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Significance of beach geomorphology on fecal indicator bacteria levels

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A B S T R A C T

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.

1. 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, > 3100 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 among 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.

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2. 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.

2.1. 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 small impact of seasonal sampling, 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.

2.2. 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 (< 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.

2.2.1. 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

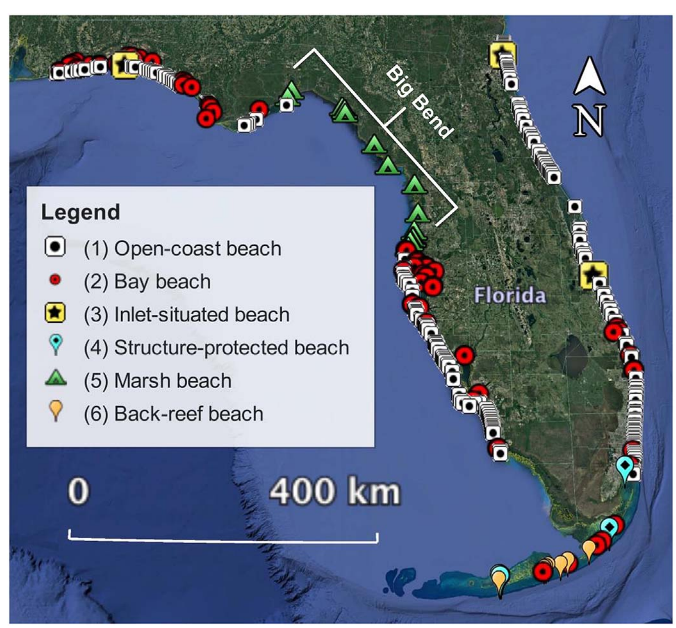

Fig. 1. The geographic distribution and categorization of 316 recreational beaches in the study. The Big Bend area includes Pasco, Dixie, Taylor, Levy, Hernando, Citrus, and Wakulla counties.