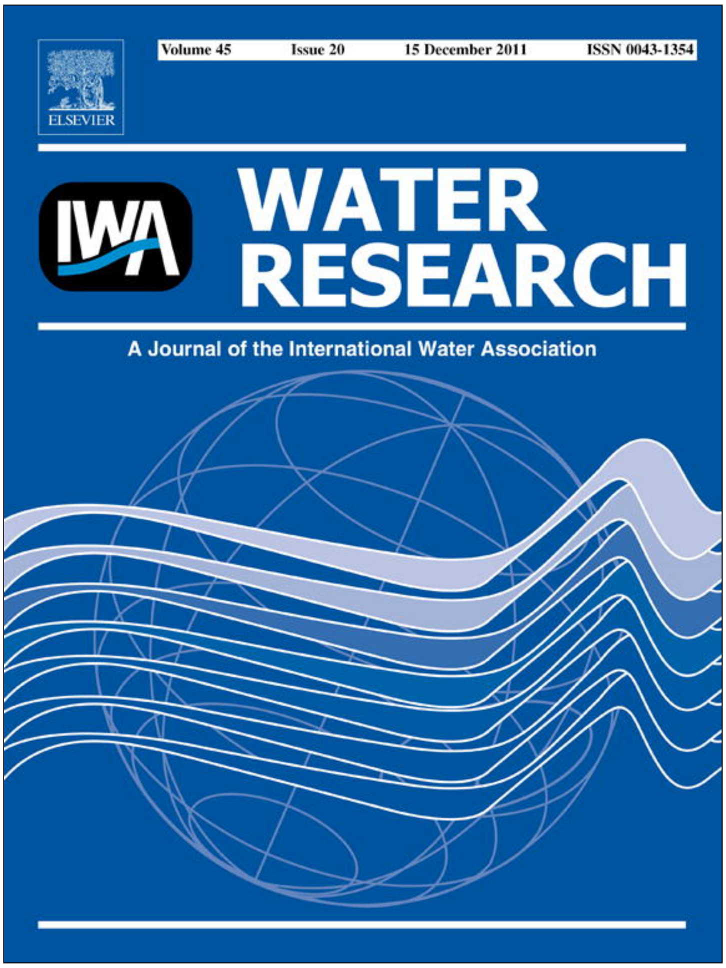

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Relationships between sand and water quality at recreational beaches

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ABSTRACT

Enterococci are used to assess the risk of negative human health impacts from recreational waters. Studies have shown sustained populations of enterococci within sediments of beaches but comprehensive surveys of multiple tidal zones on beaches in a regional area and their relationship to beach management decisions are limited. We sampled three tidal zones on eight South Florida beaches in Miami-Dade and Broward counties and found that enterococci were ubiquitous within South Florida beach sands although their levels varied greatly both among the beaches and between the supratidal, intertidal and subtidal zones. The supratidal sands consistently had significantly higher ($p < 0.003$) levels of enterococci (average 40 CFU/g dry sand) than the other two zones. Levels of enterococci within the subtidal sand correlated with the average level of enterococci in the water (CFU/100mL) for the season during which samples were collected ($r_s = 0.73$). The average sand enterococci content over all the zones on each beach correlated with the average water enterococci levels of the year prior to sand samplings ($r_s = 0.64$) as well as the average water enterococci levels for the month after sand samplings ($r_s = 0.54$). Results indicate a connection between levels of enterococci in beach water and sands throughout South Florida's beaches and suggest that the sands are one of the predominant reservoirs of enterococci impacting beach water quality. As a result, beaches with lower levels of enterococci in the sand had fewer exceedences relative to beaches with higher levels of sand enterococci. More research should focus on evaluating beach sand quality as a means to predict and regulate marine recreational water quality.

1. Introduction

Enterococci are recommended by the Environmental Protection Agency (EPA) for use in assessing the health risk of recreational waters (U.S. EPA, 1986). While enterococci are not commonly pathogenic, they have been shown in past epidemiological studies to correlate with adverse human health effects. These negative health effects are commonly

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associated with pathogens found in sewage and thus enterococci are used to protect human health in waters thought to be impacted by fecal pollution (Cabelli et al., 1982; Dufour, 1984; Wade et al., 2003). In recent years however, researchers have discovered that beach sediments can sustain populations of enterococci and are potential non-sewage sources of these indicator bacteria in recreational waters (Shibata et al., 2004; Whitman and Nevers, 2003; Badgley et al., 2010; Wright et al., 2011; Abdelzaher et al., 2010). Even without a point source of sewage, high enterococci levels in beach water may still represent an increased risk for bathers at these beaches (Fleisher et al., 2010; Sinigalliano et al., 2010) and enterococci levels in sand have been shown to correlate with higher levels of human pathogens in beach sand (Shah et al., 2011). Due to this risk to human health, it is important to assess the beach sediment's affect on the overall quality of the beach and associated recreational water. Regulatory agencies, such as the State Departments of Health (DOH), use water quality measurements to assess the human health risk of recreational swimming at local beaches. In Miami-Dade and Broward counties, Florida, the DOH collects weekly water samples from waist deep water at each recreational beach and analyzes these samples for enterococci in the water. Beach advisories are posted to alert swimmers of increased health risks when the level of bacteria in the water for two consecutive samples are measured above a maximum of 104 colony forming units (CFU) per 100 mL of water or if the geometric mean for the past 5 water samples is above 35 CFUs/100 mL (U.S. EPA, 1986). The present study set out to compare results from regulatory water quality monitoring with the enterococci levels within the sediments of 8 South Florida Beaches and to evaluate if sediment levels of enterococci have a potential for predictive regulatory measures. Two water quality measures were evaluated; one that utilized the percent exceedances of the regulatory maximum value and another that utilized the actual measured levels of enterococci in water. In the process of comparing the results for the 8 beaches, the study also established the ubiquity of enterococci within the beach sands of South Florida's beaches and characterized the spatial distribution of enterococci across the supratidal, intertidal and subtidal zones.

2. Methods

2.1. Site descriptions and sampling

Sediment samples were collected from 8 South Florida Beaches (Fig. 1; Supplemental Table 1). Beaches were chosen based on where the DOH conducts their weekly sampling and to represent a wide range of both beach conditions and DOH recorded levels of enterococci present in the water. Seven of the eight

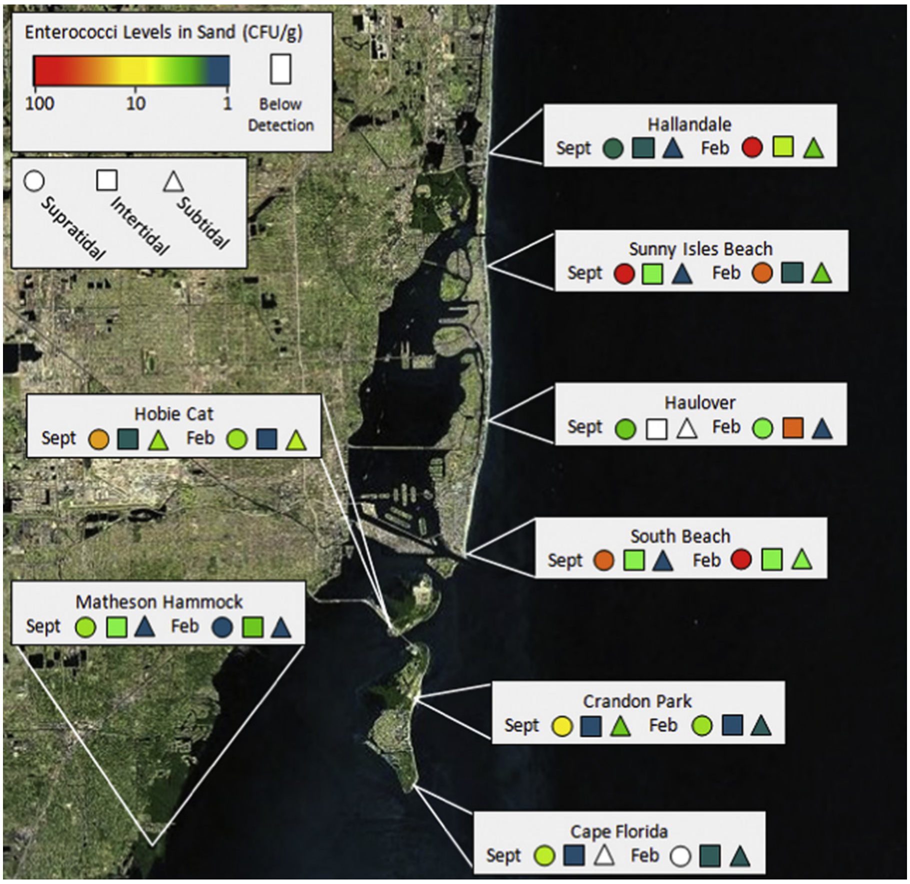

Fig. 1 – Beach sampling locations and bacterial levels in beach sand on September 11, 2010 and February 12, 2011. Background map from Bing Maps.

beaches chosen for this study are located in Miami-Dade County and one (Hallandale Beach) is located in Broward County. Two of the eight are located in Biscayne Bay (Hobie Cat Beach and Matheson Hammock) thereby experiencing weaker wave conditions. Matheson Hammock beach is located within an artificial lagoon with limited inflow of bay water providing for particularly calm water conditions. The remaining six beaches face the Atlantic Ocean with larger wave exposure and more dilution and flushing of its shoreline. The primary sources of indicator bacteria to these beaches are diffuse (i.e., non-point sources). All beaches experience significant human traffic during warmer weather with the highest usage occurring during weekends and holidays (Wang et al., 2010). Beach usage declines during the winter months and increases again in April. Gulls and other seabirds are present at all beaches especially during the fall and winter months. Hobie Cat Beach is the only beach where dogs are allowed. Of the beaches sampled, Cape Florida, Matheson Hammock and Crandon Park are run by the state park system. The other beaches are public and maintained by local jurisdictions. The three beaches run by the state parks are gated and require visitors to pay for entrance into the park and thus these beaches tend to be better maintained. Although sewage discharge pipes are located offshore north of Hallandale Beach and east of Hobie Cat Beach, extensive studies have shown that these discharges do not impact the local beaches (U.S. EPA, 2003).

Sand sampling locations were located along transects consistent with DOH water sampling locations. Samples were collected at low tide during two different sampling events, the morning of September 11th, 2010 and the morning of February 12th, 2011. Three composite samples (one from each of the following zones: supratidal, intertidal, and subtidal) were collected at each beach. Supratidal samples were located at 0.25 m above the wrack (mean high tide) line, the intertidal samples were located halfway between the wrack line and water line and the subtidal samples were located below the water line in 30 cm deep water. Each composite sample consisted of a series of 31 sediment cores (2.54 cm, 4 cm deep) that were collected every 20 cm along a 6-meter transect parallel to the shoreline. Upon collection the 31 cores were placed into a sterile tin and covered for transport. In an effort to document physical–chemical parameters (pH, salinity, turbidity) for each beach site, a water sample was also collected upstream of the subtidal transect using a sterile Whirl-Pak bag. Water temperature was documented using a multi parameter probe (YSI 650MDS, YSI Incorporated, Yellow Springs, Ohio).

2.2. *Laboratory analysis of sediment samples*

Laboratory analysis was conducted within 4 h of sample collection. Each tin containing the composite sand sample was mixed thoroughly using sterile spoons for 3 min prior to analysis. Triplicate aliquots (20 g) of each homogenized sand sample were analyzed gravimetrically (dried for 24 h at 110 °C) to obtain the moisture content. Grain size analysis was conducted utilizing the wet sieve method (Alekseeva and Sval'nov, 2005). Data from the grain size analysis was used to extrapolate total surface area of the sediment samples and D_{50} (diameter at which 50% of sand grains by weight are finer). See Supplemental text for details.

In order to extract microbes from the sand grains, approximately 10 g of sand was aseptically transferred into a sterile bottle containing 100 mL of sterile phosphate buffered saline solution and shaken vigorously for 2 min (Shibata et al., 2004; Boehm et al., 2009). After allowing the sediment to settle (2 min), two volumes of the eluent (25ml and 3ml) were filtered (Pall, GN-6 Grid) and placed on mEI agar as per Method 1600 (U.S. EPA, 2006).

2.3. *Enterococci water monitoring data*

Enterococci beach water monitoring data was provided by the Florida Department of Health as part of the Florida Healthy Beaches program (http://esetappsDOH.DOH.state.fl.us/irm00beachwater/default.aspx) which implements weekly monitoring for regulatory purposes. Only the DOH's routine weekly samples were used in calculating water enterococci levels. Daily supplementary samples taken after exceedances were excluded to avoid skewing the averages with multiple high values. The regulatory water quality data was then averaged over set time periods (yearly, seasonally, monthly, and based on rainfall) to minimize the impacts of spatial and temporal variability inherent in single water samples (Boehm et al., 2002). Yearly averaging corresponded to the year prior to each of the two sand sampling events at all beaches except Hobie Cat Beach. Hobie Cat Beach was closed for sand renourishment between October 12th, 2009 and May 31st, 2010. During this time sand on the beach was replaced with exogenous sand, and so only beach water monitoring samples taken after the beach reopened were included when evaluating the data from Hobie Cat Beach. For the seasonal averaging, the September sampling data was paired with DOH water enterococci measurements taken during wet season in south Florida (May, 2010–October, 2010) and the February data was paired with DOH water samples taken during the dry season (November, 2010–April, 2011). Monitoring data for one month after each sand sampling event was also used to analyze the possible predictive capacity of the beach sand. Averaging based upon rainfall corresponded to averaging water quality values through an amount of time needed to acquire a certain amount of rainfall.

2.4. *Data analysis*

All statistical analysis was performed using Microsoft Excel, XL STAT (Addinsoft USA, New York, NY). Averages from 78 DOH water samples (September 14, 2009 to March 29, 2011) and 6 sand samples per beach (September 11, 2010 and February 12, 2011) were compared and correlations were acquired using Spearman's Rank Order Test (r_s). Comparisons between sand tidal zones and sampling days were made using a single variable ANOVA. An alpha of 0.05 was used for all tests.

3. Results and discussion

3.1. *Variation between sand tidal zones*

Enterococci were found at every beach sampled during this study (Fig. 2) which is consistent with other studies that have

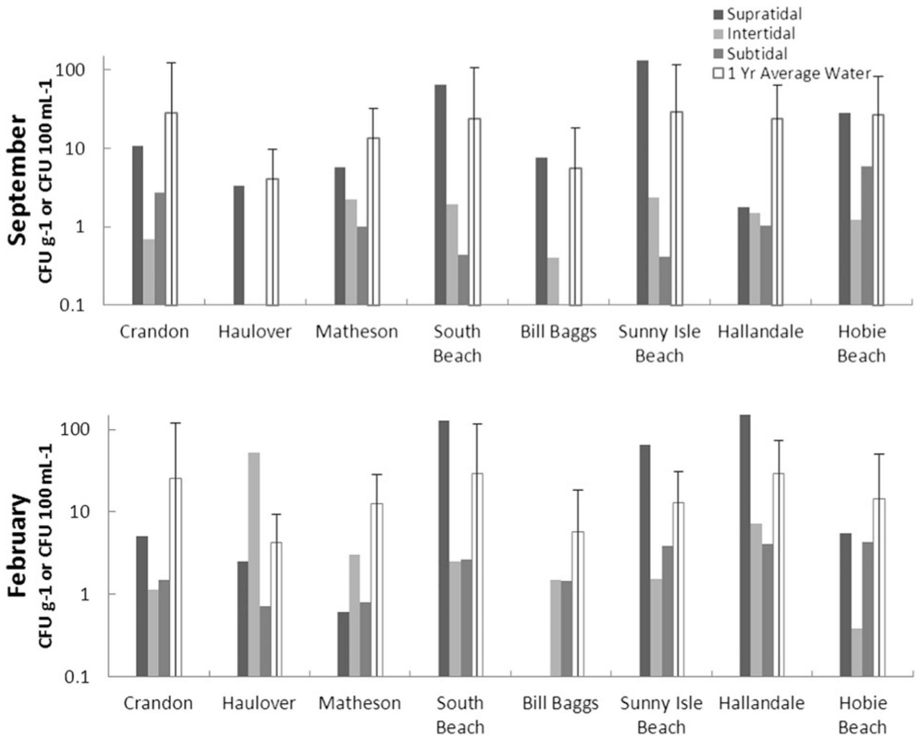

Fig. 2 – Levels of enterococci in all beach zones and the 1 year prior average of enterococci in the water. Levels of enterococci within the water varied greatly over the year prior to sampling at all beaches. Error bars represent one standard deviation.

quantified fecal indicator bacteria in beach sands (Alm et al., 2003; Whitman et al., 2006; Halliday and Gast, 2011), Moreover, enterococci levels were consistently higher in the supratidal sand compared to the intertidal sand and subtidal sand (Fig. 3). This was particularly evident at sites that were characterized by higher levels of enterococci. The higher level in the supratidal sand was significant when considering results from both sampling days ($p < 0.02$) but was more pronounced for the September sampling day ($p < 0.05$) as compared to the February sampling day ($p = 0.08$). Although higher levels of enterococci were observed in the supratidal sand these levels did not correlate with any grain size parameters of the sands including surface area (28.0–83.2 cm^2/g), the diameter at which 50% of the sand grains are finer (0.32–0.89 mm) and uniformity coefficient, a relative measure of similarity in the sizes of sand grains (1.69–5.45) (1 is perfectly uniform, the higher the number the less uniform the sand grains). Thus differences in grain size characteristics among the different beaches did not appear to impact enterococci levels. A negative correlation was observed between moisture content and log normalized enterococci for all beach sands ($r_s = -0.52, p < 0.0005$) which is consistent with past studies of Hobie Cat Beach (Shah et al., 2011). This trend was not noted in sands within the same tidal zones. The elevated levels of enterococci within the supratidal zone may be due to the combined effects of proximity to on-shore non-point sources of enterococci such as humans, birds, leachate from garbage cans, run off after storms, lack of tidal washing and regrowth (Elmir et al., 2007; Bonilla et al., 2007; Abdelzaher et al., 2011; Hartz et al., 2008). Differences in these factors could account for the variability seen between the 8 beaches sampled during this study. Since the supratidal sands are not often exposed to the water, it is unlikely that the enterococci could have been deposited there from the ocean. The supratidal sand is also not exposed to the same wave energy and tidal forces experienced by the sands

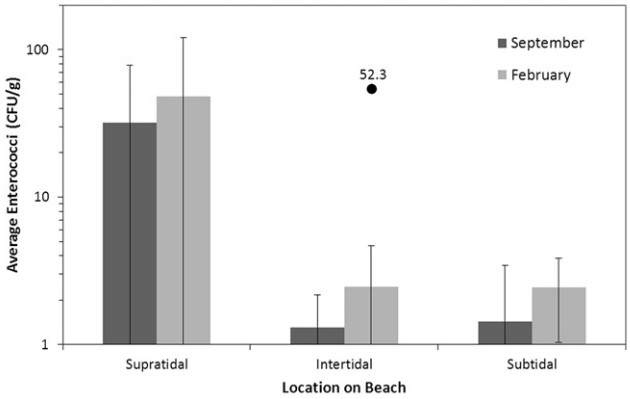

Fig. 3 – Average enterococci levels of south Florida beach sand. Results indicate that supratidal sand is consistently and significantly ($P < 0.01$) higher than both the intertidal and subtidal sand while there was no significant difference between intertidal and subtidal sands. Results showed very high levels of variability between the 8 beaches. The 52.3 CFU/g value was a statistical outlier of the intertidal samples during the February sampling. Error bars represent one standard deviation.

Table 1 – Summary of correlations between DOH water quality data and levels of enterococci within the sand.

DOH water quality measurements	Correlated with	r_s	P
Percentage of prior year exceedences (Both)	Average sand ENT across all tidal zones	0.5	0.05
	ENT in supratidal sand	0.48	0.06
	ENT in subtidal sand	0.56	0.03
Percentage of prior year exceedences (Feb)	Average sand ENT across all tidal zones	0.73	0.05
	ENT in supratidal sand	0.73	0.05
	ENT in subtidal sand	0.58	0.15
Percentage of prior year exceedences (Sept)	Average sand ENT across all tidal zones	0.38	0.36
	ENT in supratidal sand	0.27	0.54
	ENT in subtidal sand	0.83	0.02

in the intertidal and subtidal zones. Thus intertidal and subtidal sands would have lower levels of enterococci because the energy from the waves and tides is capable of removing the on-shore sources of enterococci that deposit in the sand (Yamahara et al., 2007; Ge et al., 2010).

3.2. *Correlations with DOH water quality measurements*

Both water quality measures evaluated (average levels over a pre-described period of time and percent exceedences), showed significant correlations with sand enterococci levels. The prior year average DOH water enterococci levels correlated with the average level of sand enterococci across all tidal zones ($r_s = 0.64$, $p = 0.008$). The average DOH water enterococci levels over the prior year also positively correlated with levels of enterococci in supratidal sand ($r_s = 0.6$, $p = 0.015$) (Figure S-2). The levels of enterococci in the subtidal sand also correlated ($r_s = 0.69$, $p = 0.004$) with the average levels of DOH water enterococci for the season during which the samples were collected.

The percent of DOH samples from the prior year that exceeded 104 CFU/100 mL positively correlated with the average level of sand enterococci across all tidal zones for all sampling days ($r_s = 0.5$, $p = 0.05$). This was primarily driven by the significant correlation of percent exceedance to levels of enterococci in the subtidal sand ($r_s = 0.56$, $p = 0.03$) and the non-significant correlation ($r_s = 0.48$, $p = 0.06$) to levels in the supratidal sand. This trend between the percent exceedance and sand enterococci levels was noted for the February sampling ($r_s = 0.73$, $p = 0.05$) but not for the September sampling ($r_s = 0.38$, $p = 0.36$). The lack of correlation in the September data set was primarily due to the supratidal sand not correlating with percent exceedance ($r_s = 0.27$, $p = 0.54$), although the subtidal sand did show a correlation ($r_s = 0.83$, $p = 0.02$). For the February data set, both subtidal and supratidal sand levels showed relatively high correlations ($r_s > 0.5$) (although subtidal was not significant) (supratidal: $r_s = 0.73$, $p = 0.05$; subtidal: $r_s = 0.58$, $p = 0.15$). All correlations are summarized in Table 1 and raw data is available in Table S-1, located in the supplemental text. The heavy rains during and prior to September could possibly be responsible for the lack of correlation seen in the supratidal sands because of more frequent sand washing. Also the heavier beach traffic could have raised levels in the supratidal sand (Elmir et al., 2007) relatively quickly, in comparison to the levels observed in the water during the prior year. There were no trends seen with enterococci levels in intertidal sands, possibly because of wave action and tidal movements making this tidal zone more variable and inconsistent with ambient enterococci levels in the water (Yamahara et al., 2007; Abdelzaher et al., 2010).

At beaches where the predominant source of enterococci is thought to be the sand; the potential exists to use levels of enterococci in the sand as guidance for management decisions such as where and how often to sample. In this study, water enterococci for the two weeks following the sand samplings positively correlated ($r_s = 0.63$, $p = 0.01$) with enterococci levels in the subtidal sand. The water enterococci for the month following the sand samplings also positively correlated ($r_s = 0.54$, $p = 0.04$) with the average enterococci over all the tidal zones on the beach. Correlations could also be seen by setting averaging times equal to the amount of time needed to acquire a certain amount of rainfall. For example, the average enterococci in the water, for a time period after sand sampling corresponding to 1.25 cm of rain at the beach, correlated ($r_s = 0.56$, $p = 0.05$) with the levels of bacteria in the subtidal sand for all sampling days. This amount was also significant for the February sampling ($r_s = 0.85$, $p = 0.02$) and was strengthened if the time series was lengthened until the beach received 2.54 cm of rainfall ($r_s = 0.96$, $p = 0.003$). While these correlations are not enough to encourage beach closures based solely on sand sampling, they suggest that sand sampling could be used to allocate monitoring resources to focus on non-point source beaches with higher likelihoods of exceedences. Instead of sampling all beaches at an equal frequency (example: once per week), beaches with low levels of sand enterococci could be sampled less frequently (example: once per month) as opposed to beaches with high levels of enterococci within the sand (example: twice per week). Further studies should be conducted to confirm results and evaluate the geographic extent of these potential trends.

4. Conclusions

Enterococci were found at all 8 of the South Florida beaches sampled. They were also consistently found at higher levels in the supratidal sand than in other zones on the beach. This suggests a constant, on-shore source of enterococci throughout South Florida (Zhu et al., 2011).

Percent exceedance and average levels of enterococci in the water can be looked at as relative measures of the overall health of the recreational water. This would mean that the overall health of recreational waters in south Florida was correlated with the levels of enterococci present in the beach sands.

One of most important implications from this study was that the average quality of the beach waters and the quality of the beach sands seem to be related. Beaches with low levels of enterococci in the sand generally have lower levels in the water and thus will have fewer closures than beaches with higher levels of enterococci in the beach sands.

Since beach sands represent a more time-averaged representation of enterococci inputs to the beach environment, they might be more likely to reflect human health risks for specific beaches. Utilizing beach sand composite samples could help account for the inherent variability in enterococci levels of single water samples and help avoid needless beach closures because of this variability. Furthermore, sand samples could be used to focus beach monitoring efforts towards high-risk beaches with a higher likelihood of exceedences.

5. Recommendations

The correlations found in this study should be further validated by evaluating the mechanisms by which enterococci in the beach sands are transported into the water column (Phillips et al., 2011). Both the horizontal shear forces of waves and the vertical pumping action of tides should be examined for a better understanding of how enterococci enter into recreational waters.

Further studies should be conducted to evaluate the causes of elevated enterococci levels at certain beaches and between tidal zones. The different sources of enterococci should be examined (number of human visitors, types and number of animals, practices for waste collection and disposal) and the characteristics of the different beach sediments should also be documented (moisture content, grain size, levels of biofilm, composition of sand grains and volatile organics). This data should be used to establish possible correlations between causative parameters to levels of enterococci. Controlled laboratory experiments with microcosms could validate these correlations. Further sampling should also be conducted over longer periods of time to further corroborate the trends noticed in this study. Expanding to more beaches in other areas of the country would also assist in determining if the levels of enterococci in the sediment actually can be used as a predictive tool to guide beach management decisions.

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Appendix. Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.watres.2011.10.028.

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