fecal coliform | 0.98 | 92 | 1.76 | 206 | 0.002 | 0.49 | 64 | 0.72 | 139 | 0.115 |
| Lifeguards | | | | | | | | | | |
| Enterococci | 2.14 | 157 | 4.69 | 69 | <0.001 | 1.43 | 137 | 2.16 | 28 | 0.017 |
| Fecal coliform | 1.08 | 157 | 1.98 | 69 | 0.002 | 0.65 | 137 | 0.68 | 28 | 0.800 |
| Marinas Near Beach | | | | | | | | | | |
| Enterococci | 4.11 | 108 | 2.29 | 112 | <0.001 | 1.76 | 64 | 1.50 | 91 | 0.368 |
| Fecal coliform | 2.28 | 108 | 0.75 | 112 | <0.001 | 0.78 | 64 | 0.35 | 91 | 0.017 |

**Table 6**
Statistics for enterococci and fecal coliform percent exceedances for select survey questions associated with drainage and sanitary infrastructure.

| Question | All Responses | | | | | Open Coast | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Yes | n | No | n | p value | Yes | n | No | n | p value |
| Storm Water Management | | | | | | | | | | |
| Enterococci | 2.97 | 141 | 5.15 | 62 | 0.038 | 1.43 | 101 | 1.37 | 39 | 0.811 |
| Fecal coliform | 2.47 | 141 | 3.13 | 62 | 0.281 | 0.53 | 101 | 0.52 | 39 | 0.937 |
| Public Restrooms | | | | | | | | | | |
| Enterococci | 3.57 | 261 | 3.89 | 38 | 0.701 | 1.64 | 177 | 1.94 | 27 | 0.345 |
| Fecal coliform | 1.38 | 261 | 2.62 | 38 | 0.057 | 0.56 | 177 | 1.30 | 27 | 0.012 |
| Public Restroom Open Overnight | | | | | | | | | | |
| Enterococci | 3.03 | 238 | 3.22 | 57 | 0.015 | 1.25 | 54 | 1.65 | 79 | 0.273 |
| Fecal coliform | 1.27 | 238 | 1.60 | 57 | 0.010 | 0.160 | 54 | 0.72 | 79 | <0.001 |
| Public Shower/Rinsing Facilities | | | | | | | | | | |
| Enterococci | 3.13 | 238 | 5.83 | 57 | 0.015 | 1.79 | 170 | 1.15 | 30 | 0.017 |
| Fecal coliform | 1.27 | 238 | 2.73 | 57 | 0.010 | 0.66 | 170 | 0.66 | 30 | 0.996 |

low fecal coliform levels appeared to be associated with restroom facilities open overnight ($p = 0.010$ for all beaches, $p = <0.001$ for open coast beaches). Lower enterococci percent exceedances were also associated with restroom facilities open overnight ($p = 0.015$) when all of the beaches were considered (Table 6).

We then asked if there were public shower or rinsing facilities at the beaches. Significant differences in percent exceedances ($p < 0.02$) were present for the "all responses" groups; analyses showed that the "yes" category had lower exceedances (3.13% for enterococci and 1.27% for fecal coliform) than those in the "no" category (5.83% for enterococci and 2.73% for fecal coliform). Statistical differences were observed for enterococci only in the open coast group (Table 6).

This section demonstrates the associations that drainage and sanitary infrastructure may have with FIB levels at recreational beaches. Attempts to manage storm water were associated with lower FIB levels in the "all responses" categories. Beaches with amenities such as public restrooms demonstrated lower FIB levels, specifically fecal coliform. Beaches with public shower and rinsing facilities also demonstrated lower FIB levels, but the only statistical differences were observed for enterococci levels in the open coast group.

### 3.8. Factor analysis and linear regression

The factor analysis of the seven aggregated beach management measures with orthogonal rotation identified two dominant factors. In Factor 1, the drainage score and the numbers of humans score made up the highest proportion; in Factor 2, the beach type score, grooming score, and beach access score made up the highest proportion. With these factors, a linear regression was performed for both enterococci and fecal coliform. Our model resulted in an R-square of 0.300 for enterococci, meaning that it explained about 30% of the exceedances. Both Factor 1 (coefficient of 1.30, p-value 0.0002) and Factor 2 (coefficient of 4.23, p-value <0.0001) were significant. For fecal coliform, the R-square was 0.155, demonstrating that it explained about 15%. Factor 1 (coefficient of 0.003, p-value of 0.1) was marginally significant; Factor 2 (coefficient of 1.55, p-value <0.0001) was significant. These results indicate that categories associated with Factor 2 (beach type, grooming, and beach access) were the most significant.

### 3.9. County-level sampling and analysis policies

County-level data for the 34 counties in this study focused on assessing associations between FIB and sampling policies (collection time, holding time, day of week sampled, sampling depth, method of transporting/storing samples) and sample laboratory analysis (laboratory method versus type of lab). The 34-county dataset resulted in a total of 35 surveys, due to a split in Monroe County.

For sampling policies, no associations were found with day of the week (23 counties sample on Monday, 6 on Tuesday, 2 on both Monday and Tuesday, and 4 on Wednesday, Supplemental Table S6), sampling depth (knee depth, $n = 16$; waist depth, $n = 17$; knee to waist deep $n = 1$; thigh-deep, $n = 1$, Supplemental Table S7), or cooling method (ice packs, $n = 15$ versus wet ice, $n = 20$, Supplemental Table S8). Holding time (split into more than 2 h, $n = 33$ or 2 h or fewer, $n = 2$) also did not appear to be associated with FIB levels ($p = 0.28$, Supplemental Table S8). For sampling time (Supplemental Table S8), the responses were divided into samples collected at noon or earlier, and those collected after noon.

The percent exceedance means were not statistically different ($p = 0.261$) for enterococci (noon or before $n = 31$, percent exceedance 4.12; after noon $n = 2$, percent exceedance 13.1) and did not vary as much for fecal coliform (noon or before 1.58%; after noon 1.32%).

With respect to the analysis methods, differences were not statistically different between the type of lab used (government, $n = 19$ versus private, $n = 13$, $p = 0.108$. Three responded "other" and were not included in the *t*-test). With respect to the laboratory methods used (Supplemental Table S8), enterococci were analyzed by two different methods: membrane filtration (MF) (EPA method 1600 (EPA, 2009), $n = 29$) or chromogenic substrate (Enterolert™, $n = 6$). Fecal coliform was analyzed by MF only. The only statistically significant differences observed for the county-level sample collection and analysis data is in the method of analyses, with laboratories using chromogenic substrate reporting lower enterococci relative to laboratories using MF techniques (6.01% exceedance for laboratories that use MF versus 2.04% laboratories that use chromogenic substrate, $p = 0.008$). This difference is present ($p = 0.05$) even when the "Big Bend" counties (Wakulla, Dixie, Levy, Citrus, Hernando, Taylor, and Pasco) were removed (EPA method 1600 3.37%; Enterolert™ 2.04%)

Overall, the only question that demonstrated significant difference was in the type of analysis method used.

## 4. Discussion

Our study revealed insights into beaches with lower FIB exceedances through investigation of beaches of different geomorphological type, beach management policies, and water sampling and analysis procedures. Specifically, our beach management survey provided a wealth of information that was previously unavailable on the association between FIB levels and human, dog, and bird densities as well as the ways in which the beach is used, including amenities.

This work also revealed novel information on differences in beach geomorphology throughout the state and the association with these differences and FIB exceedances. Protected beaches, such as bay or marsh beaches, demonstrated higher FIB exceedance, which is similar to the higher FIB levels seen in embayed beaches in Byappanahalli et al. (2015). Overall, we found that open coast beaches were characterized by low percent exceedances relative to other beach types. This was consistent when both enterococci and fecal coliform were used as indicators. However, for other beach types, in particular marsh beaches, the indicator chosen gave significantly different results, with marsh beaches showing much higher percent exceedances for enterococci (14.5%) than for fecal coliform (2.9%) ($p < 0.001$).

The different percent exceedances observed for marsh beaches calls into question about which FIB is a stronger indicator of possible public health issues. We found that the switch from a fecal coliform to an enterococci standard resulted in major impacts on the computed percent exceedance for marsh beaches, with percent exceedance increasing by a factor of five (from 2.9% to 14.5%). High enterococci and fecal coliform percent exceedances were associated with different questions in our study. The results of this study suggest that fecal coliform may be more strongly associated with human fecal sources due to stronger relationships with human impact, such as the presence of human visitors (including homeless populations), and lack of restroom facilities at the beach. Responses related to the sources of human fecal waste showed relationships with low fecal coliform exceedances, such as the availability of public restroom facilities, as in Korajkic et al., (2010), and if the restroom facilities are open overnight.

Enterococci percent exceedances appear to be more strongly associated with animals (dogs and birds) and environmental sources (seaweed, sand renourishment). In Florida, the change of FIB indicator to enterococci resulted in a higher frequency of beach closures at marsh beaches; these closures may be a result of higher wildlife influences at these beaches as opposed to human influences. Microbial source tracking studies designed to identify the sources of enterococci and fecal coliform (Shanks et al., 2012; Sinigalliano et al., 2010; Brooks et al., 2016; Griffin et al., 2001) to marsh beaches are highly recommended to further explore the hypothesis that enterococci are more sensitive to environmental sources.

When these factors were selected through factor analysis, the results were similar to those observed from T-tests. Drainage and the number of humans made up the highest proportions of Factor 1; Factor 2, was made up of beach type, grooming, and beach access. Our overall analysis revealed that Factor 2 (beach type, grooming, beach access) had the most significant effects on both the enterococci and fecal coliform score. Factor 1 was significant only for enterococci. These results demonstrate once again that enterococci and fecal coliform may not indicate the same sources.

Our study of beach management policies revealed that both enterococci and fecal coliform exceedances were shown to be lower for beaches with fewer humans, dogs, and birds. Our analysis showed that beaches without homeless populations had lower FIB. For open coast beaches, lower enterococci were associated with beaches that had lower densities of human visitors. Similarly, beaches with low densities of dogs and low densities of birds were associated with lower FIB levels. Our results showed that FIB levels were lowest at beaches where dogs were not allowed and at beaches with policies for addressing dog waste; results on birds were similar, showing that beaches with policies for birds were associated with lower FIB levels. Low densities of dogs and birds, as indicated in studies such as Ervin et al. (2013), demonstrated lower FIB levels. Our results are consistent with studies that quantify the contribution of FIB by humans and animals to beach sites. For example, Elmir et al. (2009) estimated that bathers shed $1.8 \times 10^4$ to $2.8 \times 10^6$ CFU per 15-min swim. Wright et al. (2009) quantified the amount of FIB released per dog fecal event at a beach that allows dogs, attributing dogs as the major source. Studies documenting the contribution of birds to FIB at beaches (Oshiro and Fujioka, 1995; Edge et al., 2010; Riedel et al., 2015) suggested that birds can also be major contributors. This correlates with many studies on birds, particularly gulls, and increased enterococci levels (Converse et al., 2012; Sinigalliano et al., 2013).

Our analysis of beach access and beach use revealed that beaches where seaweed levels are low, those that are renourished, charge fees to access the beach, have lifeguards ("all responses" only), or lack nearby marinas ("all responses" only), have lower FIB levels. These results echo the results of studies on seaweed (Byappanahalli et al., 2015; Imamura et al., 2011), with similar findings. Seaweed densities were associated with enterococci exceedances (as seen in Quilliam et al., 2014), while grooming of beach sand showed relationships to both enterococci and fecal coliform. Beach renourishment was also associated with lower levels of enterococci, as in Hernandez et al., (2014), but this association was not seen in fecal coliform. We found that some beach management policies may be incompatible with maintaining low FIB levels at the beaches, such as grooming designed to address seaweed. Beaches with naturally low levels of seaweed had lower FIB levels; higher levels of beach wrack had higher FIB levels, as demonstrated in Nevers et al. (2016). Studies of the contributions of beach sand, as in Whitman et al. (2014) and the associations with grooming have demonstrated that specific grooming practices allowed for lower levels of *E. coli* at Great Lakes beaches (Kinzelman et al., 2003; Verhougstraete and Rose, 2014). Russell et al. (2014)

found results similar to ours, in which "beach grooming was generally associated with either no change or a slightly increase in coastal FIB concentrations." Increased concentrations due to grooming were also found in a study of beaches in York, Maine (Jones and Kaczor, 2017). Future work on Florida beaches could follow similar approaches, to understand the effects of these grooming practices on enterococci and fecal coliform. Of specific interest would be to evaluate grooming and wrack disposal methods, as the survey indicated that different methods of disposal are used, including placement around vegetation, burial at the beach, or collection and disposal via trash (see Supplemental text for details). Marinas may contribute to anthropogenic currents and increased FIBs in the area, as described in Ho et al., (2011). Low percent exceedances were also found for beaches where there are provisions for the management of storm water. This finding is consistent with the work of Parker et al., (2010) and Ahn et al., 2005 both of whom found that storm water significantly contributed to elevated levels of FIB.

As the study was conducted we found that beaches were managed through various unrelated agencies. This frequently resulted in independent actions by different groups that can impact beach quality. To receive the answers to our survey, team members had to contact multiple agencies in each county. In some cases, overlapping agencies existed at the private, municipal, county, state, and national levels to carry out and enforce beach management policies. Examples include the departments of health, beach erosion and shoreline protection agencies, the National Park Service, departments of environmental protection, state park agencies, public works agencies, solid waste departments, and parks and recreation departments. These multiple agencies resulted in a mix of redundancies, gaps, and conflicting priorities making it difficult to manage the beach as a whole. Through increased standardization and the united effort of agencies as stated in Nevers et al. (2013), policies could be designed to better address FIB levels at recreational beaches, setting forth a list of best practices, similar to the process for setting standards for wastewater treatment facilities, or through a program to lower FIBs through multiple targets, as described in Dorsey (2010). These strengthened policies will need to take into account best practices as well as the individual communities and natural environments at each beach (as recommended in Amorim et al., 2014), and will need to provide a baseline for understanding current environments while planning for future environmental change.

Funding is also an issue for continued monitoring of recreational beach water quality. As mentioned, effective 2011, many beaches were dropped from the Florida Healthy Beaches Program altogether due to lack of funding. Other beaches are monitored on a less frequent basis and the analysis of fecal coliform was dropped from all beach monitoring programs throughout the state. In agencies where many interests need to be met, such as the Department of Health, monitoring and management must compete with other programs that also require funding, including school lunch programs, vaccines for children, and assistance for the disabled. When faced with these choices, water quality funding is frequently a low priority. Where beaches have their own funding, even though it is frequently not applied toward routine monitoring, water quality tends to be better.

## 5. Conclusions

Our work identified potential causes of poor water quality at Florida's recreational beaches through an innovative analysis that coupled a very large water quality data set with responses to a beach management survey. Similar analyses could be used by other researchers to evaluate and optimize beach water quality in other areas of the world. The size of the dataset ($n > 150{,}000$ measurements per FIB) was critical for being able to identify significant associations between FIB and beach management practices.

Our study supports the work of researchers who found that the presence of birds (Sinigalliano et al., 2013; Goodwin et al., 2017), humans, and dogs (Elmir et al., 2009; Wright et al., 2009; Ervin et al., 2014), cause an increase in FIB at recreational beaches. We also found similarities between our results on beach sand, beach grooming studies, and that of work demonstrating that the way in which the beach is groomed can affect FIBs. Beach sand can provide an area in which FIBs can proliferate (Halliday and Gast, 2011; Phillips et al., 2011). Grooming in areas with heavy beach wrack that involve disturbance of the wrack may actually increase concentrations (Imamura et al., 2011; Nevers et al., 2016; Whitman et al., 2014; Kinzelman et al., 2003; Verhougstraete and Rose, 2014; Russell et al., 2014; Jones and Kaczor, 2017). Additionally, our work investigated gaps in areas such as the availability of restrooms and showers; concession stands; solid waste management; and fees to access the beach. We found that these amenities have an effect on FIBs.

Given the associations demonstrated here between beach management and FIBs, our results support the concept of sustainable beach management (James, 2000; Micallef and Williams 2002; Russell et al., 2014, and in Lamberti and Zannutigh 2005). Such management would streamline or even unify the operations of different agencies that manage beach erosion, wildlife, solid waste, beach patrol and law enforcement, amenities for beach visitors, water quality monitoring, and maintenance. Sustainable beach management will become even more critical in the future given anticipated sea level rise and increased flooding along Florida's coast, which will likely require more frequent integration of resources between sister agencies that address beaches. Unification of the agencies that address beaches would allow for an integration of policies that can promote better recreational water quality.

## Acknowledgments

This study was funded through the support of the University of Miami's Leonard and Jayne Abess Center for Ecosystem Science and Policy, and the Oceans and Human Health Center. We would also like to thank David Polk, Samir Elmir, Jan Mandrup-Poulsen, Bill Brookman, and Jane Parthemore of the Florida Department of Health, along with everyone who participated in our beach manager meetings in Miami-Dade and Monroe Counties where we preliminarily tested the survey. Thanks also to Laura Vogel, Noha Abdel-Mottaleb, Rachel Wood, Sathvika Ramaji, and Sabina Rakhimbekova for their work with the FHBP dataset. The early portion of this work was funded in part by the NSF–NIEHS Oceans and Human Health Program (NIEHS #P50 ES12736 and NSF #OCE0432368/0911373/1127813).

## Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jenvman.2018.02.012.

## References

Amorim, E., Ramos, S., Bordalo, A., 2014. Relevance of temporal and spatial variability for monitoring the microbiological water quality in an urban bathing area. Ocean Coast Manag. 91, 41–49.
Ahn, J., Grant, S., Surbeck, C., DiGiacomo, P., Nezlin, N., Jiang, S., 2005. Coastal water quality impact of stormwater runoff from an urban watershed in southern California. Environ. Sci. Technol. 39 (16), 5940–5953.
Brooks, Y., Baustian, M., Baskaran, M., Ostrom, N., Rose, J., 2016. Historical associations of molecular measurements of Escherichia coli and enterococci to anthropogenic activities and climate variables in freshwater sediment cores.

Environ. Sci. Technol. 50 (13), 6902–6911.
Byappanahalli, M., Nevers, M., Whitman, R., Ge, Z., Shively, D., Spoljaric, A., Przybyla-Kelly, K., 2015. Wildlife, urban inputs, and landscape configuration are responsible for degraded swimming water quality at an embayed beach. J. Great Lake. Res. 41, 156–163.
Converse, R.R., Kinzelman, J.L., Sams, E.A., Hudgens, E., Dufour, A.P., Ryu, H., Santo-Domingo, J.W., Kelty, C.A., Shanks, O.C., Siefring, S.D., Haugland, R.A., Wade, T.J., 2012. Dramatic improvements in beach water quality following gull removal. Environ. Sci. Technol. 46, 10206–10213.
Donahue, A., Feng, Z., Kelly, E., Reniers, A., Solo-Gabriele, H., 2017. Significance of beach geomorphology on fecal indicator bacteria levels. Mar. Pollut. Bull. 121 (1–2), 160–167.
Dorsey, J., 2010. Improving water quality through California's Clean Beach Initiative: an assessment of 17 projects. Environ. Monit. Assess. 166, 95–111.
Edge, T., Hill, S., Seto, P., Marsalek, J., 2010. Library-dependent and library-independent microbial source tracking to identify spatial variation in faecal contamination sources along a Lake Ontario beach (Ontario, Canada). Water Sci. Technol. 62 (3), 719–727.
Elmir, S.M., Shibata, T., Solo-Gabriele, H.M., Sinigalliano, C.D., Gidley, M.L., Miller, G., Plano, L.R.W., Kish, J., Withum, K., Fleming, L.E., 2009. Quantitative evaluation of enterococci and bacteroidales released by adults and toddlers in marine water. Water Res. 43 (18), 4610–4616.
Elmir, S.M., Wright, M., Abdelzaher, A., Solo-Gabriele, H.M., Fleming, L.E., Miller, G., Rybolowik, M., Shih, P., Pillai, S.P., Cooper, J.A., Quaye, E.A., 2007. Quantitative evaluation of bacteria released by bathers in a marine water. Water Res. 41 (1), 3–10.
Environmental Protection Agency, 2017. Frequent questions - final water quality standards for coastal and Great Lakes recreation waters. https://www.epa.gov/beach-tech/frequent-questions-final-water-quality-standards-coastal-and-great-lakes-recreation.
Ervin, J., Russell, T., Layton, B., Yamahara, K., Wang, D., Sasssoubre, L., Cao, Y., Kelty, C., Sivaganesan, M., Boehm, A., Holden, P., Weisburg, S., Shanks, O., 2013. Characterization of fecal concentrations in human and other animal sources by physical, culture-based, and quantitative real-time PCR methods. Water Res. 47, 6873–6882.
Ervin, J.S., Van De Werfhorst, L.C., Murray, J.L.S., Holden, P.A., 2014. Microbial source tracking in a coastal California watershed reveals canines as controllable sources of fecal contamination. Environ. Sci. Technol. 48 (19), 9043–9052.
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.
Florida Department of Health, 2016. Florida Healthy Beaches Program. http://www.floridahealth.gov/environmental-health/beach-water-quality/index.html.
Goodwin, K.D., Schriewer, A., Jirik, A., Curtis, K., Crumpacker, A., 2017. Consideration of natural sources in a bacteria TMDL - lines of evidence, including beach microbial source tracking. Environ. Sci. Technol. 51 (14), 7775–7784.
Griffin, D., Lipp, E., McLaughlin, M., Rose, J., 2001. Marine recreation and public health microbiology: quest for the ideal indicator. BioScience 51 (10), 817–825.
Halliday, E., Gast, R., 2011. Bacteria in beach sands: an emerging challenge in protecting coastal water quality and bather health. Environ. Sci. Technol. 45 (2), 370–379.
Hernandez, R., Hernandez, Y., Jimenez, N., Piggot, A., Klaus, J., Feng, Z., Reniers, A., Solo-Gabriele, H., 2014. Effects of full-scale beach renovation on fecal indicator levels in shoreline sand and water. Water Res. 48, 579–591.
Ho, L., Litton, R., Grant, S., 2011. Anthropogenic currents and shoreline water quality in avalon bay, California. Environ. Sci. Technol. 45, 2079–2085.
Imamura, G., Thompson, R., Boehm, A., Jay, J., 2011. Wrack promotes the persistence of fecal indicator bacteria in marine sands and seawater. FEMS (Fed. Eur. Microbiol. Soc.) Microbiol. Ecol. 77, 40–49.
James, R., 2000. From beaches to beach environments: linking the ecology, human-use and management of beaches in Australia. Ocean Coast Manag. 43, 495–514.
Jones, S., Kaczor, K., 2017. Personal Communication.
Kinzelman, J., Whitman, R.L., Byappanahalli, M.N., Jackson, E.K., Bagley, R.C., 2003. Evaluation of beach grooming techniques on Escherichia coli density in foreshore sand at North Beach, Racine, WI. Lake Reservoir Manag. 19, 349–354.
Korajkic, A., Brownell, M., Harwood, V., 2010. Investigation of human sewage pollution and pathogen analysis at Florida Gulf Coast Beaches. J. Appl. Microbiol. 110, 174–183.
Lamberti, A., Zanuttigh, B., 2005. An integrated approach to beach management in Lido di Dante, Italy. Estuar. Coast Shelf Sci. 62, 441–451.
Micallef, A., Williams, A., 2002. Theoretical strategy considerations for beach management. Ocean Coast Manag. 45, 261–275.
Molina, M., Hunter, S., Cyterski, M., Peed, L.A., Kelty, C.A., Sivaganesan, M., Mooney, T., Prieto, L., Shanks, O.C., 2014. Factors affecting the presence of human-associated and fecal indicator real-time quantitative PCR genetic markers in urban-impacted recreational beaches. Water Res. 64, 196–208.
Nevers, M., Byappanahalli, M., Whitman, R., 2013. Choices in recreational water quality monitoring: new opportunities and health risk trade-offs. Environ. Sci. Technol. 47, 3073–3081.
Nevers, M.B., Przybyla-Kelly, K., Spoljaric, A., Shively, D., Whitman, R.L., Byappanahalli, M.N., 2016. Freshwater wrack along Great Lakes coasts harbors Escherichia coli: potential for bacterial transfer between watershed environments. J. Great Lake. Res. 42, 760–767.
Oshiro, R., Fujioka, R., 1995. Sand, soil, and pigeon droppings: sources of indicator bacteria in the waters of Hanauma Bay, Oahu. Hawaii Water Sci. Technol. 31 (5–6), 251–254.
Parker, K., McIntyre, D., Noble, R., 2010. Characterizing fecal contamination in stormwater runoff in coastal North Carolina, USA. Water Res. 44 (14), 4186–4194.
Phillips, M.C., Solo-Gabriele, H.M., Reniers, A.J.H.M., Piggot, A., Klaus, J.S., Zhang, Y., 2011. Relationships between sand and water quality at recreational beaches. Water Res. 45, 6367–6769.
Quilliam, R.S., Jamieson, J., Oliver, D.M., 2014. Seaweeds and plastic debris can influence the survival of faecal indicator organisms in beach environments. Mar. Pollut. Bull. 84, 201–207.
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., Jay, J.A., 2015. Long-term monitoring of molecular markers can distinguish different seasonal patterns of fecal indicating bacteria sources. Water Res. 71, 227–243.
Rippy, M.A., Franks, P.J.S., Feddersen, F., Guza, R.T., Warrick, J.A., 2013. Beach nourishment impacts on bacteriological water quality and phytoplankton bloom dynamics. Environ. Sci. Technol. 47, 6146–6154.
Russell, T., Sassoubre, L., Zhou, C., French-Owen, D., Hassaballah, A., Boehm, A., 2014. Impacts of beach wrack removal via grooming on surf zone water quality. Environ. Sci. Technol. 48, 2203–2211.
Shanks, C., Sivaganesan, M., Peed, L., Kelty, C., Blackwood, A., Greene, M., Noble, R., Bushon, R., Stelzer, E., Kinzelman, J., Anan'eva, T., Sinigalliano, C., Wanless, D., Griffith, J., Cao, Y., Weisberg, S., Harwood, V., Staley, C., Oshima, K., Varma, M., Haugland, R., 2012. Interlaboratory comparison of real-time PCR protocols for quantification of general fecal indicator bacteria. Environ. Sci. Technol. 46 (2), 945–953.
Sinigalliano, C.D., Ervin, J.S., Van De Werfhorst, L.C., Badgley, B.D., Ballesté, E., Bartkowiak, J., Boehm, A.B., Byappanahalli, M., Goodwin, K.D., Gourmelon, M., Griffith, J., Holden, P.A., Jay, J., Layton, B., Lee, C., Lee, J., Meijer, W.G., Noble, R., Raith, M., Ryu, H., Sadowsky, M.J., Schriewer, A., Wang, D., Wanless, D., Whitman, R., Wuertz, S., Santo Domingo, J.W., 2013. Multi-laboratory evaluations of the performance of Catellicoccus marimammalium PCR assays developed to target gull fecal sources. Water Res. 47, 6883–6896.
Sinigalliano, C.D., Fleisher, J.M., Gidley, M.L., Solo-Gabriele, H.M., Shibata, T., Plano, L.R.W., Elmir, S.M., Wanless, D., Bartkowiak, J., Boiteau, R., Withum, K., Abdelzaher, A.M., He, G., Ortega, C., Zhu, X., Wright, M.E., Kish, J., Hollenbeck, J., Scott, T., Backer, L.C., Fleming, L.E., 2010. Traditional and molecular analyses for fecal indicator bacteria in non-point source subtropical recreational marine waters. Water Res. 44 (13), 3763–3772.
Sutton-Grier, A.E., Wowka, K., Bamford, H., 2015. Future of our coasts: the potential for natural and hybrid infrastructure to enhance the resilience of our coastal communities, economies and ecosystems. Environ. Sci. Pol. 51, 137–148.
Tanner, W.F., 1960. Florida coastal classification. Trans. Gulf Coast Assoc. Geol. Soc. 10, 259–266.
US EPA Method 1600, December 2009. Enterococci in Water by Membrane Filtration Using Membrane-Enterococcus Indoxyl-β-d-glucoside Agar (MEI).
Verhougstraete, M., Rose, J.B., 2014. Microbial investigations of water, sediment, and algal mats in the mixed use watershed of Saginaw Bay. Michigan J. Great Lakes Res. 40 (S1), 75–82.
Whitman, R.L., Harwood, V.J., Edge, T.A., Nevers, M.B., Byappanahalli, M., Vijayavel, K., Brandao, J., Sadowsky, M.J., Alm, E.W., Crowe, A., Ferguson, D., Ge, Z., Halliday, E., Kinzelman, J., Kleinhenz, G., Przybyla-Kelly, K., Staley, C., Staley, Z., Solo-Gabriele, H.M., 2014. Microbes in beach sands: integrating environment, ecology and public health. Rev. Environ. Sci. Biotechnol. 13, 329.
Wright, M.E., Solo-Gabriele, H.M., Elmir, S., Fleming, L.E., 2009. Microbial load from animal feces at a recreational beach. Mar. Pollut. Bull. 58 (11), 1649–1656.
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.