Enterococci Concentrations in Diverse Coastal Environments Exhibit Extreme Variability

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Fecal indicator bacteria (FIB) concentrations in a single grab sample of water are used to notify the public about the safety of swimming in coastal waters. If concentrations are over a single-sample standard, waters are closed or placed under an advisory. Previous work has shown that notification errors occur often because FIB vary more quickly than monitoring results can be obtained (typically 24 h). Rapid detection technologies (such as quantitative polymerase chain reaction) that allow FIB quantification in hours have been suggested as a solution to notification errors. In the present study, I explore variability of enterococci (ENT) over time scales less than a day that might affect interpretation of FIB concentrations from a single grab sample, even if obtained rapidly. Five new data sets of ENT collected at 10 and 1 min periodicitities for 24 and 1 h, respectively, are presented. Data sets are collected in diverse marine environments from a turbulent surf zone to a quiescent bay. ENT vary with solar and tidal cycles, as has been observed in previous studies. Over short time scales, ENT are extremely variable in each environment even the quiescent bay. Changes in ENT concentrations between consecutive samples (1 or 10 min apart) greater than the single-sample standard (104 most probable number per 100 ml) are not unusual. Variability, defined as the change in concentration between consecutive samples, is not distinct between environments. ENT change by 50% on average between consecutive samples, and by as much as 700%. Spectral analyses reveal no spectral peaks, but power-law decline of spectral density with frequency. Power-law exponents are close to 1 suggesting ENT time series share properties with white noise and are fractal in nature. Since fractal time series have no characteristic time scale associated with them, it is not obvious how the fractal nature of ENT can be exploited for adaptive sampling or management. Policy makers, as well as scientists designing field campaigns for microbial source tracking and epidemiology studies, are cautioned that a single sample of water reveals little about the true water quality at a beach. Multiple samples must be taken to gain a snapshot into the patchy structure of microbial water quality and associated human health risk.

Introduction
The United States Clean Water Act and BEACH Act require coastal states to monitor recreational waters for fecal indicator bacteria (FIB) to assess water quality. Exposure to FIB from municipal wastewater and urban runoff in marine waters correlates to adverse health outcomes in swimmers according to formal epidemiology studies (1-3). Monitoring results are used for public notification of water quality via beach advisories and closures. In the United States, 98% of agencies conducting monitoring use a single-sample exceedance criteria for issuing advisories and closures (4). If FIB concentrations in a single grab sample of water exceed the criteria, public notification of poor water quality is required. For enterococci (ENT), the preferred FIB for monitoring marine waters (5), the recommended single sample standard for beaches is 104 most probable number (MPN) of colony forming units (CFU)/100 ml (6).

United States Environmental Protection Agency approved methods to measure FIB require an 18-96 h incubation period as they are culture-based. Several studies have shown that temporal changes in FIB concentrations in beach water occur at shorter time scales (7, 8). Thus, out-of-compliance beaches remain open during the labor day incubation period and may be in compliance by the time warnings are posted (8, 9). Rapid detection technologies are culture independent, allowing FIB quantification in under 4 h (10, 11). Transitioning to rapid methods has been proposed as a means for addressing management errors resulting from the delay associated with culture-based assays.

However, there is strong evidence that no matter how rapidly a test result can be obtained, a single sample of water will not adequately describe water quality for an entire day. It is now known that FIB vary at time scales less than a day. In particular, FIB vary with diurnal and solar cycles (12, 13) which modulate their transport and inactivation in coastal waters, respectively. Fortunately, the manner in which FIB vary with tides and sunlight is predictable, so health-protective monitoring can be conducted (for example, periods with highest FIB can be sampled). A single study has documented FIB variability at time scales less than an hour in a turbulent surf zone and attributed this to rip current mixing (14). In this case, variation did not appear to be predictable. More work is needed to examine FIB variability at short time scales (less than an hour) at diverse beach environments to determine if short-period variability is present along all coastlines or only present in turbulent surf zones. Such extreme variability could have profound influence on the policy outcomes (i.e., beach advisories and closures), monitoring plans, and usefulness of rapid detection technologies.

There is reason to believe that FIB variability at time scales less than an hour will be common based on work with other physical, chemical, and biological parameters in the coastal environment (15-18). For example, temporal variability in temperature, nitrite, and fluorescence has been documented at scales of seconds to hours in coastal waters (15, 16, 19). These studies found that parameter variability, or "patchiness", is not confined to a set of frequencies, nor did they find that the variability is random (i.e., white noise). Rather, they found that extreme variability of many coastal parameters is fractal in nature. That is, variability is observed at all time scales and there is no characteristic time scale associated with the signal.

Fractal time series are identified from a power-law decay in spectral density (E) with frequency (f) (16). The power
law-exponent $\beta$ in $E(f) \sim f^{-\beta}$ can be related to the fractal dimension $D$ as follows: $D = 2 - 0.5(\beta - 1)$ where $D$ varies between 1 and 2 (16). $D$ and $\beta$ are useful for describing how energy in a time series varies from one time scale to the next. Their magnitudes are controlled by physical (e.g., turbulent-velocities and dispersion) and biological (e.g., variation in growth and grazing rates) processes (15, 18). If $\beta = 0$, the signal in the time domain is referred to as white noise because $E(f)$ is constant. In this case, the signal is not fractal, but is considered random because variability at every frequency contributes equally to the time series. If $\beta = 1$, the signal is fractal and classified as $1/f$ noise which is ubiquitous in nature (for example, low in streams (20) and DNA sequences (21)). In this case, the energy associated with each frequency falls off as frequency increases. Because $E(f)$ and $\beta$ are related, the signal in the time domain is considered structured. When turbulent velocities are responsible for advecting a passive scalar, $\beta = 5/3$ as described by Kolmogorov (19).

In the present study, I examine extreme temporal variations (periods between 1 min and 24 h) in FIB concentrations in diverse marine coastal environments ranging from wave-sheltered to wave-exposed open ocean beaches. I report five new ENT data sets, collected at 10 and 1 min periodicities. A goal of this paper is to determine if ENT variation at short time scales is dictated by the physical environment in which they were measured (i.e., a quiescent, wave-sheltered cove or a turbulent surf zone). In addition, I examine how variation at different time scales or frequencies contributes to the overall ENT signal using Fourier analysis. In particular, I examine if high frequency variability is random or fractal in nature. The implications of the results for monitoring beaches for ENT and human health risk are discussed.

Materials and Methods

Enterococci (ENT) are the focus of this study because they correlate best to human health outcomes in marine waters (5). ENT concentrations were measured every 10 min for 18 h at Huntington State Beach (HSB, 33°36' N, 117°36' W) in 2002, and every 10 min for 22 and 24 h in 2005 and 2007, respectively, at Lovers Point, CA (LP, 36°37' N, 121°55' W). In 2005, ENT concentrations at LP were measured every 1 min for approximately an hour during the longer duration 10-min study (Table 1). During each experiment, samples were taken at a fixed location, and thus sampling was Eulerian in nature.

Tides and waves are major factors affecting mixing and transport in the very nearshore and might explain heterogeneity in ENT variability between experiments. To characterize the tides and waves during each experiment, tide level and range were obtained from XTide (http://www.flaterco.com/xtide/files.html) and breaker heights were recorded visually by the author (Table 1). In 2002, water samples were collected from HSB at station 5N 22' (hereafter referred to as experiment HSB02). HSB is characterized by a well-developed surfzone, and during HSB02 breakers were 1 m high. During 2005 and 2007, samples were collected at LP, which is sheltered from waves under the majority of conditions except during long-period northwest (NW) swell. During 2005, I sampled LP at a single location on the beach once every 10 and 1 min, as described above (hereafter referred to as LPS05 and LPmin for 10 and 1 min period experiments, respectively, Table 1). The experiments began under quiescent conditions with no waves, and over the course of the study a NW swell built until 1 m waves were breaking on the beach. During 2007 at LP, I collected samples at two locations on the beach, approximately 50 m apart (sites N and S) (hereafter referred to as LPS07 and LPmin, respectively). Waves were absent during the entire study, and the water was extremely quiescent. The tide range during all studies was similar, with the exception of the study where samples were collected every minute for 1 h at LP (LPmin) during which the water level barely changed.

Fifty mL of water was collected in sterile containers and immediately stored on ice and analyzed within an hour of collection. Prior to analysis, containers were mixed by inverting three times. Ten mL subsamples were assayed for ENT using Enterolert defined chromogenic substrate assays implemented in a 97-well format (IDEXX, Westbrook, ME). An interlaboratory comparison study in southern California using waters adjacent to HSB found that Enterolert yielded results consistent with traditional methods of membrane filtration and multiple tube fermentation with low error rates (22). Therefore, Enterolert is expected to perform well in the present study. Ten mL of well-mixed sample water and reagent were dispensed into 90 mL of Butterfields buffer. This allowed detection of ENT between 10 and 24152 MPN/100 mL. Concentrations and 95% confidence intervals were determined from MPN tables. The 95% confidence intervals represent a measure of the method uncertainty. For data analysis purposes, ENT concentrations below the lower limit of detection (10 MPN/100 mL) were assigned a value of 5 MPN/100 mL.

Data were analyzed using SPSS v.11 (SPSS) and Matlab v7.0.4 (Mathworks). Kruskal-Wallis tests were used to compare ENT concentrations measured between sites or conditions. Following Whitman and Nevers (24), the number of samples (n) required during the experiments to achieve a specific level of certainty, or coefficient of variation (CV), about the experiment average (x̄) given the standard deviation (s) was calculated as $n = (s/x̄ CV)^2$. CV values of 20% and 50% were chosen for simplicity, although any CV could have been used.

Fourier transforms were applied to detrended ENT data series. To determine whether spectral densities decayed as power laws with frequency and were thus fractal, spectral density estimates were averaged within equal logarithmically spaced intervals following Lovejoy et al. (15). Linear regressions were applied to determine power-law exponents $\beta$ and their 95% confidence intervals. This approach assumes that a single fractal dimension can be used to describe data (16).

Results

Ten Minute Time Series. Time series of ENT measured once every 10 min are illustrated in Figure 1 along with tide level (HSB02, LPS05, LPS07, LPN07). High frequency variability is evident that cannot be explained by measurement uncer-
The average change in ENT concentration between consecutive samples during the experiments ranges from 26 (HSB02) to 45 (LPS07) MPN/100 mL per 10 min (Table 2). The maximum change in ENT concentration between samples is 345 MPN/100 mL per 10 min measured at LPS05. At all sites, the maximum change in ENT concentration between consecutive samples is greater than the California single-sample ENT standard of 104 MPN/100 mL. This indicates that changing the sampling time by as little as 10 min could result in a change in the posting or advisory status of the beach. There are instances when there is no change between ENT measurements between consecutive samples. Many of these (approximately 40%) occur when 5 MPN/100 mL is assigned as the lower limit of detection and thus may be an artifact of our detection limit.

The difference between ENT concentrations measured in consecutive samples relative to the experiment average ($\delta$) was calculated (Table 2). The distributions of $\delta$ are not different between experiments ($p > 0.05$) and range from 0 to 7 (10 min$^{-1}$ and average 0.5 (10 min)$^{-1}$. This means that overall, ENT concentrations typically vary by 60% every 10 min.

Using the standard deviations and means reported in Table 2, a beach manager would need to collect 39 (HSB02), 31 (LPS05), 25 (LPS07), and 25 (LPN07) samples to obtain an estimate of concentration within a coefficient of variation of 25%.
Symbols show measurements lower and greater than the 5th and 95th percentiles, respectively.

**TABLE 2. ENT Concentration Measurement Results**

<table>
<thead>
<tr>
<th>experiment</th>
<th>N</th>
<th>UD</th>
<th>ave</th>
<th>SD</th>
<th>GM</th>
<th>ave change (min-max)</th>
<th>ave δ (min-max)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HSB02</td>
<td>102</td>
<td>24</td>
<td>33</td>
<td>41</td>
<td>19</td>
<td>20 (0-234)</td>
<td>0.8 (0-7.1)</td>
</tr>
<tr>
<td>LPS05</td>
<td>131</td>
<td>14</td>
<td>54</td>
<td>60</td>
<td>31</td>
<td>35 (0-345)</td>
<td>0.8 (0-6.4)</td>
</tr>
<tr>
<td>LPS07</td>
<td>144</td>
<td>22</td>
<td>96</td>
<td>95</td>
<td>44</td>
<td>45 (0-318)</td>
<td>0.5 (0-3.3)</td>
</tr>
<tr>
<td>LPN07</td>
<td>144</td>
<td>28</td>
<td>60</td>
<td>59</td>
<td>32</td>
<td>36 (0-238)</td>
<td>0.6 (0-4.0)</td>
</tr>
<tr>
<td>LPmin</td>
<td>49</td>
<td>0</td>
<td>62</td>
<td>39</td>
<td>51</td>
<td>34 (0-140)</td>
<td>0.5 (0-2.3)</td>
</tr>
</tbody>
</table>

* N is the number of samples collected and UD is the number of samples with ENT below the lower detection limit of 10 MPN/100 mL; ave is arithmetic average, SD is standard deviation, GM is geometric mean, all with units of MPN/100 mL; ave change is the average change between consecutive samples with minimum and maximum given in parentheses and units of MPN/100 mL per 10 min except for LPmin where units are MPN/100 mL per min; ave δ is the average change between samples relative to the experiment average with units (10 min)^{-1} except for LPmin where units are (min)^{-1}.

20% about the experiment mean. If a coefficient of variation of only 50% were desired, 6 (HSB02), 5 (LPS05), 4 (LPS07), and 4 (LPN07) samples would be required.

There are no peaks in the spectral densities at specific frequencies (Figure 3). Rather, spectral densities decay as power-laws with frequency. Power-law exponents β for each spectra are within 5% confidence of 1 with the exception of LPS05. β for LPS05 ranges between 0.3 and 0.9 with 95% confidence. All linear regressions were statistically significant (p values reported in Figure 3, p < 0.05).

**Spatial Variation between LPS07 and LPN07.** During the LP experiment during 2007, samples were collected concurrently at two sites on the beach approximately 50 m apart. The measurements at these sites are well correlated to each other (Spearman’s r = 0.71, p < 0.05); however the two data series are significantly different (p < 0.05) with LPS07 having higher ENT concentrations than LPN07. The same concentration was measured simultaneously at the two sites 18 out of 144 (12.5%) times. The mean difference between measurements at LPS07 and LPN07 collected at the same time is 56 MPN/100 mL and the maximum is 379 MPN/100 mL. Importantly, 59/144 (41%) measurements at LPS07 are over the California single-sample standard of 104 MPN/100 mL while only 27/144 (19%) are over the standard at LPN07.

**Discussion**

ENT concentrations collected at 10 and 1 min intervals along the shoreline of marine beaches illustrate that temporal variability is extreme. Changes in ENT concentrations between consecutive samples greater than the California single-sample standard of 104 MPN/100 mL are not unusual. Extreme variability is present in experiments conducted in a turbulent, well-mixed surf zone (HSB02), in waters transitioning from quiescent/tide-dominated to wave-dominated (LPS05 and LPmin), and in a quiescent tide-dominated system.
environment (LPN07 and LPS07). Variability, measured as the change in consecutive ENT measurements normalized by the experiment average ENT concentration, is not different between sites, thus does not appear to be a function of the degree of wave exposure.

It should be noted that the extreme variability documented here is not a result of the method used to enumerate ENT. In another study, we used membrane filtration in conjunction with qEI media to measure ENT concentrations at LP every 20 min (28). We saw similar ENT variability; it is likely that any ENT analysis method will give similar results regarding variability. However, experiments need to be conducted to document variability with methods that measure nucleic-acid targets for ENT quantification.

Although results are not reported here, E. coli were also measured using Colilert-24 and Colilert-18 (IDEXX) during the experiments described in Table I. Colilert has been shown to perform well in California marine waters for E. coli enumeration (23, 28). Conclusions regarding variability in ENT apply to these bacteria as well. It is likely that variability over similar time scales will apply to other microbial targets including source-specific markers like those in Bacteroidales (29), but this should be confirmed.

Low frequency patterns associated with sunlight and tides are apparent in each time series that lasted for longer than 1 h. It is interesting that neither diurnal nor semidiurnal peaks are evident in the spectra (Figure 3). This is likely due to the relatively short duration of the time series relative to diurnal and semidiurnal periods.

Despite the lack of spectral peaks, coastal ENT concentrations are structured because time series can be described mathematically as decaying power-laws in the frequency domain. Even though the physical environments studied are different with regard to wave exposure, ENT concentrations are structured similarly with power-law exponents close to 1 (Figure 3). The fact that the power-law exponents are not equal to zero implies that the variability is not random, or white noise, as this would have produced a flat spectra. ENT time series share properties of 1/f noise (30) and have a fractal dimension $D = 2$. Seuront and Lagadec (32) report $D$ between 1.367 and 1.626 for temperature, salinity, and fluorescence in tidally mixed waters in the English Channel. $B(f)$ of their data series declined more rapidly with increasing $f$ compared to those in Figure 3. Relative to my data series, low-frequency oscillations were more dominant than high-frequency oscillations in their data series.

The fact that the ENT data share characteristics with 1/f noise indicates ENT are "patchy" and that there were ENT patches or filaments of all durations or sizes transported by the fixed sampling site during the experiments. Patchiness in time and space is expected to develop in coastal environments where intermittent sources, nonuniform currents, turbulent diffusion, and changing chemical or biological characteristics influence persistence and transport of ENT (15, 32).

How knowledge of the fractal dimension of the ENT series might be harnessed to provide recommendations for sampling plans to protect human health is not clear. By definition, a fractal time series has no characteristic time scale associated with it, so sampling at a particular time interval cannot be recommended. An important point is that ENT concentrations are not random while even though there are no spectral peaks. More work on understanding fate and transport of ENT in coastal waters is needed so that researchers can fully understand how patchiness develops.

The result reported here regarding extreme variability presents a challenge to policy makers and the protection of human health. Assuming ENT are from an urban runoff or municipal wastewater source and the epidemiological models (1-9) are correct, ENT concentrations correlate to health risk. This suggests that not only are ENT patchy in time and space behaving as 1/f noise, but so are human pathogens and human health risks. An inability to estimate the true concentration of ENT in coastal waters limits our ability to protect human health. A way of sampling the coastal ocean for ENT to uncover a true estimate of human health risk is needed. If a health-protective estimate is desired, then sampling should be conducted at night during ebbing (at HS08) or flooding (at LP) tides. The high frequency variability indicates that regardless of sampling time, a single sample of ENT does not tell one little about the true water quality, so multiple samples need to be collected. If it is not feasible to collect multiple samples, then a spatially or temporally composited sample will improve the estimate of the true water quality. At minimum, consecutive samples collected at 1 min intervals could be composited to obtain a better estimate of water quality. Policy makers, as well as scientists designing field campaigns for microbial source tracking and epidemiology studies, are cautioned that a single sample of water reveals little about the true water quality at a beach.

Predictive models (25, 33-35) may help to estimate average water quality given high frequency variability of measurements. These models use physical, chemical, and biological factors to predict concentrations of ENT. If enough high quality data are used to train models, they may be able to provide better estimates of the central tendency of daily ENT concentrations than single grab-sample measurements. Future work should examine this possibility by comparing model predictions to high frequency data measurements.

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Supporting Information Available

Figures S1 and S2. This information is available free of charge via the Internet at http://pubs.acs.org.

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Public Mis-Notification of Coastal Water Quality: A Probabilistic Evaluation of Posting Errors at Huntington Beach, California

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Whenever measurements of fecal pollution in coastal bathing waters reach levels that might pose a significant health risk, warning signs are posted on public beaches in California. Analysis of historical shoreline monitoring data from Huntington Beach, southern California, reveals that protocols used to decide whether to post a sign are prone to error. Errors in public notification (referred to here as posting errors) originate from the variable character of pollutant concentrations in the ocean, the relatively infrequent sampling schedule adopted by most monitoring programs (daily to weekly), and the intrinsic error associated with binary advisories in which the public is either warned or not. In this paper, we derive a probabilistic framework for estimating posting error rates, which at Huntington Beach range from 0 to 41%, and show that relatively high sample-to-sample correlations (> 0.4) are required to significantly reduce binary advisory posting errors. Public mis-notification of coastal water quality can be reduced by utilizing probabilistic approaches for predicting current coastal water quality, and adopting analog instead of binary, warning systems.

Introduction

Many government-sponsored environmental monitoring programs issue health advisories whenever pollutant concentrations reach levels that might pose a threat to human health. The utility of health advisory programs logically depends on their ability to disseminate timely and accurate information, in a format that is useful and easy to understand. This study examines the health advisory component of a large (statewide) shoreline water quality monitoring program in California. Health advisories take the form of warning signs that are posted at public beaches whenever shoreline water quality (as measured by fecal indicator bacteria) fails to meet one or more of seven different state standards. The California health advisory program is one of a growing number of such programs nationwide, sponsored in part by the Federal Beaches Environmental and Coastal Health Act passed by the U.S. Congress in October 2000 (1–4). A noteworthy aspect of the California program is its binary nature, in which information about coastal water quality is conveyed to the public by the presence or absence of warning signs on the beach during the high-use period from April 1 through October 31 of every year. This binary approach stands in contrast to other long-standing reporting programs, for example, weather forecasts, in which the information provided to the public is probabilistic in nature (5).

In this paper, we set out to answer several questions: (1) What is the magnitude of error associated with binary health advisories? (2) How are these error rates affected by the degree to which the concentrations of bacteria in consecutive samples are correlated? (3) Can the accuracy and effectiveness of health advisories be improved by changing the way data are collected and analyzed and/or by changing the way water quality information is conveyed to the public? To answer these questions, we develop a probabilistic framework for analyzing posting errors and compare the predictions of posting errors at Huntington Beach in southern California. Huntington Beach is an ideal natural laboratory to examine shoreline water quality issues because of the magnitude of the historical water quality problem, the wealth of available shoreline monitoring data, and the fact that a series of special studies have been conducted with a wide range of sampling frequencies (6–8).

Public Notification of Shoreline Water Quality in California

Beginning July 1, 1999, the State of California mandated fecal indicator bacteria monitoring at all public beaches with more than 50,000 annual visitors and established seven statewide concentration standards for fecal indicator bacteria in the surf zone. When the concentration of indicator bacteria at a monitoring site exceeds any of the California standards, the local health official must post a sign warning beach goers of potential health risks associated with entering the water (surf zone posting). If a sewage spill is suspected, the local health official may close the surf to public access (surf zone closure). Four of the seven standards are single-sample standards, for which a monitoring site is considered to be out of compliance if the concentration of indicator bacteria in a single sample exceeds specified concentrations for total coliform (TC), fecal coliform (FC), and Enterococcus species (ENT). The California single-sample standards for TC, FC, and ENT are respectively 10,000, 400, and 104 most probable number (MPN) or colony forming units (cfu)/100 mL, a fourth single-sample standard for TC of 1000 MPN or cfu/100 mL applies when the TC/FC ratio falls below 10. The remaining standards are 30-day geometric mean standards, for which a monitoring site is considered to be out of compliance if the geometric means of TC, FC, and ENT in all samples collected within a 30-day period exceed 1000, 200, and 35 MPN or cfu/100 mL, respectively. These standards correspond, at least theoretically, to a threshold rate of bacterial illness of 19 cases of highly credible gastrointestinal disease for every 1000 bathers (3, 9–11). There are many historical reasons for choosing this particular threshold, including the fact that it represents the background rate of gastrointestinal illness among the general population (12).

Observations of Posting Errors at Huntington Beach

The surf zone posting protocols described above were adopted with the goal of conveying to the public up-to-date information about surf zone water quality. However, a post de facto comparison of posting records and water quality test results indicates that the public is often mis-notified about current water quality conditions. This point is illustrated in Figure 1A where we compare measurements of...
ENT in the surf zone at Huntington Beach (color ranging from blue to black) with the posting and closure history (black and red polygons, respectively) over the period May 1–October 31, 1999. This time period was selected because it includes the summer of 1999 when Huntington Beach experienced a record number of postings and closures, and it straddles the start of California’s new water quality regulations that went into effect July 1, 1999. Most (95%) of the postings indicated in the figure were triggered by the single-sample and geometric mean standards for ENT. Yet there are many instances when the concentration of ENT exceeded the single-sample standard but signs were not posted (referred to here as underprotection errors) or where the concentration of ENT was below the single-sample standard but signs were posted (overprotection errors). Often, overprotection errors immediately follow underprotection errors (e.g., see events 1–3 in Figure 1A). Presumably, posting errors caused by the single-sample standards originate from the variable nature of water quality in the surf zone (see next section) and the inherent time delay (ca. 2–3 d) between when a sample is collected and when a sign is posted or taken down. The geometric mean standard also triggered overprotection errors involving multiple shoreline stations and lasting several weeks (see last half of event 4 in Figure 1A). The geometric mean is computed from test results collected at a particular site over the preceding 30 days (the so-called 30-day geometric mean standard); therefore, once a violation has occurred, a relatively large sequence of compliant samples are required before the geometric mean falls back below the standard. It should also be noted that the use of geometric means for evaluating human health risk has been challenged on theoretical grounds (13).

Importantly, we note that beach closures can be more accurate predictors of poor water quality than beach postings. Beginning on July 1, 1999, the local health officer closed sections of Huntington Beach out of concern that the surf zone contamination might be from a source of sewage (red polygon in Figure 1A). From personal observations, the health officer was aware that the concentration of fecal indicator bacteria in the surf zone at Huntington Beach was generally highest during full and new moons when (the daily tide range is maximal, compare Figure 1, panels A and B) (14). Awareness of these lunar cycles influenced the health officer’s decisions about when to close the beach and was one of the factors that allowed him to correctly anticipate the large pollution event that occurred during the full moon in early September (see large closure event in Figure 1A). This anecdote suggests that posting error rates might be reduced if posting protocols were designed to take into account factors known, through past experience, to influence local water quality. Some of the factors affecting surf zone water quality are described next.

**Patterns and Randomness in Shoreline Water Quality**

Surf zone water quality has both periodic patterns and random fluctuations. The concentration of fecal indicator bacteria in the surf zone at Huntington Beach, for example, exhibits a cascade of periodic patterns including (6–8): (1) tidal cycling in which the concentration is higher during ebb tides and lower during flood tides (or vice versa); (2) diurnal cycling in which the concentration is higher at night and lower during the day; (3) spring–neap cycling in which the concentration is higher during spring tides and lower during neap tides (evident in Figure 1A); (4) seasonal cycling in which the concentration is higher during the winter storm season and lower during the summer dry season; (5) El Niño cycling...
in which the concentration is higher during stormy El Niño winters and lower during dry La Niña winters; (6) multi-decadal patterns in which periodic large-scale investment in sewage and storm runoff infrastructure improves coastal water quality.

Monitoring programs can detect these periodic patterns only if the time interval between samples is smaller (by at least a factor of 2) as compared to the characteristic period of a particular pattern of interest (15). For example, samples must be collected at least every 3 h in order to detect tidal cycling because each ebb and flood tide lasts ca. 6 h. Routine monitoring programs in California, which typically sample each site once per day to once per week, can detect patterns 3–6 described above depending on the length of time over which data are available. Importantly, processes with characteristic periods less than the sampling interval cannot be detected because the water quality signal is aliased by the sampling program. The relative uncertainty associated with the water quality sampling and testing methods, which ranges up to 23% (16), is also a source of noise (17). In the next several sections, we develop and test a probabilistic model that can account for the repeating patterns and random noise inherent in water quality measurements. To make the results of the probabilistic analysis accessible to a broad audience, each section begins with the primary question to be addressed, immediately followed by the answer supported by the analysis.

**Probability of Single-Sample Exceedences**

**Question:** Can the fraction of samples violating single-sample standards be predicted from statistical features of local water quality, such as measures of central tendency and spread?  

**Answer:** The fraction of samples violating single-sample standards can be predicted from the log-mean and standard deviation of fecal indicator monitoring data, provided that the data are well described by a log-normal distribution. Furthermore, the theory predicts and observations confirm that, under certain conditions, a marginal change in water quality can lead to a substantial change in the number of signs posted at the beach.

The probability that the concentration of bacteria in a single sample will exceed a standard (S) can be represented mathematically as follows:

\[
P_{ex} = \Phi [C > S] = \int_{S}^{\infty} f(c) dc\]  

where C is a random concentration variable, c is a particular realization of the random variable, and \(f(c)\) is the probability density function for the concentration of fecal indicator bacteria in the surf zone. The exceedence probability \(P_{ex}\) is a measure of water quality: \(P_{ex} \rightarrow 0\) if water quality is very poor, and \(P_{ex} \rightarrow 1\) if water quality is very good.

The monitoring data at Huntington Beach conform reasonably to a log-normal distribution (based on Kolmogorov–Smirnov normality tests (18); maximum difference \(K - S = 0.08\) at the significant level \(\alpha < 0.01\)) (see Figure S1 in the Supporting Information) as do monitoring data at other coastal sites throughout the world (19–21). Accordingly, we replaced C with \(\log C\) in eq 1 and substituted the Gaussian probability distribution function for \(f_{\log c}(\log c)\). After simplification, the following relationship was obtained between the exceedence probability and a nondimensional variable referred to here as \(S^*\):

\[
P_{ex} = \frac{1}{2} \text{erfc} \left( \frac{S^*}{\sqrt{2} \sigma_{\log c}} \right) \]  

**Equation (2a)**

**Equation (2b)**

\[
S^* = \frac{\log \frac{S - \mu_{\log c}}{2 \sigma_{\log c}}}{\sqrt{2} \sigma_{\log c}} \]

In these equations, erfc is the complementary error function, and \(\mu_{\log c}\) and \(\sigma_{\log c}\) represent the mean and standard deviation of the log-transformed bacterial concentrations, respectively.

This simple theoretical result predicts that the exceedence probability decreases with increasing values of the parameter \(S^*\), ranging from \(P_{ex} > 99\%\) when \(S^* < -2\) to \(P_{ex} < 1\%\) when \(S^* > 2\) (solid line in Figure 2). In turn, the value of \(S^*\) depends on local water quality \((\mu_{\log c}\) and \(\sigma_{\log c}\)) and the magnitude of the single-sample standard (log 4).

These theoretical predictions compare well with observations of single-sample exceedences at Huntington Beach. To compute the latter, summertime measurements of ENT in the surf zone at Huntington Beach were grouped, or binned, by station and year. For example, one bin constituted all ENT measurements collected at surf zone station 9N during the summer of 1999; for the purposes of this analysis, summer is defined as the time period June 1–August 31. From each data bin, we calculated the fraction \(P_{ex}\) of samples that violated the single-sample standard for ENT and an empirical approximation of the parameter \(S^*\); denoted here as \(S^*\) (see Supporting Information, note that the circumflex or "hat" denotes empirical approximations of population parameters). Values of \(P_{ex}\) and \(S^*\) track the theoretical prediction closely (compare solid line with data points in Figure 2); hence, eq 2a appears to capture the relationship between measured water quality \((\mu_{\log c}\) and \(\sigma_{\log c}\)) and the fraction of samples that exceed a single-sample standard \(P_{ex}\). At Huntington Beach, the percentage of samples exceeding the single-sample standard for ENT ranges from a low of 0% \((P_{ex} = 0)\) at surf zone station 0 during the summer of 2000 to a high of 40% \((P_{ex} = 0.4)\) at station 9N during the summer of 1999 (see arrows in Figure 2).

From the shape of the theoretical curve in Figure 2, a marginal change in water quality can result in a very large or a very small change in the number of signs posted at the beach, depending on the absolute magnitude of the parameter \(S^*\). In particular, eq 2a predicts that \(P_{ex}\) is sensitive to marginal changes in water quality when \(|S^*| \leq 1\) and
Probabilty of Binary Advisory Posting Errors

Question: How is the posting error rate influenced by the degree to which bacterial concentrations in consecutive samples are correlated? At Huntington Beach, are bacterial concentrations in consecutive samples correlated or independent realizations?

Answer: Theory predicts very high posting error rates when \( S^* \) is close to zero, even in the case where the concentrations of fecal indicator bacteria in consecutive samples are moderately correlated. This prediction is borne out by an analysis of ENT measurements in the surf zone at Huntington Beach. Posting error rates at Huntington Beach are indistinguishable from the predictions of Bernoulli trial theory, which is premised on the idea that test outcomes are independent realizations.

When \( S^* \) is close to zero, posting error rates are predicted to range from 35% (for moderately correlated samples) to 50% (for weakly correlated samples).

Let \( c(t) \) represent the measured concentration of fecal indicator bacteria at a particular site at time \( t \). The single-sample standard posting protocol can be stated succinctly as follows. A water sample is collected at a particular site at time \( t \), and the concentration of fecal indicator bacteria in that sample \( c(t) \) is compared to a single-sample standard \( s \). If \( c(t) \) is greater than \( s \), a sign is posted at the site; if \( c(t) < s \), a sign is not posted at the site (or an existing sign at the site is removed). If \( t \) denotes the time at which a sign is posted (or removed), four possible outcomes can be identified: (1) \( c(t) > s \) and \( c(t-1) < s \), (2) \( c(t) < s \) and \( c(t-1) < s \), (3) \( c(t) > s \) and \( c(t-1) > s \), and (4) \( c(t) > s \) and \( c(t-1) < s \). No error occurs in cases 1 and 2 because the public has been correctly informed that water quality exceeds standards (case 1) or does not exceed standards (case 2). Posting error occurs when the public is incorrectly informed that water quality meets standards (case 3), or incorrectly informed that water quality does not meet standards (case 4). Consistent with the discussion of Figure 1A (see above), we refer to cases 3 and 4 as underprotection and overprotection posting errors, respectively.

Letting the superscripts \( U \), \( O \), and \( T \) represent underprotection, overprotection, and total posting error (as the sum of underprotection and overprotection errors), the following expressions can be derived for the probability that posting errors will occur at a particular site (see Supporting Information):

\[
P_{\text{err}}^U = P_{\text{err}}^O = \frac{1}{2} \text{erfc} \left( S^* \left[ 1 - \frac{1}{2} \text{erfc} \left( \frac{S^*}{\sigma}(S^*, \rho(1)) \right) \right] \right) \quad (3a)
\]

\[
P_{\text{err}}^T = \text{erfc} \left( S^* \left[ 1 - \frac{1}{2} \text{erfc} \left( \frac{S^*}{\sigma}(S^*, \rho(1)) \right) \right] \right) \quad (3b)
\]

The function \( G(S^*, \rho(1)) \) depends on the value of \( S^* \) and \( \rho(1) \), where \( S^* \) has been defined previously (see eq 2b) and \( \rho(1) \) is the correlation coefficient between fecal indicator bacteria concentrations at times \( t \) and \( t \). A mathematical definition and graphical representation of \( G(S^*, \rho(1)) \) is included with the Supporting Information (Figure S2). The total posting error predicted by eq 3b is plotted against \( S^* \) in Figure 3. Different lines in the figure correspond to different choices of the correlation coefficient \( \rho(1) \), ranging from strong positive correlation (\( \rho(1) = 0.95 \)) to strong negative correlation (\( \rho(1) = -0.95 \)). For the choice of \( \rho(1) = 0 \), the concentrations of bacteria in consecutive samples are completely uncorrelated (i.e., every concentration measurement is independent of the one before it), and the function \( G(S^*, \rho(1)) \) reduces to unity for all choices of \( S^* \). In this limit, referred to here as the Bernoulli trial theory limit, the probability of an overprotective or underprotective posting error peaks at \( P_{\text{err}}^U = 0.5 \) when \( S^* = 0 \) (dashed line in Figure 3). Put another way, when the concentrations of bacteria in consecutive samples are uncorrelated (\( \rho(1) = 0 \)) and half of samples exceed the single-sample standard \( S^* = 0 \), posting rates calculated from the surf zone monitoring data at Huntington Beach data bins described in the last section (see Supporting Information). Values of \( P_{\text{err}}^U \) track closely the theoretical line for \( \rho(1) = 0 \) (i.e., the Bernoulli trial theory limit, compare data points with dashed line in Figure 3), consistent with the idea that the concentrations of ENT in consecutive samples at Huntington Beach are uncorrelated. To explore this issue further, for each data bin, we calculated the correlation coefficient between ENT concentrations in consecutive
samples, referred to here as $p(l)$ (see inset in Figure 3). Empirical correlation coefficients range from $p(l) = 0.04$ to $0.58$; averaging across all bins, we obtain $p(l) = 0.32 \pm 0.13$. The concentration of ENT in consecutive samples are not completely uncorrelated (i.e., $p(l) = 0$); however, the sample-to-sample correlation is sufficiently weak such that total posting error rates are indistinguishable, within the resolution of our estimates of $P_{err}$, from the predictions of Bernoulli trial theory. An exception may be the three data bins with the highest correlation coefficients: station 6N in 1998, station 3N in 1999, and station 9N in 2000 (compare red points and dashed line in Figure 3).

Can Increasing the Sampling Frequency Reduce Posting Errors?

**Question:** Would the sample-to-sample correlation be higher and the rate of single-sample posting errors be lower if surf zone samples were collected more frequently?

**Answer:** An analysis of ENT data at Huntington Beach reveals that posting decisions would have to be updated every 40 min (or more frequently) to significantly reduce posting errors. Even if posting decisions were revised every 10 minutes, when $S^*$ is close to zero as much as 30% of the signage would be in error. This result will likely apply to any shoreline site where the sampling time interval is longer than the persistence time of pollution patches in the surf zone.

The question is motivated by the growing interest in developing rapid fecal indicator bacteria tests that could, in principle, dramatically reduce the time between when a sample is taken and the bacterial indicator concentration is known (22). The answer derives from an analysis of autocorrelation functions computed from four different time series (Figure 4): (1) Routine ENT monitoring data at station 9N, subsampled to yield a sampling frequency of once per week ($\Delta t = 1$ week, panel A). (2) Routine ENT monitoring data at station 9N subsampled to yield a sampling frequency of once per 3 days ($\Delta t = 3$ days, panel B). (3) A special ENT monitoring study at station 3N in which water samples were collected every hour, 24 h per day, for 2 weeks ($\Delta t = 1$ h, panel C). (4) A second special ENT monitoring study at station 6N in which water samples were collected every 10 min for a total of 12 h ($\Delta t = 10$ min, panel D). The autocorrelation functions in Figure 4 represent the correlation $p(\Delta t)$ between a time series and itself after introducing a lag of $j$ points or, equivalently, a time lag of $\Delta t = j \Delta t$. For comparison, also plotted in each panel of the figure are autocorrelation functions calculated from a sequence of random numbers ranging in magnitude from 1 to 1 (black lines in each panel).

Correlation $p(\Delta t)$ falls off very rapidly with increasing lag $\Delta t$, for sampling intervals of $\Delta t = 1$ week and 3 days (red curves in panels A and B, respectively). When $\Delta t = 1$ week (panel A), a broad peak is evident at time lags of 40–50 weeks (i.e., approximate 1 yr), presumably due to the influence of seasonal rainfall on bacterial concentrations in the surf zone. Spring–neap cycling of bacterial concentration is apparent in panel B where the correlation values peak every 2 weeks. Apart from the seasonal (panel A) and spring–neap (panel B) patterns, the correlation coefficients calculated for these two cases are generally within the range calculated from a sequence of random numbers (black lines). Correlation peaks are present at multiples of 24 h when the surf zone is sampled every hour ($\Delta t = 1$ h, panel C). This diurnal cycle probably arises from the germicidal effect of sunlight (7), although tidal processes may also play a role (e.g., during the summer at Huntington Beach there is typically just one large ebb tide per day). Remarkably, the sign of $p(\Delta t)$ in Figure 4C is periodically negative, implying that posting error rates might increase if the sampling frequency is increased, for example, from once per day to once every 12 h (see peak error rates when $p(l) < 0$ in Figure 3). Compared to the other autocorrelation functions, $p(\Delta t)$ decays with $\Delta t$ more slowly when samples are collected every 10 min (panel D). Even in this case, however, the correlation coefficient for a lag of 10 min ($p(\Delta t = 10$ min$) = 0.6$) is such that substantial posting errors (30%) are predicted when $S^* \approx 0$ (see Figure 3). Put another way, if the time interval between when a sample is taken and a sign is posted (or removed) was reduced to just 10 min, as much as 30% of the signage could be in error. The technology for rapid detection of fecal indicator bacteria is maturing such that near real-time measurements of these organisms may be feasible soon. Even if bacterial measurements could be carried out instantaneously (i.e., $\Delta t = 0$ and $p(l) = 1$), however, it is not clear how that information would be used in practice. Given the highly variable nature of the coastal water quality signal, health advisories would have to be updated on a minute-by-minute basis, creating an untenable...
situation for both local officials who issue health advisories and the beach-going public.

On the basis of the autocorrelation functions presented in Figure 4A, B and the correlation values calculated from ENT monitoring data at Huntington Beach (inset in Figure 3), it appears that at 0.4 is typical of sampling frequencies in the once-per-day to once-per-week range. Because the posting error rates calculated from the daily to weekly monitoring data closely follow the predictions of Bernoulli trial theory (see Figure 3), it seems reasonable to adopt 0.4 as the critical correlation value above which Bernoulli trial theory begins to break down (\( R < 0.4 \)). Referring to Figure 4D, the correlation \( R(t, t + 1) \) appears to lie below 0.4 for lag times greater than approximately 40 min (see dashed arrow in figure). This lag is very close to the time it takes tidally generated patches of fecal pollution in the Huntington Beach surf zone to advect past a fixed location by wave-driven long-shore currents (6). Therefore, the concentration of bacteria in a water sample from the surf zone appears to have little memory of previous samples (and hence Bernoulli trial theory applies) so long as the time interval between samples is less than the persistence time of pollution patches. While the persistence time scale will vary by site, given the highly dynamic nature of ocean currents at most coastal sites it is unlikely that the persistence time scale will exceed 1 d, the sampling frequency of the most aggressive shoreline monitoring programs. Hence, the large posting error rates reported in this paper are probably not unique to Huntington Beach. Rather, large errors can be expected at any marine or freshwater beach when \( |s| < 1 \) and the time interval between samples is greater than the persistence time scale for patches of contaminated water.

Toward an Analog Public Health Advisory System

**Question:** Can less error-prone approaches be developed for assessing current water quality and reporting that information to the public?

**Answer:** Several different approaches can be adopted to predict (or "now-cast") current coastal water quality and report that information to the general public. At Huntington Beach, the current concentration of ENT at a particular surf zone station is generally more correlated with the maximum daily tide range, than with the concentration of bacteria in the last sample.

An approach that follows naturally from the probability theory presented above involves computing analog (i.e., continuously varying) estimates of current water quality and/or human health risk, periodically updated as new information becomes available. Predictions of current water quality, or now-casts, could utilize a variety of data resources including recent water quality test results and real-time (or near-real-time) measurements of quantities known to correlate with local surf zone water quality. Now-casts, in turn, could be conveyed to the public through a combination of web sites, newspaper reports, and/or beach signage either in raw form or using a grading scale like that employed by Heal the Bay (23).

As an example, below we present a prototypical algorithm that now-casts three different measures of water quality. For the sake of simplicity and to demonstrate the power of even a modest algorithm, our prototype requires only estimates of tide range (predicted from WXTide32 (24)) and water quality measurements collected over the previous 30 d. At the heart of the algorithm is the assumption that current water quality is conditioned on maximum daily tide range, as expressed quantitatively through the conditional probability density function, \( \delta_{\text{P}}(\log c | L) \). Here, \( \log c \) and \( L \) represent random variables for the log-transformed bacterial concentration and maximum daily tide range, respectively, and \( \log c \) and \( L \) are specific realizations of the random variables. For a fixed value of the tide range \( L \), the probability of single-sample exceedence and expected value of the bacterial concentration can be calculated as follows:

\[
P_{\text{P}}(\log c > \delta | L = \delta) = \int_{-\infty}^{\log c} f_{\log c}(x) dx\]  

\[
\mu_{\log c} = E[\log c | L = \delta] = \int_{-\infty}^{\log c} \mu_{\log c} f_{\log c}(x) dx
\]

An analysis of maximum daily tide-range predicted for Huntington Beach reveals that \( L \) conforms reasonably well to a normal distribution (based on Kolmogorov-Smirnov normality tests; maximum difference \( K - S = 0.04 \) at the significant level \( \alpha < 0.01 \) as do the log-transformed concentrations of fecal indicator bacteria (see earlier). This implies that eqs 4a,b can be written explicitly as follows (see Supporting Information):

\[
P_{\text{P}}(\log c > \delta | L) = \frac{1}{2} \text{erfc}(\sqrt{1 - \rho_{L}^2})\]  

\[
\mu_{\log c} = \mu_{\log c} + \rho_{L} \sigma_{\log c} \sigma_{\log c} (\mu - \mu_{L})
\]

\[
\sigma_{\log c} = \sqrt{\sigma_{L}^2 + \rho_{L}^2 \sigma_{\log c}^2}
\]

where \( \rho = (\log c - \mu) \sigma_{\log c} \), \( \rho_{L} \) is the correlation coefficient between \( \log c \) and \( L \), \( \mu_{L} \) and \( \sigma_{L} \) are the mean and standard deviation of the maximum daily tide range, and the other parameters have been defined previously. Equation 5b is a linear model for the dependence of \( \mu_{\log c} \) on \( L \), with coefficients equivalent to those obtained by a mean-square regression of \( \mu_{\log c} \) against \( L \). To develop an expression for bather illness rate, we utilized the linear relationship for gastrointestinal illness rate per 1000 bathers (Y) reported by Cabelli et al. (9):\[ Y = a + b \log GM_{c}, \] where \( GM_{c} \) represents the geometric mean of ENT measurements, and \( a = -5.1 \) and \( b = 24.2 \) are empirical constants. Rewriting Cabelli et al.'s model in terms of the conditional log-mean \( \mu_{\log c} \), we obtain:

\[
Y = a + b \log \mu_{\log c}
\]

\[
\sigma_{Y} = \sqrt{\sigma_{L}^2 + \rho_{L}^2 \sigma_{\log c}^2 + b^2 \sigma_{\log c}^2}
\]

The estimate of uncertainty in \( Y \) (eq 6b) was derived by propagating uncertainties in the variables on the RHS of eq 6a (17). This set of expressions (eqs 5a-c and 6a,b) were employed to now-cast water quality at surf zone station 6N over the period May 1–October 31, 1999 (i.e., the same period of time encompassed by Figure 1A). Now-casts for a particular day were generated using the current day's maximum tide range \( L \) (estimated from WXTide32) and updated estimates for \( \mu_{\log c} \) or \( \delta_{\text{P}} \) calculated from daily tide range and ENT measurements collected over the previous 30 d (see Supporting Information). Values for \( \delta_{L} = 6.35 \) and \( \sigma_{L} = 4.15 \) were estimated from data reported in Cabelli et al. (9).

Now-casts of the ENT concentration at 6N correctly capture the magnitude and spring-neap cycling of actual ENT measurements (compare red and blue curves, second panel of Figure 5). Over the 6-month period, 56% and 92% of the ENT measurements at 6N fell in the predicted range \( \mu_{\log c} \pm 2\delta_{\text{P}} \) (blue band in second panel) and \( \mu_{\log c} \pm 4\delta_{\text{P}} \), respectively. Now-casts of illness rate (third panel) are generally above the threshold level of 19 in 1000 (dashed
horizontal line), peaking at about 60 excess illnesses per 1000 bathers; these illness attack rates are in the range estimated by other researchers for the Huntington Beach area (26). Now-casts for the exceedence probability (fourth panel) exhibit spring-neap cycling, and importantly, periods of high exceedence probability (e.g., \( P_{\text{ent}} > 0.2 \)) generally coincide with single-sample violations (compare second and fourth panels, Figure 5). The last panel in the figure is a plot of the correlation coefficient between ENT concentrations in consecutive samples (\( \hat{\rho} (1) \), red line) and between ENT concentration and maximum daily tide range (\( \hat{\rho}_{\text{cl}} \), blue line). These two coefficients were updated every day in the 6-month period encompassed by Figure 5, using ENT and maximum daily tide range data collected (ENT) or calculated (tide range) over the previous 30 d. In general, \( \hat{\rho}_{\text{cl}} \) is larger than 0.4 (i.e., \( \hat{\rho}_{\text{cl}} > \hat{\rho}_{\text{ent}} \) see earlier) and larger than the correlation between the concentrations of bacteria in consecutive samples (\( \hat{\rho}_{\text{ent}} \geq \hat{\rho} (1) \)). The exception is an approximately 1-month period, centered around August 1, when \( \hat{\rho}_{\text{cl}} \approx 0 \). Not surprisingly, this was also the period when our now-cast model performed least well. In general, at Huntington Beach, the current concentration of bacteria at a particular surf zone station is more correlated with the maximum daily tide range than with the concentration of bacteria in the last sample.

The model presented above could be improved by utilizing all physical variables known through past experience to correlate with coastal water quality and/or by adopting alternative now-casting methodologies (e.g., artificial neural networks (27–29)) that tolerate nonlinear relationships between dependent and independent variables. As mentioned above, the ideal advisory system will be analog in nature; however, even if the current binary approach is retained, posting decisions based on now-cast methodologies, like the one described here, would be an improvement over the status quo. If the now-casts of ENT presented in Figure 5 had been used as the basis for posting decisions at Huntington Beach during the summer of 1999, for example, the total posting error rate there would have been reduced between 7.5% and 50% (depending on the particular surf zone station of interest).

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**Supporting Information Available**

Mathematical derivations and additional data. This material is available free of charge via the Internet at http://pubs.acs.org.

**Literature Cited**


(23) Heal the Bay (available at http://www. healthbay.org/brc/).


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ES034382V
Final Report: Identification and Control of Non-Point Sources of Microbial Pollution in a Coastal Watershed

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Investigators: Sanders, Brett, Grant, Stanley B., Horne, Alex, Keller, Robin, Sobsey, Mark D.
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Description:

Objective:

The objectives of this study were to: (1) characterize the magnitude and variability of fecal indicator bacteria (FIB) loads in the watershed along an inland to coastal gradient that includes street gutters, storm channels, tidal channels, and the surf-zone at Huntington Beach; (2) examine linkages between FIB and other indicators of human pathogens; (3) develop strategies to control FIB loads during nonstorm periods; and (4) aid decisionmaking by examining the perspectives of stakeholders, including beachgoers, environmentalists, local businesses, public health officials, and wastewater utility managers on various aspects of beach pollution problems, such as the causes, health risks, and responsibility to pay.

California beaches are a critical component of the culture and economy of California and are threatened by coastal pollution. Beach recreation in California accounts for $5.5 billion of the Gross State Product (King and Symes, 2003). Nowhere has there been greater attention on beach pollution than at Huntington Beach in southern California.

Huntington Beach, consisting of Huntington State Beach and Huntington City Beach, is located along a northwest to southeast striking section of the Pacific coastline between Los Angeles and San Diego, in Orange County, California. Several areas of Huntington State Beach have suffered chronic beach postings and closures over the past several years as a result of elevated concentrations of FIB in the surf zone (Kim and Grant, 2004). This beach is very popular (more than 5 million visitors per year), and the combination of surf zone pollution and significant beach usage implies that a large number of people (perhaps as many as 50,000) may acquire highly credible gastroenteritis from swimming and surfing in this area each year (Turbow, et al., 2003). FIB pollution at Huntington State Beach is thought to be caused by a combination of sources, including dry and wet weather runoff from the...
surrounding community, bird droppings deposited in the Talbert Marsh, and regrowth of bacteria on vegetation and marsh sediments (Grant, et al., 2001; Reeves, et al., 2004). Additional potential sources of FIB include the offshore discharge of partially treated sewage effluent (Boehm, et al., 2002a), the offshore discharge of power plant cooling water that contains FIB from plant wash-down and other activities (Boehm, et al., 2002b), resuspension of contaminated sediments (Sanders, et al., 2004), bather shedding, the accumulation of bird droppings along the shoreline and offshore, the exfiltration of sewage-contaminated groundwater, and contributions from watershed outlets located north and south of the study area, including the Los Angeles River, the San Gabriel River, and outlets for Huntington Harbor and Newport Bay (Kim, et al., 2004).

This project focuses on the Talbert Watershed in Huntington Beach and Fountain Valley, California, which drains to Huntington Beach and is a significant stressor of Huntington Beach water quality. The Talbert Watershed encompasses 3,400 hectares in the cities of Huntington Beach and Fountain Valley. The watershed is urbanized and consists of residential developments, commercial districts, plant nurseries, and light industry. This area of southern California has separate storm water and sanitary sewer systems, therefore, dry and wet weather runoff flows to the ocean without treatment. Runoff from the Talbert Watershed is conveyed along street gutters to inlets that connect to underground storm water pipelines. These pipelines connect to a network of three flood control channels (Fountain Valley, Talbert, and Huntington Beach) that converge near the ocean at a constructed wetland known as the Talbert Marsh. Ocean water floods both the Talbert Marsh and the lower reaches of the open channels during rising tides (flood tides), and a brackish mixture of ocean water and runoff drains from the system during falling tides (ebb tides). The Talbert Watershed is nearly flat and only a few feet above sea level. This geographical setting hinders drainage by gravity alone, so a system of transfer stations is used in the lower reaches of the Talbert Watershed to pump runoff into the open channels from storm water pipelines. Each transfer station, or pump station, consists of a forebay, where runoff can be stored, and several pumps. Pumping of runoff to the channels occurs intermittently during dry weather periods and continuously during storms.

Talbert Marsh is a 10-hectare remnant of what used to be an extensive (1,200 hectare) saltwater wetland and dune system in coastal Orange County. The majority of this wetland system was drained and filled over the past century for agricultural reclamation and urban development. Most of what remained of the historical wetland, including Talbert Marsh, was cut off from tidal flushing by the construction of the Pacific Coast Highway and channelization of the surrounding area for flood control. As part of a habitat restoration effort, tidal flushing in the Talbert Marsh was restored in 1990 when a new tidal inlet was constructed. Since its restoration, Talbert Marsh has become a typical southern California tidal saltwater marsh with open water, wetland, and upland habitats (Grant, et al., 2001). Pickle weed (Salicornia virginica) is the dominant macrophytic vegetation, and the marsh is utilized by several special-status bird species, including the California least tern, brown pelican, and Beldings savannah sparrow.

Summary/Accomplishments (Outputs/Outcomes):

To achieve the objectives, extensive monitoring of Talbert Watershed surface waters was conducted to measure the spatio-temporal variability of FIB loads (total coliform, *Escherichia coli*, and *Enterococcus*) and analysis was performed to examine the factors that control fate and transport. Monitoring also was performed to examine the association between FIB and other indicators of fecal pollution. Both one-dimensional and two-dimensional hydrodynamic models were developed to analyze the FIB loads in tidal channels and into the surf-zone and to develop a predictive tool that can be used to examine how bacteria loads would be altered by operational changes to the infrastructure. Surveys were performed to measure stakeholder preferences in the context of multi-
stakeholder, multi-objective beach pollution problems and to support decisionmaking analysis.

Closure and posting of Huntington Beach, California, during the study period was the source of widespread media attention. In response, members of the research team redirected efforts and/or engaged in a number of additional studies to better understand the factors controlling surface water quality in the Huntington Beach surf zone, as well as the response of stakeholders to the unfolding pollution problem. For example, co-principal investigator (PI) Keller focused attention on the decisionmaking of beachgoers (to swim or not to swim) in response to warning signs posted on the beach. Co-PI Keller also focused attention on the decisionmaking of public agencies, who were under great public pressure to remedy the pollution problem but had little understanding of its cause. To better understand the pollution problem, co-PI Grant analyzed short- and long-term FIB monitoring data to identify trends in Huntington Beach bathing water quality. The observed variability was examined in the context of historical management measures, such as passage of the Clean Water Act, construction of a new ocean outfall, and efforts to prevent urban runoff from draining directly to the beach. Co-PI Grant also developed a method to identify and rank the sources of pollution to the surf-zone using high-frequency monitoring data collected along the beach. PI Sanders teamed with University of California (UC) Irvine and UC San Diego researchers to examine the potential for Orange County Sanitation District effluent, discharged roughly 7 km offshore of Huntington Beach, to be transported onshore by internal tides. After the Talbert Marsh was identified as a contributor of FIB to the Huntington Beach surf zone, co-PI Sobsey focused attention on potential health risks associated with water contaminated with bird feces. In particular, marsh bird feces and surface water was examined for Campylobacter, Salmonella, and male-specific coliphages.

During dry weather, concentrations of FIB were highest in inland urban runoff, intermediate in tidal channels harboring variable mixtures of urban runoff and ocean water, and lowest in ocean water at the base of the watershed. This inland-to-coastal gradient is consistent with the hypothesis that urban runoff from the watershed contributes to coastal pollution. On a year-round basis, the vast majority (> 99%) of FIB loading occurs during storm events when runoff diversions, the management approach of choice, are not operating. During storms, the load of FIB in runoff follows a power law of the form \( L \sim Q^n \), where \( L \) is the loading rate (in units of FIB per time), \( Q \) is the volumetric flow rate (in units of volume per time), and the exponent \( n \) ranges from 1 to 1.5. This power law and the observed range of exponent values are consistent with the predictions of a mathematical model that assumes FIB in storm runoff originate from the erosion of contaminated sediments in drainage channels or storm sewers. (Reeves, et al., 2004)

During dry weather periods, urban runoff controls surface water concentrations of FIB in channels where flushing is weak, and resuspension of FIB from the sediment/water interface controls surface water concentrations near the mouth where flushing by ocean water occurs once per day. The reservoir of FIB at the sediment/water interface is probably linked to settling of bacteria from both dry and wet weather urban runoff, deposition of animal feces, decaying vegetation, and bacterial regrowth. It is not clear whether the FIB are primarily attached to sediments, suspended in pore water, or incorporated into microbial biofilms. Nevertheless, surface water concentrations of FIB are rapidly amplified as turbulence in water column increases. A result is that dry weather urban runoff has little direct impact on surf zone water quality, but significant indirect impact given FIB loads from runoff accumulate at the sediment/water interface and are subsequently resuspended and exported to the surf-zone by tidal currents (Grant, et al., 2001; Arega and Sanders, 2004; Sanders, et al., 2004).

During the project period, dry-weather diversions of urban runoff to the sanitary sewer system were implemented to mitigate impacts to the surf-zone, at a cost of at least $5 million to the County of
Orange and City of Huntington Beach. The efficacy of this approach is unclear, because the vast majority of watershed loads are shed during wet weather, whereas during dry weather, the tidal channels and marsh serve to dissipate loads by promoting die-off and settling. On the other hand, diversions presumably serve to reduce loads of other contaminants, including oil, grease, heavy metals, and so forth and, therefore, may be justified on these grounds. To evaluate whether the diversions are justified on the basis of FIB control, a better understanding of the cycling of FIB in sediments is needed. The alternative is to focus management efforts on wet weather controls. For example, if erosion of sediments is driving the loading of FIB, then regular removal of contaminated sediments accumulating in the storm sewer system might be an appropriate management strategy. The creation of distributed wetland treatment systems, in which contaminants in urban runoff are removed near their source, might also prove useful for reducing downstream impacts (Reeves, et al., 2004).

Research lead by PI Sanders shows that numerical modeling can be performed to predict FIB loads in tidal wetlands, analytes that are notoriously difficult to model because of poorly characterized non-conservative processes. The key parameters needed for accurate predictions of FIB loads, using a validated hydrodynamic model, are: (1) the load as a result of urban runoff; (2) sediment erodibility parameters; and (3) sediment concentrations and surface water die-off rates of enteric bacteria. For channels in the Talbert Watershed, literature values for sediment erodibility and water column die-off rates were used and average concentrations of indicator bacteria were predicted within one-half log unit of measurements. Total coliform were predicted more accurately than E. coli or enterococci, both in terms of magnitude and tidal variability. This work is important because it represents the first case where first-principle models were successfully applied to predict FIB in an estuarine setting with significant nonpoint sources. The approach adopted here is highly transferable and could benefit both wetland restoration and water quality compliance efforts on a widespread basis (Sanders, et al., 2004).

Plume tracking studies conducted by UC Irvine and UC San Diego researchers, including PI Sanders, show that Orange County Sanitation Department (OCSD) effluent occasionally moves shoreward toward Huntington Beach into water less than 20 m deep. Analyses of current and temperature observations indicate cold water is regularly advected crossshelf, into and out of the nearshore, at both semi-diurnal and diurnal frequencies. Isotherms typically associated with the wastefield near the outfall are observed just outside the Huntington Beach surf zone, where the total depth is less than 6 m, highlighting the extent of the cross-shelf transport. This advection is attributed to a mode 1 internal motion, or internal tide. Based on this analysis, it is not possible to rule out the possibility that the OCSD plume contributes to poor bathing-water quality at Huntington Beach (Boehm, et al., 2002a). Concerned over potential shoreline impacts, OCSD began a disinfection program in 2002 and initiated a roughly $300 million program to build the necessary infrastructure for full secondary treatment.

Analysis of Huntington Beach monitoring data lead by co-PI Grant shows that the concentration of FIB varies over time scales that span at least seven orders of magnitude, from minutes to decades. Sources of this variability include historical changes in the treatment and disposal of wastewater and dry weather runoff, El Niño events, seasonal variations in rainfall, spring-neap tidal cycles, sunlight-induced mortality of bacteria, and nearshore mixing. On average, total coliform concentrations have decreased over the past 43 years, although point sources of shoreline contamination (storm drains, river outlets, and submarine outfalls) continue to cause transiently poor water quality. These transient point sources typically persist for 5 to 8 years and are modulated by the phase of the moon, reflecting the influence of tides on the sourcing and transport of pollutants in the coastal ocean. Indicator bacteria are very sensitive to sunlight; therefore, the time of day when samples are
collected can influence the outcome of water quality testing. These results demonstrate that coastal water quality is forced by a complex combination of local and external processes and raise questions about the efficacy of existing marine bathing water monitoring and reporting programs (Boehm, et al., 2002b). Further analysis led by co-PI Grant reveals that protocols used to decide whether to post a sign are prone to error. Errors in public notification (referred to here as posting errors) originate from the variable character of pollutant concentrations in the ocean, the relatively infrequent sampling schedule adopted by most monitoring programs (daily to weekly), and the intrinsic error associated with binary advisories in which the public is either warned or not. We derived a probabilistic framework for estimating posting error rates, which at Huntington Beach range from 0 to 41 percent, and show that relatively high sample-to-sample correlations (> 0.4) are required to significantly reduce binary advisory posting errors. Public misnotification of coastal water quality can be reduced by utilizing probabilistic approaches for predicting current coastal water quality, and adopting analog, instead of binary, warning systems (Kim and Grant, 2004).

Research lead by co-PI Sobsey on the potential health risks of bathing water contaminated by bird feces has lead to only preliminary findings. Specifically, Campylobacter and male specific coliphages were identified in Talbert Marsh bird feces and in marsh surface waters near the marsh. Salmonella was found only in bird feces samples and not water samples. Analysis continues to understand the relationship between microbes in bird feces and surrounding surface waters, and potential health impacts.

Research lead by co-PI Keller indicates that stakeholders share diverse opinions about the causes of beach pollution, the risks to beachgoers, and the responsibility to pay. In the context of a multi-objective decision model, stakeholders disagree on the appropriate weights of objectives. For example, local businesses heavily weigh economics whereas beachgoers heavily weigh health risks. Stakeholders also disagree on the severity of pollution problems. For example, environmentalists believe the probability of an environmental health problem is high when beaches are posted, but beachgoers do not. Relative to beachgoers' perceptions of potential health risks, surveys showed a peer effect: decisions to enter the water at posted beaches were strongly affected by whether or not others were in the water (Biswas and Keller, 2004; Biswas, et al., 2004).

Conclusions:

The vast majority of FIB loads in runoff from the Talbert Watershed are shed during storms and are associated with particles that appear to be scoured from the water collection system, including street gutters, storm pipes, and storm channels. Loads in runoff during dry weather periods account for roughly 1 percent of the annual runoff load and dissipate within the tidal channels by a combination of die-off and settling.

Loads exported from the watershed to the surf zone during dry weather period are deflected along the shoreline by wave driven currents and can cause exceedances of water contact recreation standards. Model predictions show the origin of such loads is the scouring by tidal currents of FIB at the sediment/water interface of tidal channels and Talbert Marsh. FIB at the sediment/water interface are linked to urban runoff FIB loads during both dry and wet weather periods, bird droppings, decaying vegetation, and bacterial regrowth. Because intertidal wetlands are to some extent natural generators of FIB, these results call into question the exclusive use of FIB as the basis of water contact recreation standards at beaches near the outlet of these water bodies.

On the basis of FIB control, the efficacy of dry weather diversions in Talbert Watershed is unclear,
although diversions presumably serve to mitigate other types of pollution as well. A better understanding of the cycling of FIB between the water column and sediments is needed to evaluate the linkages between wet weather and dry weather loads in relation to sediment interactions.

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Print As-Is
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Bird Droppings Are Blamed for Bacteria

By Stanley Allison June 02, 2001 in print edition B-9

A team of UC Irvine researchers has concluded that waterfowl and other animal droppings from a saltwater marsh and the Santa Ana River are a significant source of bacteria contaminating the ocean waters off Huntington Beach.

In a report that will be published in the June 15 issue of Environmental Science and Technology, the researchers point to inherent flaws in the design of the man-made saltwater Talbert Marsh.

Stanley Grant, the UCI professor who led the 18-month study of the ocean contamination problem at Huntington Beach, said water containing fecal bacteria, pesticides, nutrients and other materials filters through the marsh and then flows into the ocean in about 40 minutes—which is too fast.

For the marsh to act as a natural cleanser and remove contaminants, the water must spend at least a week filtering through the wildlife preserve, Grant said.

Even though other sources such as urban runoff from the Santa Ana River may have contributed to the contamination that resulted in four miles of beach closures for most of the summer of 1999, the levels of bacteria from the marsh were hundreds of times more than the state limits, the researchers said.

The team’s conclusions contradict the accepted environmental theory that wetlands purify contaminated water flowing into the ocean.

The findings suggest that approximately 4.6 million saltwater marshes in the U.S. could be similarly affected, Grant said.

Mark Gold, a spokesman for the conservation group Heal the Bay, said that finding animal droppings in a nature preserve is nothing new, and insists that marshes still serve as a cleanser for other, more hazardous, contaminates.

“It’s not surprising that wetlands are sources of fecal bacteria,” Gold said. “What wetlands are great at doing is removing nutrients and metals.”

The 25-acre wetlands preserve is on the inland side of Pacific Coast Highway at Brookhurst Street. Part of the Talbert watershed that encompasses 12 square miles in Huntington Beach and Fountain Valley, it attracts thousands of migratory birds and other wildlife each year.

The UCI researchers also say that the nearby AES power plant contributes to the shore’s contamination. The study suggests that partly treated sewage released four miles offshore from the Orange County Sanitation District treatment plant is being pulled back to the shore by tides and the plant as it draws water to cool its towers.
Bacterial Contamination at Huntington Beach, California—Is It From a Local Offshore Wastewater Outfall?

During the summers of 1999 and 2000, beaches at Huntington Beach, California, were repeatedly closed to swimming because of high bacteria levels in the surf zone. The city's beaches are a major recreational and commercial resource, normally attracting millions of visitors each summer. One possible source of the bacterial contamination was the Orange County Sanitation District's (OCSD) ocean outfall, 4.5 miles (7 km) offshore at a depth of 200 feet (60 m). The beach closures were caused by elevated levels of three categories of bacteria—total coliform, fecal coliform, and enterococci. These bacteria, which live in the digestive tracts of warm-blooded animals including humans, are also found in the treated effluent discharged from the OCSD outfall. Because of this, it was suspected that coastal ocean processes might be bringing bacteria-rich effluent from the ocean outfall to shore.

In most years, more than 5 million people visit the wide sandy beaches at Huntington Beach, California. Unfortunately, in recent summers, stretches of these beaches had to be repeatedly posted with advisories against swimming or even closed (inset), because levels of live bacteria in the surf zone exceeded State public-health standards. These closures resulted in serious economic losses to local business communities.

The wide sandy beaches at Huntington Beach, California, just south of Los Angeles, attract residents and visitors alike. Typically, more than 5 million people visit these beaches each summer, helping to support a regional tourism industry of $80 million annually.

During the summers of 1999 and 2000, stretches of these beaches had to be repeatedly closed to swimming or posted with advisories against swimming, because levels of live bacteria in the surf zone exceeded beach sanitation standards in the California Health and Safety Code (Assembly Bill 411, or AB411). Because people stayed away from the beaches, local recreational and beachfront business communities suffered serious economic losses.

Local agencies conducted a variety of studies in 1999 and 2000 to try to determine the cause of the beach contamination at Huntington Beach. They investigated known sources of bacteria, such as broken sewer pipes, outflow from the Santa Ana River, feces of bird populations in coastal marshes, and the plume of treated wastewater from the Orange County Sanitation District's (OCSD) ocean outfall, 4.5 miles (7 km) offshore at a depth of 200 feet (60 m). The beach closures were caused by elevated levels of three categories of bacteria—total coliform, fecal coliform, and enterococci.

These bacteria, which live in the digestive tracts of warm-blooded animals including humans, are also found in the treated effluent discharged from the OCSD outfall. Because of this, it was suspected that coastal ocean processes might be bringing bacteria-rich effluent from the ocean outfall to shore.

To evaluate whether the OCSD outfall could be the source for the bacterial contamination at Huntington Beach, scientists from the U.S. Geological Survey (USGS) and cooperating organizations...
designed and carried out an extensive study. Begun in the summer of 2001, this study focused on the area's coastal ocean circulation and transport pathways. It was known from the 1999–2000 studies done by local agencies that the beaches were most often contaminated during “spring” tides in the 2-week tidal cycle. Spring tides occur when the gravitational pulls of the Moon and Sun reinforce each other, resulting in the highest high waters and lowest low waters of this cycle. Additionally, previous field observations and theoretical modeling indicated that, in summer, the effluent plume from the OCSD outfall remains trapped below the thermocline, a zone of rapid change in temperature that divides ocean water into cold dense water below and warmer, less dense water above. In the ocean off southern California, the thermocline is typically about 50 to 65 feet (15 to 20 m) below the sea surface during the summer.

In light of these earlier findings, the USGS-led study focused on coastal ocean processes, such as tides, daily sea breezes, upwelling, and vertical mixing, that could move significant volumes of bacteria-laden OCSD plume water from offshore below the thermocline into the nearshore region and surf zone during summer months. In the summer of 2001, scientists deployed a sophisticated set of oceanographic instruments at 12 mooring sites in the coastal ocean off Huntington Beach and Newport Beach to monitor current velocity, temperature, and salinity at selected depths in the water column every few minutes for 4 months. Other instruments at these sites collected real-time meteorological data at the sea surface. Additional instruments were deployed in very shallow water to monitor the transport pathways between nearshore waters and the surf zone. Surf-zone water samples were collected 5 days a week in the early morning hours to measure bacterial levels from Huntington Beach to Newport Beach.

A complementary hydrographic mapping program used arrays of instruments towed or lowered from boats along 10 tow lines and at 40 sites between these lines and the shore during six surveys centered around periods of maximum tidal range (spring tides). The surveys measured the spatial distribution of temperature, salinity, ammonia content, bacteria concentrations, and other properties of the water column. These properties were chosen in part because they could be used to identify and track the relatively low-salinity and ammonia-rich effluent from the OCSD plume. During these surveys, additional surf-zone samples were collected every hour at 11 sites along local beaches to provide additional data to evaluate the spatial and temporal distribution patterns of bacteria from offshore to the surf zone.

Analysis of the data collected in 2001 show that the bacterial beach contamination at Huntington Beach is closely associated with both tidal cycles and time of day. High values of all three categories of fecal indicator bacteria were found preferentially at times of spring tides. Additionally, values were high mainly at night, particularly for enterococci. The data show that bacteria levels in the surf zone decreased to very low levels during sunlit hours, even when beaches were closed or posted for several days. However, previous studies have shown that the categories of bacteria found in the OCSD plume can survive for several days in the deeper, colder water below the thermocline, where they are sheltered from ultraviolet light.

When it enters the ocean, the treated wastewater from the OCSD outfall rises toward the thermocline, because it is fresher, warmer, and therefore less dense than the surrounding ocean water. The

In the summer of 2001, scientists from the U.S. Geological Survey (USGS) and cooperating organizations designed and carried out an extensive study to evaluate whether the Orange County Sanitation District's (OCSD) ocean outfall could be the source of bacterial contamination at Huntington Beach. This study focused on coastal ocean processes that could move significant volumes of bacteria-laden OCSD wastewater into the nearshore region and surf zone during summer months. This map shows locations of instrument-mooring sites, hydrographic survey lines, and surf-zone bacteria sampling stations used in the USGS-led study. At mooring sites, arrays of instruments, such as the tripod shown below being lowered to the sea floor, monitored current velocity, temperature, salinity, and meteorological conditions. Hydrographic surveys used arrays of instruments towed or lowered from boats to measure the spatial distribution of temperature, salinity, ammonia content, bacteria concentrations, and other properties of the water column.
wastewater plume tends to stabilize and mix with a layer of water that has a temperature of 54 to 57°F (12 to 14°C) and for the most part is carried out of the area by alongshore currents. However, data show that water of that temperature was intermittently brought nearshore during July and August 2001. These cold-water pulses were the result of a combination of internal tides (tidal-cycle waves on density boundaries within the water column, like the thermocline) and daily circulation induced by sea breezes. It had been hypothesized that these mechanisms could bring wastewater from the OCSD plume into the proximity of the cooling-water intake and discharge pipes of the Huntington Beach AES Corporation electrical powerplant, where plume water could be sucked up and then be injected by the discharge jet into surface waters. The OCSD effluent could then easily move into the surf zone through buoyant spreading, wind forcing, or other processes. However, the USGS-led study found no association between the timing of nearshore cold-water pulses and beach closures or postings on the shoreline adjacent to the AES facility, which has been a hotspot for bacterial contamination.

**This diagram shows salinity variations offshore of Huntington Beach in early July 2001, measured along hydrographic survey lines (see map). As shown in this diagram, salinity data from the summer of 2001 clearly show two distinct bodies of relatively less saline water—one in deeper water offshore associated with the Orange County Sanitation District's (OCSD) wastewater outfall plume and one in shallower nearshore waters. The nearshore less saline water could be a possible source of the bacterial contamination that has caused beach closures at Huntington Beach. This water may be coming from the San Gabriel and Los Angeles Rivers, to the north, which carry urban runoff into the ocean.**
Observations from the USGS-led study provide no evidence that the bacteria found in the OCSD treated-effluent plume reached any part of the shoreline at Huntington Beach in significant enough quantities to cause beach closures or postings. The data show that when the beaches have high bacteria levels, very nearshore water about 0.25 mile (0.4 km) from the beach also has measurable bacteria levels, although much below AB411 standards. However, there was a spatial gap between this nearshore contamination and the high levels of bacteria measured 2 miles (3.3 km) offshore below the thermocline in the OCSD outfall plume. The lowest levels of bacteria were consistently found offshore about 0.5 mile (0.8 km) from the beach. This spatial gap suggests that the bacteria from the OCSD outfall are not the same bacteria that contaminate the beaches. The bacteria causing the beach postings and closures at Huntington Beach are most likely coming from other sources, such as water from local storm drains, marshes, or some other as-yet unidentified source.

Salinity data from the summer of 2001 clearly show two distinct bodies of relatively fresher (less saline) water—one offshore below the thermocline associated with the OCSD plume and one in shallower nearshore waters. This observation corresponds well to the spatial gap seen in the bacterial data. Although additional work needs to be done to identify the source of the nearshore body of fresher water, it may be coming from the San Gabriel and Los Angeles Rivers, to the north, which carry urban runoff into the ocean.

Beach closures from bacterial contamination continued at Huntington Beach in the summer of 2002. Even though the data show that the OCSD outfall plume is almost certainly not the source of that contamination, OCSD began chlorinating its wastewater discharge in the fall of 2002. Samples taken from the OCSD offshore outfall plume since then show low levels of bacteria, often below detection limits. However, periods of bacterial beach contamination at levels above AB411 standards have occurred at Huntington Beach after OCSD implemented chlorination, supporting the conclusion of the USGS-led study that the OCSD outfall plume is not the culprit in the beach contamination.

USGS and its cooperators are continuing to investigate how bacteria, other contaminants, and sediments are transported by coastal ocean processes not only off Huntington Beach but also in the larger region off southern California. Such research is only part of the USGS efforts to protect people’s lives and property from geologic and environmental hazards in the coastal zones of the United States.

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Generation of Enterococci Bacteria in a Coastal Saltwater Marsh and Its Impact on Surf Zone Water Quality


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Abstract

Enterococci bacteria, an indicator of fecal pollution, are routinely detected in the surf zone at Huntington State and City Beaches in southern California. A previously unreported source of enterococcal disease is identified in the estuary of a coastal saltwater marsh located off the coastline. We find that enterococcal bacteria are present at high concentrations in urban tidal marsh, in the estuary's brackish sediments, and on marine vegetation. Surprisingly, urban runoff appears to have relatively little impact on surf zone water quality because of the long time required for this water to travel from its source to the ocean. On the other hand, enterococcal bacteria generated in coastal saltwater marshes, rather than the beach, significantly impact surf zone water quality. This study identifies a potential tradeoff between reducing urban runoff and protecting beach water quality and calls into question the use of ocean bathing water standards based on enterococcal isolations near coastal wetlands.

Introduction

Beaches are an important part of the culture and economy in California. An estimated 50 million people visit California public beaches annually for a total economic benefit to the state of over $7 billion dollars (1). To protect beach goers from exposure to waterborne disease, a new state law mandates the implementation of recreational water quality monitoring programs at public beaches with 50,000 or more annual visitors. Specifically, the law requires monitoring for total coliform (TC), fecal coliform (FC), and the enterococci (ENT) groups of bacteria, all of which may indicate the presence of fecal contamination. The state also enforces a set of uniform standards for TC, FC, and ENT bacteria including single-sample standards (100:000:400) and 104 most probable number (MPN) or colony forming units (CFU)/100 mL and 30 day geometric mean standards (1000, 200, and 35.6 MPN or CFU/100 mL); a lower single-sample standard for TC of 100 MPN or CFU/100 mL also applies when the TC/FC ratio falls above 7. The enterococci standard conforms closely to the national Ambient Water Quality Criteria for the Entero- bacteriaceae established by the U.S. Environmental Protection Agency (2). If indicator bacteria levels in the ocean exceed these standards, health officials are required to either post signs that warn of the potential for waterborne disease or close the beach to public use. These regulations are implemented according to state guidelines, which are based on a series of epidemiological studies that link gastroenteritis illness with exposure to ocean water containing high levels of indicator bacteria, particularly ENT (3-11). The origin of ENT in these epidemiological studies was presumed to be anthropogenic sources of fecal pollution, such as sewage, agricultural runoff, and urban runoff.

Huntington State and City Beaches in southern California have been heavily impacted by the passage of these new regulations. According to data provided by the Orange County Health Care Agency, there have been a total of 32 postings at Huntington State and City Beaches between July 26, 1996, and September 22, 1996, approximately 17% and 22%, of which were triggered by violations of the ENT single-sample and geometric mean standards, respectively. Persistently high levels of indicator bacteria in the surf zone at Huntington State and City Beaches (in the summer of 1996) led to an extensive survey of the local watershed (12). No significant sewage flows were observed; however, urban runoff, agricultural runoff, and atmospheric deposition were identified as significant sources of enterococcal contamination. The level of enterococcal contamination was highly variable in both urban and remote areas, with the highest levels observed near coastal wetlands. The goal of the present study was to test the hypothesis that enterococcal contamination is best explained by enterococcal contamination generated in coastal saltwater marshes, rather than the beach.
Marsh, was cut off from tidal flushing by the construction of Pacific Coast Highway and channelization of the surrounding area for flood control. As part of a habitat restoration effort, tidal flushing in the Talbert Marsh was restored in 1990 when a new tidal inlet was constructed. Since its restoration, Talbert Marsh has become a typical southern California tidal saltwater marsh with open water, wetland, and upland habitats (13–15). Pickle weed (Salsola exigua) is the dominant macrophyte vegetation, and the marsh is used by several special-status bird species, including the California Least, Semi-palmated Plover, and Black-bellied Plover.

At the outset of this study it was not clear what effect the Talbert Marsh had on surf zone water quality at Huntington Beach. On one hand, wetlands, particularly freshwater wetlands, are natural treatment systems that remove chemical and biological contaminants from domestic and agricultural wastewater and urban runoff (16, 20). On the other hand, coastal marshes are an important habitat and bird feces are a potential source of E. coli (17). Therefore, the environmental growth of these organisms in the sediments and on vegetation (23–28).

Methods and Materials

A series of investigations were carried out to (1) measure the flow of water and E. coli into the ocean from the Talbert Marsh and Talbert Watershed; (2) assess the impact of E. coli from the marsh and watershed on local surf zone water quality; and (3) identify potential sources of E. coli in the watershed and the two systems (runoff, birds, vegetation, etc.). These three different investigations were carried out separately from one another: the Marsh Study, the Surf Zone Study, and the Source Study, respectively. The methods employed for the three investigations are described below.

Marsh Study. The goal of the Marsh Study was to measure the flow of water and E. coli from the Talbert Marsh and Talbert Watershed into the ocean. Measurements were carried out for 5 days starting on May 2, 2000. During the 5-day study, pump stations in the Talbert Watershed were operated in two different modes: during the first 3 days, the pump stations were running, and on the fourth day the pump stations were shut down. Once the pump stations were shut down, pumps were turned off and the sediment ponding was measured using electronic pressure transducers, and the temperature was recorded.

Huntington Beach, that converges near the ocean at a constructed wetland known as the Talbert Marsh (Figure 1A). Ocean water floods both the Talbert Marsh and the lower reaches of the open channels during rising tidal (flood tide) and a blackish mixture of ocean water and runoff drains from the system during falling tides (ebb tides).

The Talbert Marsh is nearly flat and only a few feet above sea level. The geographical setting dictates drainage by gravity alone, so a system of transfer stations is used in the lower reaches of the Talbert Marsh to pump runoff into the open channels from stormwater pipelines. Each transfer station or pump station consists of a forebay, where runoff can be stored, and several pumps. Pumping of runoff to the channels occurs intermittently during dry weather periods and continuously during storms.

Talbert Marsh is a 1200-ha wetland primarily used for agricultural reclamation and urban development. Most of what remained of the historical wetland, including Talbert

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Huntington Beach, that converge near the ocean at a constructed wetland known as the Talbert Marsh (Figure 1A). Ocean water floods both the Talbert Marsh and the lower reaches of the open channels during rising tides (flood tides) and a brackish mixture of ocean water and runoff drains from the system during falling tides (ebb tides).

The Talbert Watershed is nearly flat and only a few feet above sea level. This geographical setting hinders drainage by gravity alone, so a system of transfer stations is used in the lower reaches of the Talbert Watershed to pump runoff into the open channels from stormwater drainage. Each transfer station, or pump station, consists of a levee, where runoff can be stored, and several pumps. Pumping of runoff to the channels occurs intermittently during day, weekly, and continuous periods.

Talbert Marsh is a 160-hectare remnant of what was used to be an extensive (410-ha) natural freshwater marsh and delta in coastal Orange County. Most of the delta land system was drained and filled over the past century for agricultural reclamation and urban development. Most of what remained of the historical wetland, including Talbert Marsh, was cut off from tidal flushing by the construction of the Pacific Coast Highway and channelization of the surrounding area for flood control. As part of a habitat restoration effort, tidal flushing in the Talbert Marsh was restored in 1995, when a new tidal inlet was constructed. Since its restoration, the Talbert Marsh has become a typical southern California tidal saltwater marsh with open water, wetland, and adjacent habitats (13–15). Pickleweed (Salicornia virginica) is the dominant macrophyte vegetation, and the marsh supports several special-status bird species including the California Least Tern, Brown Pelican, and Belding's Savannah Sparrow.

At the outset of this study it was not clear what effects the Talbert Marsh had on surf zone water quality at Huntington Beach, State and City Beaches. On one hand, wetlands, particularly freshwater wetlands, are natural treatment systems that remove chemical and biological pollutants from domestic and agricultural wastewater and urban runoff (16–20). On the other hand, coastal marshes are environmentally beneficial habitats, and bird feces are a potential source of E. coli (21, 22). It is the environmental growth of these organisms in the sediments and on vegetation (23–26).

Methods and Materials

A series of investigations were carried out to (1) quantify the flow of water and E. coli into the ocean from the Talbert Marsh and Talbert Watershed, (2) assess the impact of E. coli in the marsh and watershed on local surf zone water quality, and (3) identify potential sources of indicator bacteria within these two systems. The studies were designed to provide a comprehensive understanding of the processes affecting the marsh, including the relationships between aquatic and terrestrial organisms and the overall environmental quality of the marsh.

Measurements were carried out for 15 days starting on May 2, 2000. During a 15-day study, pump stations in the Talbert Watershed were operated in two different modes: during the first 8 days the pump stations were off, and for the following 7 days the pump stations were on. When pump stations were on, runoff that would normally discharge into the drainage channels was either diverted into the regional sanitary sewer system at the pump station forebay or was intermittently discharged into the drainage channels following normal operating procedures. The impact of the operational changes was monitored at two locations: the junction of the drainage channel and the channel bank (Brookhurst Station) and the Brookhurst street bridge (PCH Station). Two additional sites (Talbert Station and Fountain Valley Station; see Figure 1A) were monitored to characterize the flow of runoff from the drainage channels to the ocean between the pump station forebay and the ocean. The data from these sites were used to estimate the total amount of runoff entering the ocean from the watershed where there are no pump stations.

Flow Measurements. The velocity and level of water at both Brooks Hutchinson Station and the PCH Station were measured with ADCP (acoustic Doppler current profiler) meters. The ADCP meters were mounted at the sediment bed (Figure 1B) and positioned at the downstream end of the Doppler cone, or area over which the velocity measurement was taken. The measurement was repeated at least 50 times to ensure the reliability of the data. The velocity data were electronically logged, downloaded to a laptop computer, and cross-plotted with water level data to determine the tidal cycle for the marsh and the channel network. The data were then analyzed to determine the tidal height and current directions within the marsh and channel network.
was then used to compute hourly average values of the volumetric flow rate at both the Brookhurst and PCH Stations over the study period. Water temperature at the two sites was recorded by a sonde (YSI, Yellow Springs, OH) positioned so that the probe was located approximately 5 cm above the sediment bed (Figure 1B).

The pump was installed into the upstream reaches of the Talbert and Fountain Valley channels to avoid loss of water by recording the time 10 pieces of submerged debris took to travel a fixed distance. Volumetric flow rates were then obtained by multiplying this average velocity by the estimated cross-sectional area of the flowing water.

No water was discharged from the pump station forebay during the first 8 days of the March and Surf Zone Studies. The volume of water discharged during the last 7 days of the study was estimated from City of Huntington Beach records of water volumes diverted into the sanitary sewer during the first 8 days of the study. The conductivity of forebay water at several pump stations varied from 30 to 90 (μS/cm), reflecting the fact that some fraction of the forebay water is ocean water that traveled up the channels during flood tides and spilled into the forebay through breaking surf. We computed the fraction of water discharged from the pump stations at times when ocean water was present (i.e., not ocean water) as follows:

\[ F = 1 - \frac{(C - C_0)}{(C_1 - C_0)} \]  

where \( C_0 \) and \( C_1 \) are the conductivity of ocean water and the average conductivity of samples from the nearest stations, and \( C \) is the conductivity of the forebay samples.

The volume of runoff exiting the channel network through the outfall to the ocean was quantified from the magnitude of the conductivity depressions and the volumetric flow rate at the PCH Station by numerically evaluating the following integral:

\[ \int F(t) Q(t) \, dt \]  

where \( F(t) \) represents the fraction of freshwater computed by applying eq. 1 to the conductivity signal measured at the PCH Station and \( Q(t) \) is the volumetric flow rate at the PCH Station computed using the calibrated hydrometric model (above). The integral was taken separately over the first 8 days and last 7 days of the study.

**EXS Measurements** At both the Brookhurst and PCH Stations, hourly water samples were collected from the surface and bottom of the water column using programmable sampling units (ISCO models 3700 and 6700, Lincoln, Nebraska; Figure 1B). Surface samples were obtained by drawing water over the lip of an acrylic box, that was submerged to approximately 1 cm below the surface and supported by a floating platform (Figure 1B). Bottom samples were drawn through a strainer suspended approximately 5 cm above the sediment bed by a pole attached to the bridge.

To obtain an average measure of water quality, each hourly sampling interval, the automated samplers were programmed to collect 200 mL of water every 15 min for a total sampling volume of 800 mL per bottle per hour. Sample bottles consisted of a disposable plastic filter (ISCO PolyPak sample bags) supported by a plastic cage (ISCO PolyPak holder). The cage was used over the bottle and then discarded. A purge cycle was performed prior to and after each sampling event, and the sampling units were filled with ice to reduce bacterial die-off.

Samples were collected from the Brookhurst and PCH Stations every 6 h and transported to a laboratory at the Orange County Sanitation District (Fountain Valley, CA) where 10 mL was immediately analyzed for E. coli, using a standard substrate test (HESST ExoTest) implemented in a 97 well, quantitative format. pH, turbidity, and conductivity (temperature-corrected to 20 °C) were also measured. A total of 1141 samples were collected using the automated samplers. Automated samplers were used here because they allowed us to collect hourly water samples in a reproducible manner from precisely the same locations in the water column, 24 h per day, 7 days per week. One potential disadvantage of the automated systems is that the tubing and sampling system (e.g., strainers) are not sterilized between sampling events, so there is a possibility that sample-to-sample cross-contamination might occur. A recent study of sources of E. coli in an estuarine system in Florida [26] found that automated samplers did not cause significant cross-contamination when a purge step was executed between sampling events, as was done here.

**Solar Radiation** To assess possible relationships between sunlight and bacterial levels in the marsh, hourly measurements of solar radiation were recorded during the 15-day study period using a thermopile radiometer (Kipp & Zonen, CSA3 Thermopile Radiometer, Netherlands) located at the San Joaquin bluffs, which is approximately 6 km west of the Talbert Marsh.

**Surf Zone Study** Dye experiments and intensive surf zone water quality monitoring were carried out to quantify the impact of EBT from the Talbert marsh and watershed on surf zone water quality at Huntington State Beach. The methods employed for this element of the study are described below.

**Dye Study** During ebb tides, water from the Talbert Washed into the drainage channels (Huntington Beach, Talbert, and Fountain Valley, through the Talbert Marsh, and into the ocean. To determine the ebb flow from the Talbert marsh and watershed interacts with the surf zone, separate dye experiments were conducted on May 1 and May 16, 2000, as follows. Rhodamine WT-dye (Keylume, Santa Fe Springs, California) was added for approximately 30 min to effluent from the Talbert Marsh during an ebb tide. The spatial distribution of the dye was recorded at a series of times post-release by a four-channel radiometer (DMSMVK-1 Spectralysys, Netherlands) flown at approximately 500 ft above sea level. The dye field in these images was visualized by forming the ratio of emission and absorption maxima (570 and 590 nm, respectively) of Rhodamine WT.

**Surf Zone Monitoring** To assess the impact of EBT from the marsh watershed on surf zone water quality, hourly samples were collected off the PCH Station to characterize the concentration of EBT entering and leaving the marsh and at three locations in the surf zone (sections 2, 21, and 27, see Figure 1A). The Surf Zone Study was conducted on the same trip as the March Study (see above). However, the methods used to collect and analyze samples in the Surf Zone Study differed from those described above for the March Study. For the Surf Zone Study, hourly grab samples (total volume of approximately 1 L) were collected in sterile Nalgene bottles at the PCH and the surf zone stations 24 h per day, 7 days per week, for 2 weeks. Within 6 h of collection, samples were transported to Sierra Laboratories, Inc. (Laguna Hills, California) on ice where 10 mL of each sample was immediately analyzed for EBT using multiple tube fermentation (MTF) and membrane filtration (MMA). To characterize cross-shore variability of the EBT signal, separate samples were collected from ankle and wave-depth at each surf zone station. A total of 2024 grab samples were collected for this element of the study.

**EBT Source Study** Additional studies were carried out to identify specific sources of EBT in the marsh and watershed. Specific sources examined included urban runoff, bird feces in the marsh, marine vegetation, and marsh and surf zone sediments. Results to be presented
Bird Feces. To assess the amount of ENT present in bird feces, bird feces were collected, along with any attached sediment from mud flats, in the Talbert Marsh where birds congregate. The nature of the feces (wet or dry) was noted at the time of collection. Sediment that appeared to contain no bird feces was also collected to determine background levels of ENT. The sediment and feces samples were weighed and placed in acid-washed Nalgene bottles with 500 mL of marsh water. The suspensions were shaken vigorously to disperse the feces and sediment and then allowed to settle for 15 min. Depending on the experiment, between 0.1 and 10 mL of supernatant was tested for ENT using the Enterolert protocol described in the Marsh Study. Control experiments were conducted to rule out the possibility that chemicals present in the feces and/or sediment might interfere with the Enterolert system. Specifically, Enterolert analyses were conducted on autoclaved suspensions of sediment and bird feces.

Bird Census. To quantify the input of ENT into the marsh from birds, a bird census was carried out as follows. Digital cameras (Kodak Model DC-290, Rochester, New York) were installed at three different locations along the northeastern margin of the marsh. These cameras were positioned to that they could provide a complete picture of the upland, wetland, and open water habitat areas. Images were shot hourly at a resolution of 2240 x 1500 pixels in 256 colors, 24 h per day, over the same period of time when samples were being collected in the marsh and in the surf zone (May 2–18, 2000). The images were uploaded to a desktop PC where they were analyzed with Adobe Photoshop (Adobe, San Jose, California). The birds in each image were enumerated manually to obtain an estimate for the total number of birds present in the marsh each hour of the 2-week study.

Urban Runoff. To characterize the concentration of ENT in urban runoff, daily grab samples were collected from all 11 pump stations in the Talbert Watershed and from the upstream reaches of the waterways at the Talbert and Fontain Valley Channel Stations (Figure 1A). Runoff sampling occurred over the same period of time that the Marsh and Surf Zone Studies were carried out (May 2–17, 2000). Prior to sampling the pump station foreways, water in the foreway was mixed by cycling the station pumps on and off. Sterile Nalgene bottles were lowered into the foreways and foreways, and approximately 1 L of water was collected. Five hundred mL samples of runoff at the Talbert and Fontain Valley Channel Stations were collected by manually placing a sterile Nalgene bottle directly in the flowing stream. All samples were stored on ice immediately after collection and transported to the Orange County Sanitation District where they were analyzed for pH, turbidity, conductivity, and ENT using the Enterolert protocol described in the Marsh Study.

Sediment and Vegetation. To assess the levels of ENT present in sediments, cores were collected from the marsh and surf zone with a Brandford SG244 Rebarhouse Vibrator (Brandford Co., New Britain, CT) outfitted with a 1.52 m (OD x 4.4 cm) and Stainless steel pipes (AMS, Inc., American Falls, ID). Each core was cut into three 15 cm segments which were sealed at the ends with Teflon lined caps and transported to Sierra Laboratories, Inc. (Laguna Hills, CA) for bacterial analyses. Upon arrival at the laboratory, 50 g of core section was suspended in 450 mL of phosphate buffered saline (PBS) 0.3 M K2HPO4, 0.17 M NaH2PO4, 2.7 mM MgCl2 in accordance with Standard Method 2521 A-3 (26). The clarified supernatant was analyzed for ENT using MTF following the protocol outlined in the Surf Zone Study. Seaweed samples were collected from the marsh, stored in glass vials, and transported on ice to Sierra Laboratories, Inc. Upon arrival at the laboratory, 50 g of seaweed was placed in a sterile container to which 450 mL of PBS was added. The solution was shaken vigorously and allowed to settle for 15 min and then resheaked. A 100 mL sample of the supernatant was analyzed for ENT using the MTF method described in the Surf Zone Study.

Results and Discussion

Marsh Study Dynamics. The Talbert Marsh is a highly dynamic system, primarily because the flow of water through the marsh is dominated by the tides (Figure 2). Because Southern California has semidiurnal unequal tides (25, 30), there are four different tidal zones each day including high-high, low-low, high-low, and low-high tide levels. Furthermore, the tide range, which is the difference between the high- and low-water levels, oscillates over a 14–15 day period. The Marsh and Surf Zone Studies were carried out over a 14 day period that began shortly before a spring tide when the tide range is maximal, passed through a neap tide when the range is minimal, and returned back to a spring tide again. The four daily tide stages and the spring–neap–spring transition are evident in the water levels measured at the Brookhurst and PCH Stations (top panel in Figure 2). During flood tides inundated by positive velocities in the second panel of Figure 2), the water levels at the Brookhurst and PCH Stations increase at a rate determined by the ocean, through the marsh, and inland along the channel network. During ebb tides (indicated by positive velocities) the water levels at the two stations decrease as water flows out of the channel network through the marsh, and into the ocean. When ebb tides occur during sunlight hours, solar heating of water moving out of the channel network causes a significant increase in the temperature of the discharged water (compare first, third, and fourth panels). The conductivity measured at the Brookhurst and PCH Stations (right panel) corresponds to pure ocean water, during flood tides (55.5 mS cm−1) and a brackish mixture of ocean water and urban runoff at the end of the ebb tides (conductivity depression).

The next panel in Figure 2 is a plot of the ENT concentrations measured at the Brookhurst and PCH Stations. ENT concentrations in the marsh varied from below the detection limit (100 MPN/100 mL) to a high of 714 MPN/100 mL. A total of 263 (15%) and 565 (46%) of the marsh samples exceeded the single-sample and geometric mean standards for ENT, 0.4 MPN/100 mL and 95 MPN/100 mL, shown as dash and light blue lines in the plot, respectively. A total of 242 (35%) of the marsh samples fell below the detection limit of 0.2 MPN/100 mL, all values falling below the detection limit were arbitrarily assigned a detection limit value. The log-transformed ENT concentrations at the top and bottom of the water column in the marsh are correlated (r = 0.70 and r = 0.72 at the Brookhurst and PCH Stations, respectively). Comparing the conductivity and ENT curves in Figure 2, we find that elevated ENT values frequently occur in the marsh during periods of time when flow from the drainage channels, as indicated by the conductivity depressions, is not present.

The last panel in Figure 2 is a plot of the total number of birds that visited the Talbert Marsh during the course of our study. The birds followed a daily routine in which their numbers started out low in the morning, peaked in the afternoon, and tapered off in the evening. Gulls and Elegant Terns comprised the majority (85%) of birds visible in the images. The whole suspension of selected bird groups occurred at 1200 in the afternoon on May 5.

Marsh Study: ENT Source. A primary objective of this study was to determine the marsh and surface runoff origin of ENT in water flowing out of the Talbert Watershed and through the marsh and into the ocean through the ebb tides. To this end, the total of the marsh ENT data into two groups based on whether the samples were collected during ebb tides (Figure 3A,B) or
The dynamics of marsh parameters measured during the 15-day study period. The solid and dashed lines (water level, flow velocity, temperature panels) correspond to the PCH and Brookhurst stations, respectively. The key for conductivity and ENT values is indicated in the figure. The dark and light blue lines denote the single sample and geometric mean standards for ENT. Water level is referenced to mean sea level. Positive and negative velocities correspond to shoreward and landward flow, respectively. The gray vertical stripes represent night-time conditions.

FIGURE 2. The dynamics of marsh parameters measured during the 15-day study period. The solid and dashed lines (water level, flow velocity, temperature panels) correspond to the PCH and Brookhurst stations, respectively. The key for conductivity and ENT values is indicated in the figure. The dark and light blue lines denote the single sample and geometric mean standards for ENT. Water level is referenced to mean sea level. Positive and negative velocities correspond to shoreward and landward flow, respectively. The gray vertical stripes represent night-time conditions.

Flood tides (Figure 3C,D). These data were further segregated based on whether the samples were collected during the first 8 days of the study (when the pump stations were offline) or the last 7 days of the study (when the pump stations were online) and based on the vertical location of samples in the water column (top or bottom). For each subcategory, we computed a geometric mean and calculated the percentage of samples that exceeded the single-sample standard for ENT. The results of this analysis identify the marsh as not urban runoff from the Talbot Watershed, as the primary source of ENT in the water flowing into the ocean. During ebb tides, the geometric mean of ENT (Figure 3A) and the percentage of samples exceeding the single-sample standard (Figure 3B) is approximately double as the water flows through the marsh from the Brookhurst to PCH Station. The trend is reversed during flood tides when the geometric mean of ENT (Figure 3C) and percentage of single-sample exceedances (Figure 3D) increase as water flows through the marsh from the PCH to Brookhurst Stations. With the exception of two flood-tide cases, water enters the marsh below the geometric mean standard for ENT (55 MPN/100 mL, dashed line in the figure) and exits the marsh in excess of the standard. In several cases, the ENT concentrations measured at the top of the water column are higher than the ENT concentrations measured at the bottom of the water column.

The idea that the marsh is a net source of ENT is also suggested by Figure 3E, where we plot the boot-strap difference between the ENT concentrations measured at the Brookhurst and PCH Stations (dashed line in the figure). On average, the ENT concentration is higher at the PCH Station during ebb tides (mean ENT = 7.25 ± 0.12 MPN/100 mL) and higher at the Brookhurst Station during flood tides (mean ENT = 5.17 ± 0.12 MPN/100 mL). A direct comparison of the ENT concentrations at the Brookhurst and PCH Stations is valid only if the residence time of water in the marsh is less than our sampling interval of 1 h. This condition appears to be satisfied based on dye study conducted on the morning of May 28, 2000, which found that the residence time of water in the marsh during a weak spring tide is less than 40 min (27).

Surf Zone Study: Dye Experiment. The above analysis demonstrates that the Talbot Marsh is a net source of ENT, but it is clear that ENT generated by the marsh negatively impacts surf zone water quality. To characterize how ebb flow from the Talbot Marsh interacts with the ocean, a set of experiments were conducted in which dye (Rhodamine WT) was injected into the surf zone of the Talbot Marsh during two separate ebb tides, one on May 1 and the other on May 10, 2000. The spatial pattern of dye released from the Talbot Marsh during the May 1 experiment is displayed in Figure 4. The dye pulse split into two plumes as it flowed into the ocean. One plume was entrained in the surf zone where it rapidly advected upcoast at velocities exceeding 0.2 m/s; a portion of this plume was subsequently taken offshore by a rip current. The second plume was carried directly offshore by a momentum jet located at the mouth of the marsh. The portion of the dye entrained in the surf zone on May 1 was advected in an upcoast direction because, on that day, ocean waves with average significant heights of 0.7 m were from the south (31). During the second release on May 10, ocean waves with significant heights of 1.4 m were from the west, and the portion of the dye entrained in the surf zone was advected rapidly (0.3 m/s) in a down coast direction (data not shown). Hence, water flowing out of the marsh during ebb tides can impact surf zone water quality at Huntington State and City Beaches directly upcoast of the Talbot Marsh outlet, provided that ocean waves strike the beach in an upcoast direction. Interestingly, wave conditions similar to those observed during the May 1 experiment were also present during the summer of 1999 when large stretches of Huntington State and City Beaches were closed to the public.
FIGURE 3. Geometric means of ENT in samples collected during ebb tides (A) or during flood tides (C). The dashed line in these figures represents the geometric mean standard for ENT (5 MPN/100 ml). Error bars represent the single sample standard deviation. B. Error bars represent the 95% confidence intervals. The number of samples used to calculate geometric mean values are indicated in the figure.

Observations in account, we estimate that the initial dilution of the dye plume into the marsh effluent stream was approximately 7 x 10^4 ([Qeffluent]/Qo). The volume of the dye field at 1:51 PDI, the time at which the EMV image in Figure 4 was of the water was approximately 7 x 10^4 m^3 assuming a 1.4 m mixing depth. Therefore, the dilution of the plume at 1:51 PDI is approximately 1.1 x 10^4 m^3. During the next 7 days, the dilution factor increased to 1.1 x 10^5 m^3 and the initial dilution (7 x 10^4) indicates that the marsh effluent stream was diluted by a factor of 1.1 as it became entrained in the surf zone. Hence, effluent leaving the Talmage Drain during flood tides suffers approximately a factor two dilution as it is entrained in the surf zone.

Surf Zone Study: Bacterial Monitoring. To measure the actual impact of effluent flow from the marsh on surf zone water quality, an intensive surf zone monitoring program was carried out in parallel with the 15 day Marsh Study described above. ENT concentrations in the surf zone varied from below detection limit (13 MPN/100 ml) to a high of 5790 MPN/100 ml. A total of 69 (52%) and 293 (18%) surf zone samples exceeded the single sample geometric mean standard for ENT respectively. A total of 99% (95%) of the surf zone samples fell below the detection limit. As with the data collected in the Marsh Study, samples falling below the detection limit were arbitrarily assigned the detection limit value.

Figure 5 displays the geometric mean and 95% confidence intervals of ENT measured at surf zone stations (S1-S7) and at the PCH Station during either rising or falling tides. These data are also segregated based on whether samples were collected in the first 7 days of the study or the last 7 days of the study (indicated in the figure.

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**FIGURE 4.** An aerial image showing the near shore distribution of a dye front (WF) at 11:51 PDI, approximately 23 km into a release from the Talmage Outlet during flood tides on May 1, 2001.
as "wk 1" and "wk 2", respectively, whether the samples were collected at ankle or waist depth, and whether the samples were collected during rising or falling tides. As described in more detail in the Methods and Materials section, all of the ENT data plotted in Figure 5 were obtained by performing MTF analysis on grab samples, while the ENT data collected for the Marsh Study were obtained by performing an Enterolit automated sampling system. Comparing the MTF/Grab data in Figure 5 with the PCH Station data, in Figure 6, we find that during each tides the geometric mean of ENT estimated using the Enterolit automated sampling system is approximately 60 MPN/100 ml, compared to 50 MPN/100 ml using MTF/Grab samples. ENT values estimated by the two approaches are weakly correlated (r = 0.53), but the magnitude of the ENT values estimated by the MTF/Grab sample method appear to be lower. This difference could arise due to differences in the analytical technique employed (MTF versus Enterolit) and/or the sampling methodology employed (grab versus automated). A strong correlation between Enterolit and MTF/Grab sample methods was not found (r = 0.05), as previously reported (22). Hence, the differences reported here are probably due to the differences in the sample collection protocols employed in the Marsh and the Surf Zone Studies.

Because all of the data presented in Figures 5 and 6 were obtained using the same procedure (MTF on grab samples), we can directly compare the ENT signal leaving the marsh during each tide with the ENT signal measured in the surf zone over the same time period. Figure 5 reveals that during falling tides, when ebb flow from the marsh enters the ocean, the geometric mean of ENT at the PCH Station is approximately two times higher compared to the geometric mean of ENT measured in the surf zone stations. With one exception, the geometric means of surf zone samples collected at ankle depth are slightly higher than the geometric mean of samples collected at ankle depth. Based on these data, the ENT signal at stations 3, 3N, and 3S could have been caused by ebb flow from the Tidewater Marsh provided that the timing of the high tides was correct. Although the marsh appears to be divided into two subtidal systems, the marsh effluent as it flows over the beach and into the ocean during falling tides (22) is more than a factor of 2 dilution as efficient as the marsh is entrained in the surf zone, and (3) lateral flow in the surf zone directed in an upstream direction. The first two conditions appear to be met based on the results of the dye study described above. Based on wave azimuth data recorded at Huntington Beach during the 15-day study (21), we induced flow in the surf zone was directed in an upstream direction 60% of the time, including long stretches of time between May 4 and 8 and again between May 12 and May 18. Hence, ENT generated in the marsh appear to have a limited localized impact on surf zone water quality at Huntington Beach. 

**Figure 5:** Geometric means and 95% confidence intervals of ENT concentrations (MPN/100 ml) at the PCH and surf zone stations measured during falling (blue background) and rising (white background) tides. The stations are displayed from north (left) to south (right): 3N, 3, 3S, PCH, and 0 (see map in Figure 1). At each station, the geometric means are shown for the first 3 days and last 7 days (denoted wk 1 and wk 2, respectively). For the surf zone stations, geometric means for samples taken at ankle and waist depth are indicated. At the PCH site, only a surface sample was analyzed. The simple tiles are shown above the bars. The dotted line represents the geometric mean for ENT (15 MPN/100 ml).
in the channel network due to the tidally driven oscillation of water flow in the drainage channels.

By integrating the conductivity depressions evident in Figure 2 (see Methods and Materials), we estimate that the volume of runoff flowing into the ocean at the FCH Station during the first 8 days and last 7 days was 5,000 m³ and 4,600 m³, respectively. Furthermore, we estimate the amount of runoff entering the upper reaches of the channels at the Basket Valley and Tabert stations to be approximately 8,000 m³ (first 8 days) and 7,000 m³ (last 7 days), and we estimate the amount of runoff discharged from the stations during the last 7 days of the study to be 16,800 m³. Hence, the net inflow and outflow of runoff roughly balance during the first 8 days (5,000 m³ + 5,000 m³), respectively, while the net inflow and outflow of runoff do not balance during the last 7 days (2,200 m³ and 4,600 m³, respectively). These volume estimates support the conclusion that the majority of the pump station water discharged in the last 7 days of the study was trapped in the channel network. Importantly, the 7,000 m³ peak of runoff continuously entering the drainage channels from the upper reaches of the Tabert Watershed had little impact on downstream water quality, at least compared to the EMT signal generated by the Tabert Marsh. Die-off of EMT and the relatively long residence time (~1 week) of runoff in the drainage channels may limit the downstream impact of urban runoff (39-39). The fate and transport of bacterial pollutants in the drainage system at Huntingdon Beach is a subject of ongoing investigations.

ENT Source Study: Sediment and Vegetation. Sediment cores were collected from May 22 to June 6, 2000 along a 50 m transect (dotted line on Figure 1A) located both in the marsh and intertidal zone. ENT levels in the sediment cores are consistent with the marsh being a significant source of these bacteria. Nineteen percent of sediment samples from the marsh (n = 96) were positive for ENT, compared to 0% of the sediment samples from the surf zone (n = 121). A total of 65% of the surface sediment samples in the marsh were positive for ENT. Vertical profiles of ENT in the marsh sediments indicate that the bacteria are concentrated in the top 1 cm of the cores (Figure 6). The largest concentration of ENT in the sediment cores (50,000 MPN/100 g) was from a surface sample collected from the northeast corner of the marsh. In the sediment collected from the surf zone, only one sample (14% of the sediment) contained ENT (8,300 MPN/100 g), and this was an unincorporated sample collected directly opposite of the Tabert Marsh outlet.

High levels of ENT, ranging from 18 to 450,000 MPN/100 g (geometric mean of 2,268 MPN/100 g, n = 9), were also found in seaweed collected from the marsh. The fact that seaweed and vegetation are enriched in ENT suggests that these organisms are surviving and perhaps growing in the marsh environment. Marine vegetation supports the growth of certain strains of ENT in New Zealand, and estuarine sediments can apparently support the growth of ENT in tropical settings such as Hawaii and Guam (21-22), although there are no published reports of this occurring in Mediterranean climates such as southern California.

ENT Source Study: Bird Feces. Bird feces are a significant source of ENT in the marsh environment. This conclusion was arrived at by measuring the ENT levels in the following: (1) marsh water alone, (2) 500 ml of marsh water after addition of approximately 10 g of marsh sediment, and (3) 500 ml of marsh water after addition of approximately 10 g of marsh sediment containing bird feces that were either wet or dry at the time of collection. The concentration of ENT in the water samples exceeded 100 MPN/100 ml in samples of pure marsh water and in marsh water containing fecal- free sediment. However, when marsh water was exposed to sediments containing feces that were wet at the time of collection, the ENT concentrations ranged from 9,000 to 24,000 MPN/100 ml (n = 10). Likewise, marsh water exposed to sediment containing feces that were dry at the time of collection had ENT concentrations ranging from 100 to 241,000 MPN/100 ml (n = 10). The geometric mean and 95% confidence intervals of the ENT measured in marsh water exposed to wet and dry feces were 1.8 x 10⁷ ± 2 ± 10⁷ x 1.4 x 10⁷ and 5.3 x 10⁷ ± 5.6 x 10⁷ x 10⁷ MPN/100 ml, respectively. Expressing these geometric means and confidence intervals on a per feces basis, we obtain 3.9 x 10⁷ ± 3.1 x 10⁷ x 10⁷ and 3.4 x 10⁷ ± 3.8 x 10⁷ x 10⁷ MPN/100 ml for wet and dry feces, respectively. The majority of the bird feces were deposited on low-lying mudflats in the marsh which became submerged to varying degrees during tides. This deposition of bird feces provided a mechanism by which ENT could be transported to the marsh. To determine the effect of bird feces deposited on the marsh, we have also observed the occurrence of ENT in water samples through the marsh. For a single mass balance calculation as follows:

$$C = C_{out}Q_{out} - C_{in}Q_{in}$$  (3)
Here $G$ is the rate of generation of bacteria in the marsh with units of MPN/m$^3$. $C_{out}$ and $C_{in}$ are the concentrations of ENT at the outlet and inlet of Talbert Marsh, respectively, with units of MPN/m$^3$, and $Q_{out}$ and $Q_{in}$ are the volumetric flow rates of water at the outlet and inlet of Talbert Marsh with units m$^3$/sec, where $L$ and $T$ represent length and time scales, respectively.

During ebb tides, in-situ measurements of flow velocity and water elevation at Brookhurst and PCH Stations indicate that the flow in and out of Talbert Marsh roughly balance so that $Q_{out} \approx Q_{in}$ and eq 3 simplifies as follows:

$$G = Q \langle \Delta C \rangle \tag{4}$$

The parameter $\Delta C$ is the increase in ENT measured in water as it flows through Talbert Marsh.

Using average ebb tide values of $\Delta C = 29$ MPN/100 mL (see Figure 3E) and $Q = 8.37$ m$^3$/min from the calibrated hydrodynamic model, we estimate a generation rate for ENT in the marsh to be $G \approx 10^4$ MPN/m$^3$. Assuming each bird dropping has $10^5$ MPN fees (the geometric mean for wetland birds), then 100 bird feces would be needed in an hour for the estimated generation rate. Our bird census indicates that, at most, 100 birds are present in the marsh, which corresponds to a deposition rate of more than 1 feces per bird every six minutes. If instead we use the minimum number of bird feces (i.e., the mean of birds present in the marsh during the day (286 birds), the deposition rate required decreases to approximately 1 feces per bird every 3 h. This latter deposition rate is comparable to rates observed for the same bird species in captivity, typically one dropping every 3 h (personal communication).

The above analysis considers the potential contributions of older, dried, bird feces, which were also found to contain significant levels of ENT. Portions of the mudflats in Talbert Marsh may remain exposed over many tidal cycles, allowing the quantity of bird feces deposited there to increase. During spring tides, when higher average high tide occurs, these older feces may become suspended in the marsh water and thereby increase the concentration of ENT in the water column. This idea is consistent with the fact that the highest level of ENT reported at Brookhurst and PCH Stations occurred during spring tides when the marsh is at its highest point (Figures 1B). Vegetation in the Talbert Marsh may also contribute to the levels of ENT in the water column, as could the growth of other organisms at the sediment/water interface. Indeed, growth of the sediment/water interface is supported by the distribution of ENT in cores taken from Talbert Marsh (see Figure 2). While bird droppings are clearly a significant source of ENT in the marsh, other sources may also contribute to the generation of ENT in the marsh including urban runoff, sediment, and vegetation.

Implications. ENT generated in the Talbert Marsh appear to be at least partially responsible for the frequency with which surf zone samples in Huntington State and City Beaches exceed state health standards. This conclusion is based on two findings from our study: (1) ENT concentrations are increased above ENT standards (both single-sample and geometric mean) as water passes through the marsh; and (2) water flowing out of the marsh can be contaminated by bacterial strains to the extent of Huntington State and City Beaches, where ENT standards are commonly exceed. The ENT appears to enter the marsh from birds and runoff, and since these organisms accumulate and perhaps even grow, on marsh vegetation and sediments. While ENT flowing into the surf zone during ebb tides may be responsible for beach postings that occur near the marsh outlet, the marsh is probably not the only source of ENT at Huntington State and City Beaches. During the summers of 1999 and 2000, for example, surf zone station 9N (see Figure 1) was frequently posted or closed (total of 70 days) due to elevated levels of ENT, even during periods of time when the concentration of ENT at stations near the Talbert Marsh outlet were relatively low (9D). Given this spatial distribution of ENT, it is unlikely that the bacteria in ENT are coming solely from the Talbert Marsh, and their exact source is a matter of ongoing investigation. Indeed, we anticipate that the impact of marsh effluent on surf zone water quality will be relatively localized, given the factor two dilution that occurs as the marsh water mixes into the surf zone, and the fact that ENT die-off in ocean water (Fig. 3). Based on the results presented in this paper, these are tradeoffs between the restoration of coastal wetlands and compliance with marine water contact standards. This tradeoff could be ameliorated by specifically designing wetlands to remove bacteria from the water column. For example, freshwater wetlands remove bacterial pollutants most efficiently when the flow velocities are slow (<0.7 m/s) and the residence time of water is long (0.25-2.7). While the flow velocities in the Talbert Marsh are within the recommended range, the residence time of water (~1.7 h) is short. On the other hand, if there are no human health risks associated with ENT from wetland effluent then marine water contact standards may need to be modified to account for the existence of both benign and non-benign sources of these bacteria. An epidemiological study could help define the human health risks associated with human exposure to nonantibiotic sources of ENT such as those identified. These issues are especially timely, as a federal law has recently been enacted that mandates national monitoring and reporting of coastal water quality (38).

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