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Temporal and spatial variability of fecal indicator bacteria in the surf zone off Huntington Beach, CA

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Abstract

Fecal indicator bacteria concentrations measured in the surf zone off Huntington Beach, CA from July 1998–December 2001 were analyzed with respect to their spatial patterns along 23 km of beach, and temporal variability on time scales from hourly to fortnightly. The majority of samples had bacterial concentrations less than, or equal to, the minimum detection limit, but a small percentage exceeded the California recreational water standards. Areas where coliform bacteria exceeded standards were more prevalent north of the Santa Ana River, whereas enterococci exceedances covered a broad area both north and south of the river. Higher concentrations of bacteria were associated with spring tides. No temporal correspondence was found between these bacterial events and either the timing of cold water pulses near shore due to internal tides, or the presence of southerly swell in the surface wave field. All three fecal indicator bacteria exhibited a diel cycle, but enterococci rebounded to high nighttime values almost as soon as the sun went down, whereas coliform levels were highest near the nighttime low tide, which was also the lower low tide.

Keywords: Sewage effluent; Surf zone; Diurnal; Internal waves; Fecal indicator bacteria; Tides

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1. Introduction

Fecal indicator bacteria (FIB) are found in the feces of humans and other animals. Although some strains are ubiquitous and not related to fecal pollution, their presence in water is used as an indication of fecal pollution and the possible presence of enteric pathogens. Epidemiological studies have demonstrated that FIB not only determine the extent of fecal contamination in recreational surface waters, but their density in recreational water samples has been shown to have a predictive relationship with swimming-associated gastroenteritis at marine and fresh water bathing beaches (Cabelli et al., 1982; Haile et al., 1999; Flesisher et al., 1993).

Under the standards contained in California Health and Safety Code §115880 (Assembly Bill 411, Statutes of 1997, Chapter 765; [AB411]), from April to October beaches must be posted when FIB concentration exceeds a single sample, or running monthly geometric mean, standard, or closed to public contact if the health authority thinks that human sewage is the cause of the high bacteria level. There were numerous beach postings and closures in the summers of 1999 and 2000, due to elevated FIB levels in the surf zone off Huntington Beach, CA (see Fig. 1). Since this beach is a heavily used recreational area, postings and closures have a potentially significant economic impact on the local community, especially during the summer.

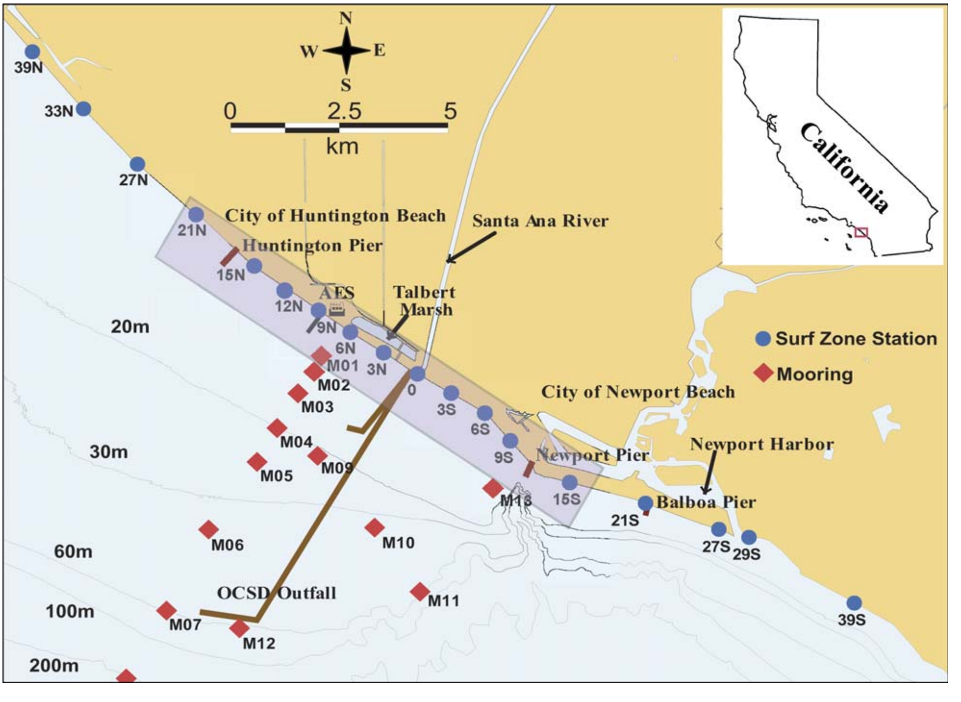

Fig. 1. Map showing Huntington Beach, and the surf zone stations from 39N to 39S, plus the locations of the OCSD outfall, Santa Ana R., Talbert Marsh, and the AES outfall/intake. The 18 regularly sampled stations are covered by the shaded rectangle.

The Orange County Sanitation District (OCSD) is the third largest southern California publicly owned treatment works. Between 1998 and 2001, OCSD discharged non-disinfected effluent through an ocean outfall with a 1.8 km long diffuser extending from 6.4 to 8.2 km offshore from Huntington Beach (Fig. 1). In 2000–2001, the average daily discharge was 244 million gallons per day (MGD) (9.2×10^8 L/d) of treated wastewater (OCSD, 2001).

During 15 years of monitoring, required by their National Pollution Discharge Elimination System (NPDES) ocean-discharge permit, OCSD never found evidence that their wastewater plume reached the surf zone. In spite of this, it was suggested that bacteria-rich effluent from the OCSD outfall plume might be responsible for the beach contamination (Grant et al., 2000), so OCSD undertook an extensive investigation of this hypothesis. The Huntington Beach Phase III (HB PIII) study took place from May to October 2001 and included moored instrumentation that provided extensive high-frequency measurements of currents and water properties. Since examination of historical monitoring data (MEC, 2000; Grant et al., 2000) suggested that the elevated bacteria levels coincided with periods of maximum tidal range (i.e., spring tides), during six 48-h periods near the time of spring tides, the standard surf zone bacterial sampling program was enhanced with higher temporal resolution sampling, and hydrographic cruises were performed to help evaluate cross-shelf transport processes and their potential to move wastewater effluent to the beach.

The hypothesis tested in HB PIII was whether internal tides transported FIB from the OCSD outfall plume to the beach. The study concluded that there was no evidence to support that mechanism (Noble et al., 2003a), but the extensive data set collected during HB PIII, in addition to the long-term OCSD monitoring data set, afforded an unparalleled opportunity to examine aspects of the spatial and temporal variability of the FIB concentrations and AB411 single sample exceedances in the Huntington Beach surf zone on time scales from weeks to hours. This examination shed light on potential sources of these FIB. Particular attention was paid to the relationships between FIB concentrations and the fortnightly lunar cycle, the diurnal sunlight cycle, and the semidiurnal tidal cycle.

This paper does not address the impact of rainfall and run-off, which are primarily wintertime phenomena in southern California, since that has been the focus of a number of other studies (Boehm et al., 2002a; Noble et al., 2003b). It should be noted however, that 99% of the annual FIB loading from this watershed occurs during winter storm events (Reeves et al., 2004).

2. Methods

2.1. Determination of bacteria concentration

The FIB concentrations and AB411 single sample exceedances in the Huntington Beach surf zone between July 1, 1998 and December 31, 2001 were considered. The three types of FIB sampled, and their allowed single sample maxima, expressed as organisms/100 ml, under AB411 are: (1) fecal coliform (FC) $\leqslant 400$, or alternately *Escherichia coli*, EC; (2) total coliform (TC) $\leqslant 10{,}000$, or 1000 if FC/TC $\geqslant 0.1$, and (3) enterococci (ENT) $\leqslant 104$.

Samples were collected from 17 mandatory locations, specified by OCSD's NPDES permit, plus one additional station, 12N, in ankle-depth water (see Fig. 1). The regularly sampled stations are named as 1000s of feet north or south of the Santa Ana River (SAR). The array of stations extends from 39,000 ft (11.9 km) north of the SAR (39N) to 39,000 ft south of the SAR (39S). Most of the locations are separated by 3000 (914.4 m) or 6000 ft (1828.8 m), and all but one, 29S, are at integer multiples of 3000 ft from the SAR. Samples were sometimes taken at additional stations to enhance spatial resolution to better address perceived localized problem sites (e.g., station 8N) or from specific geographic or man-made features of interest not within the surf zone, such as the mouth of Talbert Marsh (TM) and SAR or a nearby power plant (AES). Samples were generally collected between 05:00 and 10:30 (local time) with the typical collection strategy proceeding from north to south.

During the late springs and summers (late May–August) of 1998–2001, and continuing through the end of 2001, samples were collected five days/week, including one weekend day. During November 1999–March 2000, samples were collected two days per week; during parts of September–October 1999 samples were collected seven days per week, and during the remainder of the 3.5 year time period, samples were generally collected three days per week. The sampling schedule described above was mandated by the NPDES permit. During the late spring and summer of 2001, six 48-h, ship-based surveys (May 21–22, June 19–21, July 5–7, July 19–21, August 19–21, and September 15–17) were conducted, coinciding with spring tides. Surf zone microbiology samples were collected hourly during these six surveys at a contiguous 11-station subset of the standard OCSD sampling sites (15S–21N). During the first cruise, hourly sampling was done for only 36 h, with one several-hour break.

Sample collection, preservation and handling procedures are described in detail in OCSD (2001). OCSD used the multiple tube fermentation method for TC and FC bacteria at all permit-required surf zone stations (Standard Method [SM] 9221B, E in Eaton et al., 1995). An alternative method for simultaneous detection of TC and EC, a chromogenic substrate coliform test commonly known as Colilert-18®, was used by OCSD for the additional samples taken for the HB PIII study (SM 9223B; Eaton et al., 1995). In most environments, EC represents the majority of the FC population, but there is no absolute relationship that can be predicted. FC concentrations were estimated as 1.1 times the EC concentration for the purposes of this study. This ratio was established based on a survey of FC/EC concentrations in samples collected from OCSD's final effluent. EPA 1600, a membrane filter test method for ENT in water, is the standard methodology used for OCSD's daily permit compliance testing. Membrane filter methods (SM 9222A and 9222D in Eaton et al., 1995) were also used to determine TC and FC concentrations in some HB PIII samples analyzed by the Orange County Health Care Agency's laboratory during the hourly sampling events. OCSD also used an alternative chromogenic substrate for ENT, commonly known as Enterolert® (Idexx Corp.) for samples collected during the hourly sampling events. Minimum and maximum detection limits varied depending on the method used and sample dilution, as described in Rosenfeld (2004).

2.2. Definition of bacterial contamination events

Several types of bacterial "events" were defined in order to reduce the three FIB concentrations at 18 stations into a few variables. The events take advantage of spatial patterns appearing naturally in the data, that show that coliform contamination events were more localized and ENT events more widespread (see Fig. 2). Taken together, the three event types capture all but a handful of days on which there was an AB411 exceedance anywhere in the HB PIII data set.

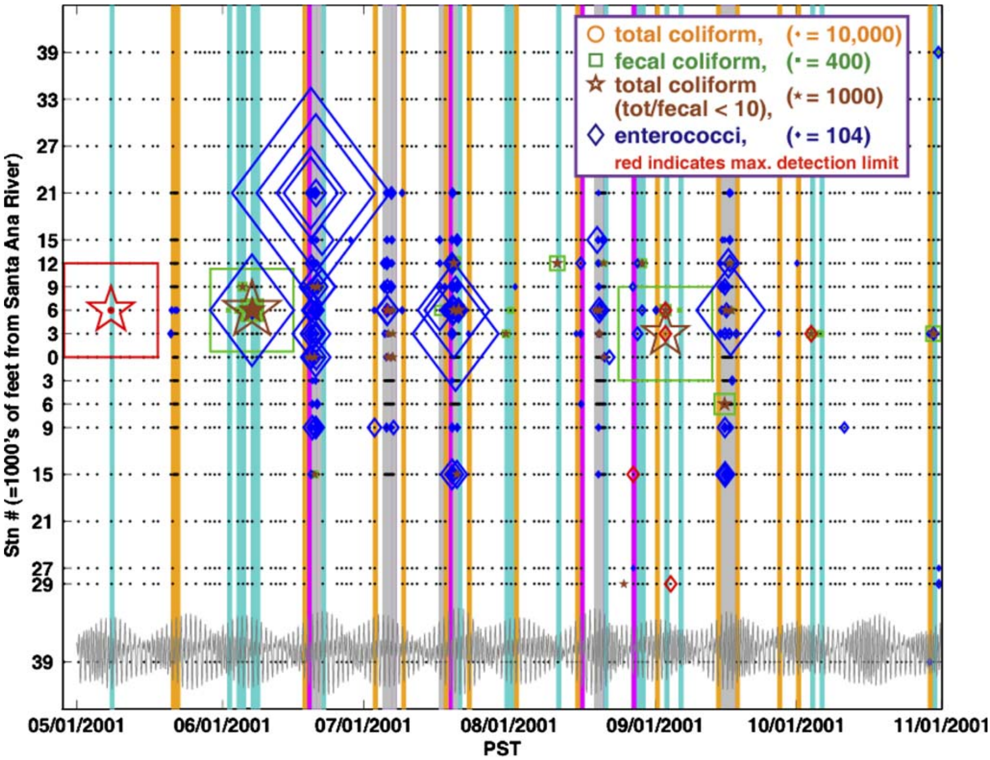

Fig. 2. The vertical bars indicate days on which bacterial events occurred, blue, type 1; magenta, type 2; gray, types 1 and 2; gold, type 3. Sea level measured at Los Angeles is shown at the bottom of the figure. A black dot is plotted at each time and location a sample was taken. Colored symbols are plotted at the time and location of samples exceeding AB411 single sample standards. The size of the symbol is proportional to the ratio of the measured bacterial concentration to the AB411 criteria. The symbol size for a sample equal to the AB411 criteria is shown to the right of the indicator species in the legend.

When TC or FC concentrations exceeded AB411 standards at one or more of the stations between, and including, 3N and 12N during any day (00:00–23:59 PST), a type 1 event was recorded for that day. During a day when ENT concentrations exceeded AB411 standards at three or more of the numbered stations from 39S to 39N, including at least one station from 3N to 12N, a type 2 event was recorded for the day. A third type of event was added to ensure that all days on which any of the single sample standards were exceeded in the Huntington Beach area would be included in at least one type of event. A type 3 event was defined as occurring on any day during which ENT exceeded AB411 standards at any station between, and including, 3N and 12N, on which there was not a type 1 or type 2 event.

Since hourly round-the-clock sampling was done during the six intensive surveys of the HB PIII study, it is possible that greater sampling frequency and/or nighttime sampling led to more frequent observation of bacterial contamination events. Hence, a data set containing no more than one sample per station per day was created. If multiple samples were available for a station for a given day, the sample closest in time to that of the average sampling time (calculated over May 1–October 31, 2001) for that station was used. The type 1–3 event analyses described above were also carried out on this daily sub-sampled data set.

2.3. Sea level and astronomical data

Hourly sea level data for Los Angeles (33°43.2′N, 118°16.3′W, station ID 9410660) for 1998–2001 were obtained through the National Ocean Service web site (http://co-ops.nos.noaa.gov/). Sea levels are given in meters above mean lower low water. While technically, the term spring tide denotes the largest tidal range in a fortnightly period, in order to assign a time unambiguously to each spring tide, the highest high water in a window of 10–20 days (9.4 days in one case) after the previous spring tide, with a neap tide in between, was picked as the date/time and height of "spring tide". Note that by using the actual sea level, rather than the phase of the moon, there is some variance in the time between "spring tides" due to meteorological effects, although on average it is 14.8 days as would be expected.

Times of new and full moons, and sunset and sunrise, were obtained from the US Naval Observatory web site (http://mach.usno.navy.mil). Averaged over 1998–2001, the spring tide high water occurs 0.6 days after a new or full moon.

2.4. Event probability versus sea level

The relationship between the height of the higher high water each day and the probability of a bacterial event occurring was considered using a simple logistic regression model. If the probability of an event on day i is denoted by p_i, then the logistic model says:

$$\log(p_i/(1-p_i)) = \beta_0 + \beta_1 \mathrm{tide}_i, \quad (1)$$

where tide_i is the height of the higher high tide on day i, and β_0 and β_1 are the logistic regression coefficients.

2.5. Moored data

An extensive moored instrument array, as well as shipboard surveys, produced a wealth of data as part of the HB PIII study (see Fig. 1). Only a small subset of those data are used in this paper and described briefly here. The instrumentation and methodology is described in much more detail in Hamilton et al. (2004).

Temperature, salinity, and current records from seven moorings in water depths from 10 to 205 m, extending in a line offshore from a point between 3N and 6N, were analyzed for the presence of internal tidal pulses. The temperature measured 0.5 m above the bottom in 10 m water depth at mooring M01, located ~1 km offshore, was used to indicate the near-bottom, near-shore temperature. These time-series, with temporal resolution of 2–5 min, are available from mid-June to mid-October of 2001.

Surface waves were measured using accelerometers and rate gyros in conjunction with a magneto-inductive compass, on the M07 surface buoy, located 8 km offshore on the 60 m isobath, just shoreward of the shelf break (see Fig. 1). Daily directional wave spectra, with directional resolution of 1°, and frequency resolution of 1/256 Hz, were computed from the earth-referenced north–south, east–west and vertical displacement time series using the maximum entropy method (MEM) described by Lygre and Krogstad (1986). Details of the data processing can be found in Hamilton et al. (2004).

2.6. Identification of internal tidal pulses

For the purposes of this study, internal tidal pulses were identified by the appearance of cold water near shore, as determined by two methods. In the first, the temperature of the sewage outfall plume was determined by looking at the temperature/salinity distribution from the moorings in two-week increments from June 17 to October 15, 2001. The maximum temperature of the plume T/S anomaly was picked as an upper limit of the temperature of the plume and this value was compared with the temperature time series at the near-shore moorings (M01 and M03). If the 10 m temperature at mooring M01 was less than, or within 0.25 °C of, the warmest temperature in the sewage outfall plume, it was designated as a cold water near-shore event. The results were found to be insensitive to whether mooring M03 or M01 was used. In the second method, designed to identify the times when water from the shelf break was brought closest to the beach, the temperatures measured by the moorings along the main line were used to determine when the 12 °C isotherm was inshore of the 30 m isobath and the water at M03 was cooler than 13 °C.

3. Results

3.1. Three and a half year record: July 1, 1998–December 31, 2001

3.1.1. Statistics

There were 14,866 samples from the 18 regularly sampled surf zone stations (from 39S to 39N) collected between July 1, 1998 and December 31, 2001 and analyzed for the three bacterial indicators. The majority of samples had bacterial concentrations less than, or equal to, the minimum detection limit (58% for TC, 73% for FC, 66% for ENT). Only 219 (1.5%) had TC concentrations (or a combination of concentration and FC/TC ratio) exceeding the AB411 single sample standard, 284 (1.9%) exceeded the FC standard, and 834 (5.6%) had ENT concentrations greater than the AB411 standard. There were 217 samples that exceeded AB411 standards for both ENT and coliform bacteria.

While many more samples exceeded the ENT standards than exceeded the coliform standards, when the exceedances were grouped into daily events, as described in Section 2.2, the number of days affected by coliform events slightly exceeded the number affected by ENT events. Referring to events calculated using the daily sub-sampled data set, it was found that out of the 1280 days, of which 692 were sampled, type 1 events occurred on 148 days, type 2 events on 67 days, and type 3 events on 75 days. Without sub-sampling to no more than one sample per day per station, an additional six days qualified as type 1 events and an additional 10 days as type 2 events.

3.1.2. Fortnightly variability

Analysis of the relationship between tidal height (or range) and the occurrence of bacterial contamination in the surf zone found that there was a higher likelihood of a type 1 or 2 bacterial event occurring the day after the spring tide high water than on any other day in the fortnightly cycle. Of all the days in a fortnightly cycle, the day that spring tide occurred had the greatest chance (60%) of experiencing an AB411 exceedance (i.e., type 1, 2, or 3) in the 3N–12N region. Classification of all bacterial events according to what day they fell on relative to the spring tide showed that about 50% of them occurred within ±2 d of the spring tide.

The logistic model for each of event types 1 and 2, plus one in which the response was type 2 or type 3 (see Fig. 3), all indicated that the tide height term was "statistically significant," meaning that the size of the effect we see in the model is such that it is very unlikely an effect of that size would have arisen in the sample if, in fact, there were no such relationship in the population. The results show that the higher the height of the high tide, or correspondingly the greater the tidal range, the more likely there is to be a bacterial contamination event.

3.2. HB PIII: June–October 2001

3.2.1. Surf zone bacteria spatial variability

All three indicator species showed higher concentrations preferentially in a band between 3N and 12N (see Fig. 4). This was particularly evident for FC. Occasionally, relatively high levels of ENT (>300 MPN/100 ml) were found almost simultaneously at stations all the way from 9S to 15N. Total coliform rarely exceeded 300 MPN/100 ml south of the SAR, but on one occasion (in mid-August) TC exceeded 200 MPN/100 ml from 15S to 12N.

3.2.2. Surface waves

The daily wave spectra were examined by eye and characterized as southerly swell, westerly wind waves, southerly wind waves, a combination of the above, or no waves (see Fig. 5). Fifty-five percent of days with a bacterial event coincided with southerly swell, while 45% of days with a bacterial event occurred on days with either no waves to speak of, or westerly wind waves alone. These are nearly identical to the percentages of all days in the study period with (54%) and without (46%) southerly swell, thus indicating that bacteria events did not occur preferentially during southerly swell. Considering each of the three event types separately, type 1 (58%) and type 3 (50%) events occur in concert with southerly swell in close to the same proportions as southerly swell occurs in general, while type 2 bacterial events have a slight bias towards southerly swell, with 75% of them occurring on southerly swell days.

3.2.3. Internal tidal pulses

The dates on which internal tidal pulses occurred, according to the criteria described in Section 2.6, are shown in Fig. 5. Subsequent complex demodulation analysis (Noble et al., 2004a) confirm that all but the June 28–29 cooling event determined by these methods, were in fact associated with the presence of an enhanced internal tidal signal at the shelf break. These large cold water sloshing events were also identified by the 14 °C isotherm reaching 5 m, or shallower, at another mooring (SIO2) on the 11 m isobath. Judged by all of these criteria, the largest internal tide pulses of the HB PIII study occurred during July 23–26. Note the general lack of correspondence between the days on which cold water was found near shore and the days on which bacterial exceedance events occurred.

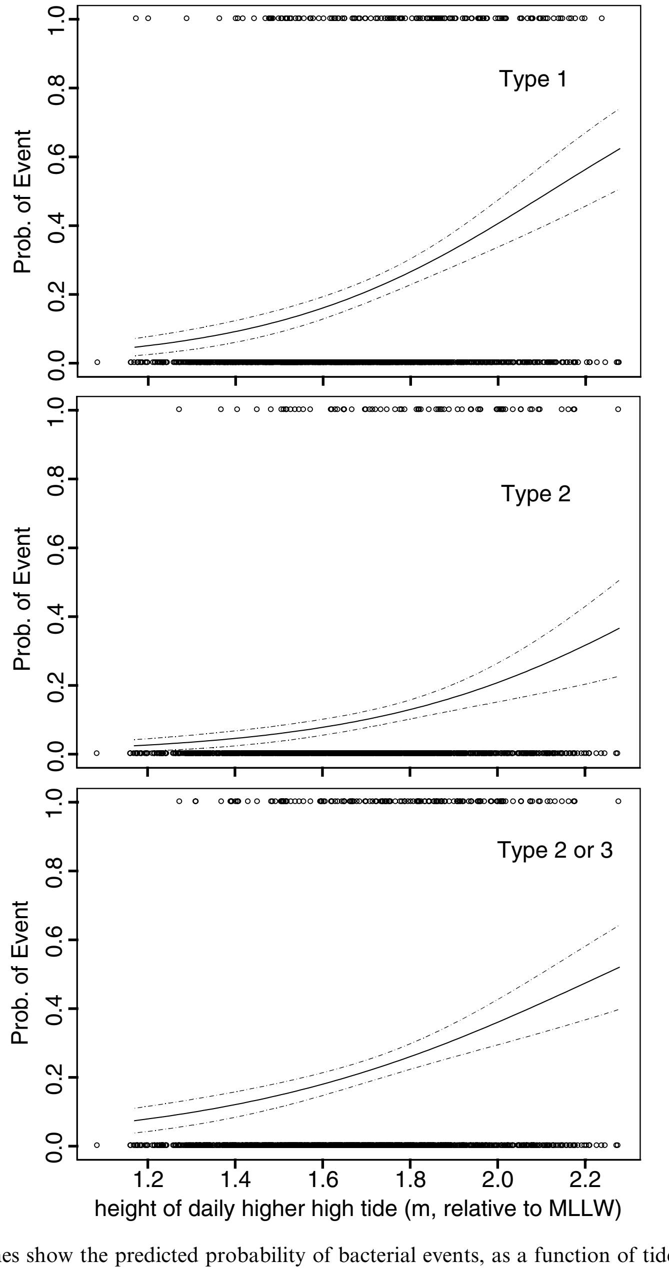

Fig. 3. The solid lines show the predicted probability of bacterial events, as a function of tide height. The open circles plotted at 1 or 0 on the y axis indicate event or no event, respectively, versus height of higher high water on the x axis. The two dotted lines give estimated 95% confidence levels for the probabilities at each point.

3.3. Hourly round-the-clock sampling during 48-h surveys

3.3.1. Spatial variability

Contour plots of the FIB concentrations during July 19–21 (see Fig. 6) are shown as a representative example of the hourly surf zone bacteria data collected during six 48-h

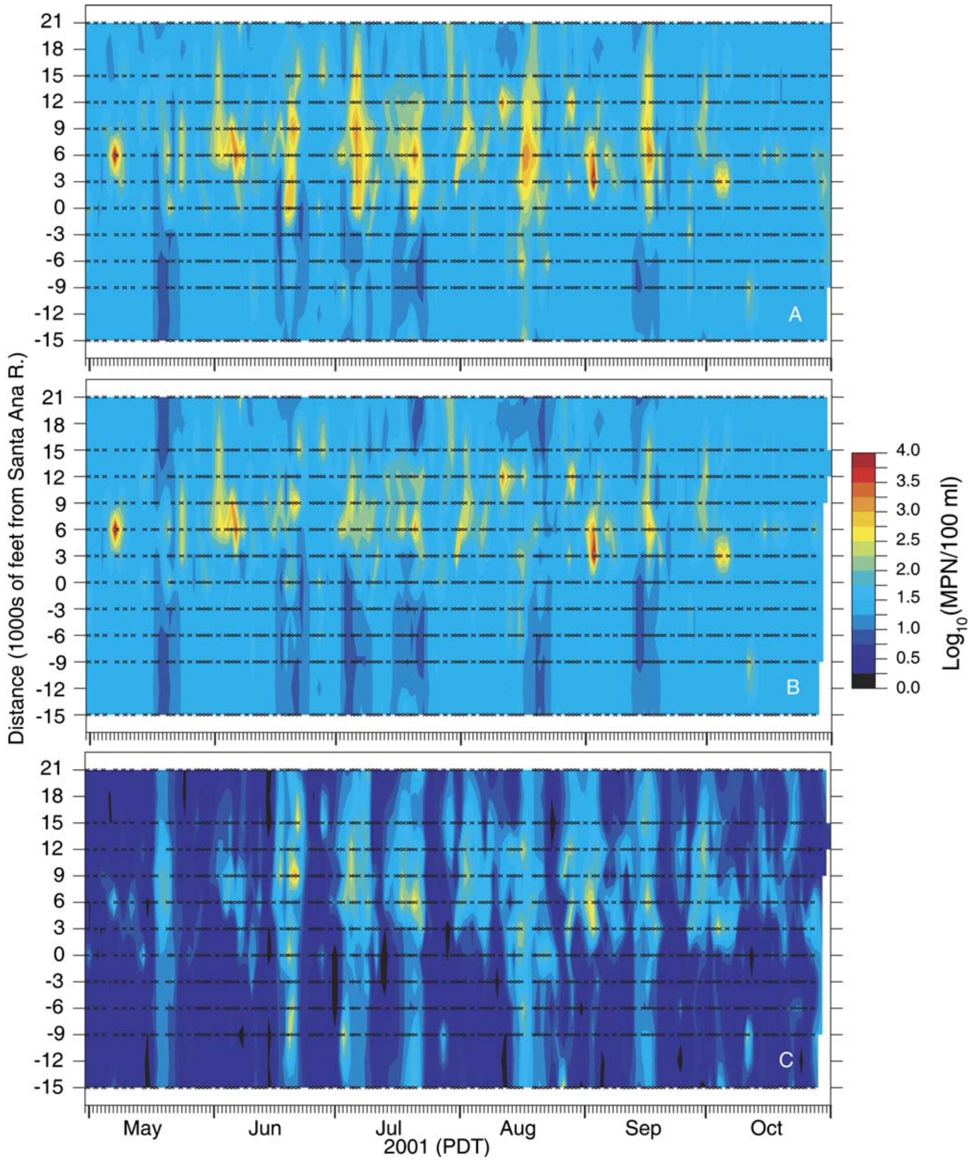

Fig. 4. Log_{10} of total coliform (A), fecal coliform (B), and enterococci (C) concentration are plotted versus time and distance alongshore. The data set subsampled to no more than daily values was used. X's indicate the day and location of each sample. Data is contoured with PlotPlus on a 180×13 grid (time and distance, respectively) using cay = 5 and nrng = 2. The cay value determines the interpolation scheme. Cay = 0 means Laplacian interpolation is used. As cay is increased, spline interpolation predominates over Laplacian. For pure spline interpolation cay = infinity. Grid points are set to "undefined", and not used, if farther than nrng away from the nearest data point.

periods coinciding with spring tides. Similar figures for other periods may be found in Rosenfeld (2004). While there are similarities in the spatial patterns for all three FIB, there are also differences. The higher concentrations tended to be found north of the

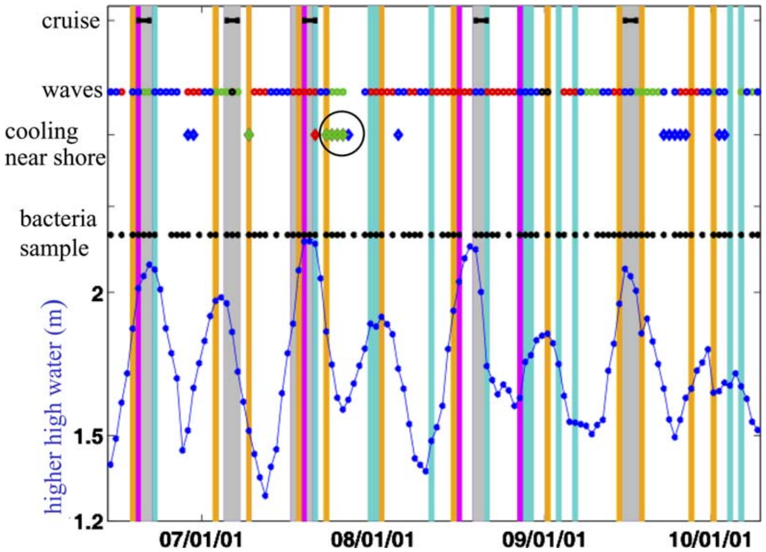

Fig. 5. Vertical bars indicate days on which bacterial events occurred, blue, type 1; magenta, type 2; gray, types 1 and 2; gold, type 3. A black dot is plotted at each time and location a sample was taken. Cruise periods are shown at the top of the figure. A characterization of the directional wave spectra is shown below that (● westerly wind waves only, ● ● ● all include southerly swell), with the occurrence of cold water near shore indicated below that (◆ 12 °C inshore of 30 m, ◆ M01 $T <$ max plume T, ◆ both; the largest internal tide pulses, July 23–26, are circled). Black dots in row 4 indicate days on which bacterial samples were taken. The day's higher high water as measured at Los Angeles is shown at the bottom.

SAR, but when there were elevated levels south of the SAR, they occurred to some degree in all three indicators (see for example 2000–2300 PDT July 19 and 2100–2200 PDT July 20, Fig. 6). The highest values of TC tended to occur at station 0 (next to the mouth of the SAR), and there was some suggestion of upcoast (northwestward) propagation from there, with a speed of about 30 cm s^{-1} (see Fig. 6a), with elevated values subsequently found in the 0–12N region. FC values generally peaked close to station 6N (see Fig. 6b), while ENT values tended to be high not only near 6N, but also at the southern (see Fig. 6c), and occasionally at the northern (not seen in this example), ends of the range. ENT had a minimum from 6S to 0. These patterns also held for the daily sub-sampled data shown in Fig. 4.

3.3.2. Diel and tidal variability

The hourly data reveal a day–night cycle in all three FIB, with the highest values occurring at night. The onset of elevated TC values at station 0 occurred between about midnight and 03:00 (see Fig. 6a), just prior to the nighttime low tide which occurred between 03:00 and 06:00 over the course of the study. Bacterial concentrations were not generally elevated near the daytime low tide (the higher low tide of the two). On the few occasions when there were high values of coliform in the middle of the day (not seen in this example), ENT values were only slightly elevated, if at all, while at night all three indicators showed notably higher concentrations. Note that the mid-day increases in bacteria level had their maxima at station 0 for all three indicators, and occurred close to the time of the higher low tide.

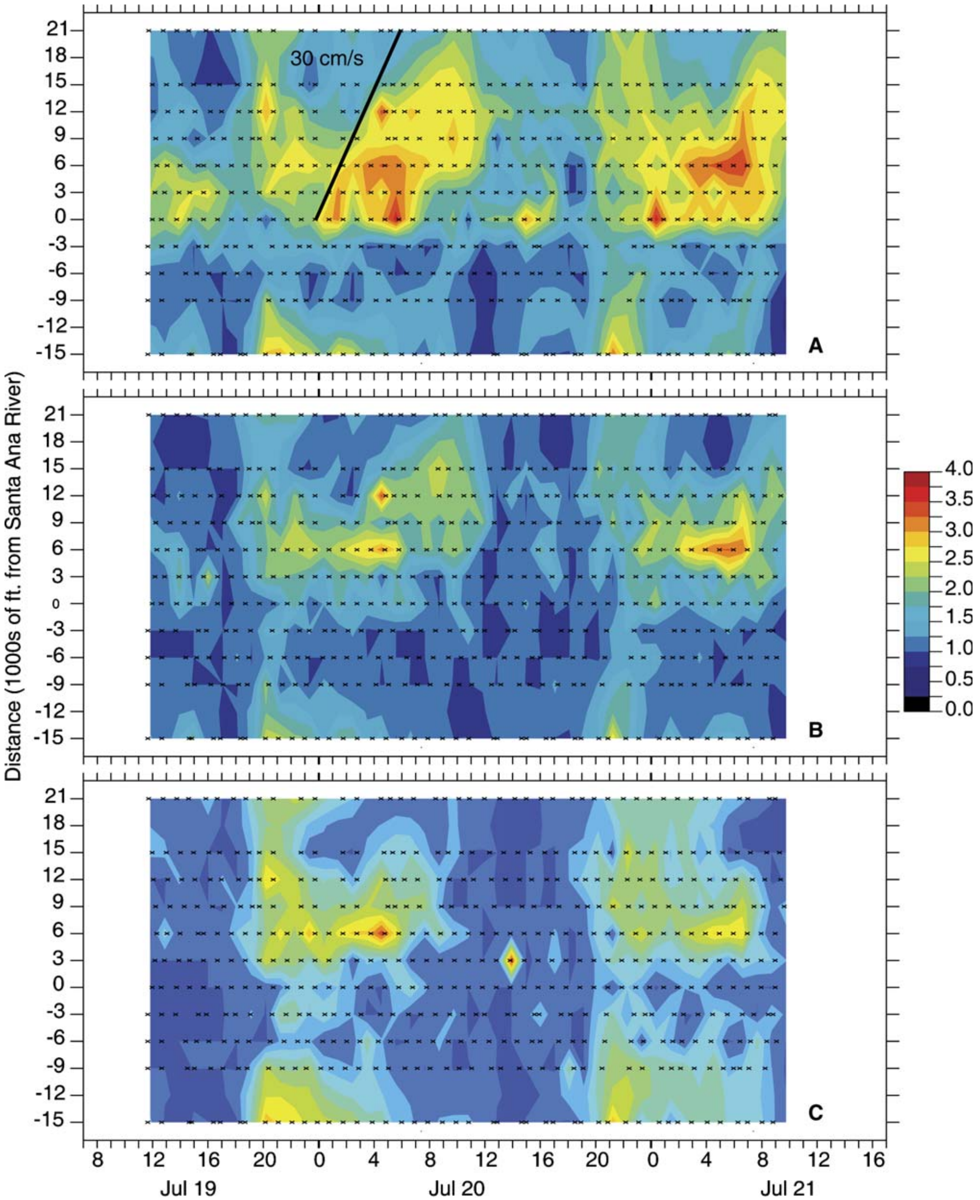

Fig. 6. Log_{10} of total coliform (A), fecal coliform (B), and enterococci (C) concentration (MPN/100 ml) are plotted versus time and distance alongshore. Black *x*s indicate the time and location of each sample. Data is contoured on a 48 by 13 grid (time and distance, respectively) using cay = 5 and nrng = 2. Time is Pacific daylight time (PDT).

The ENT exceedances, wherever they occurred, did so overwhelmingly between sunset and sunrise (see Fig. 7a). Note that the onset of ENT exceedances preceded both the high tide (the start of the ebb tidal flow) and the sudden drop in near-bottom near-shore temperature, as seen on the nights of 19 and 20 July (see Fig. 7a). The coliform exceedances, however, did not show this strong relationship to the day–night cycle, nor did such a pattern appear when a cut-off even lower than the AB411 single sample standard was used for visualization (see Fig. 7b). The predominance of high

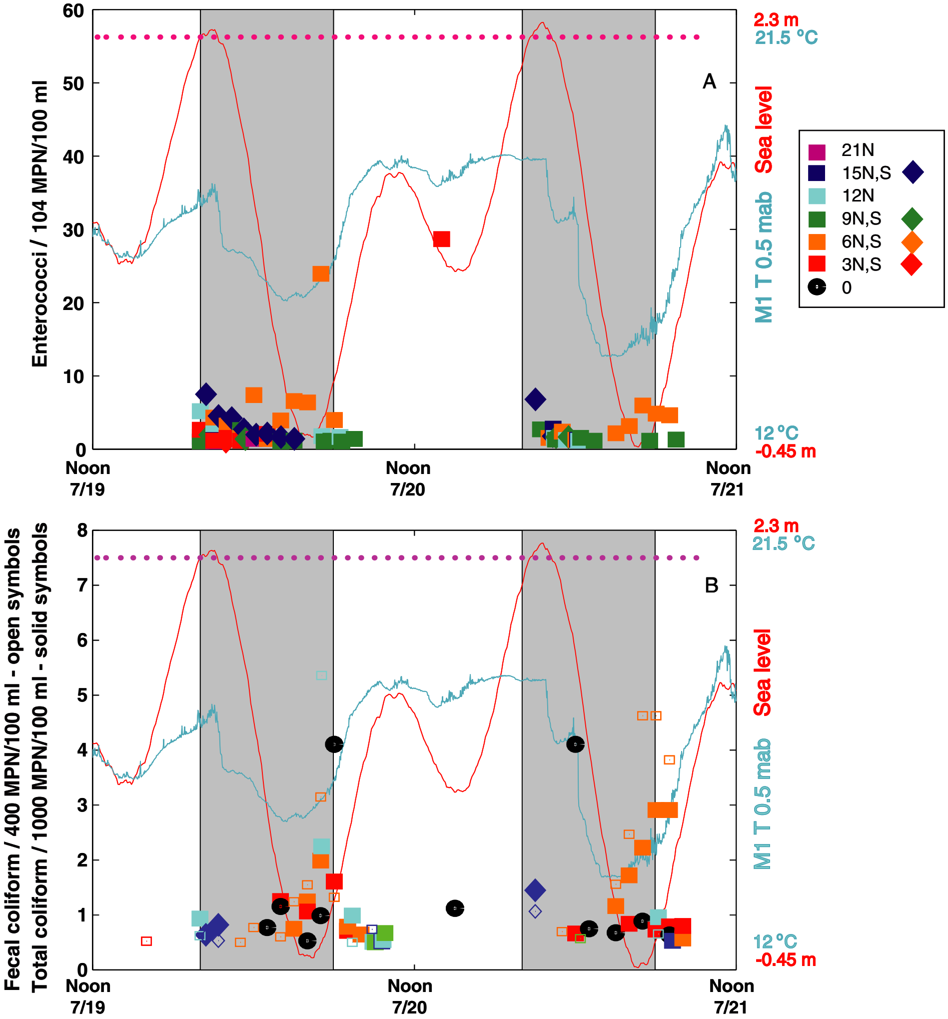

Fig. 7. The ratio of ENT concentrations (A), and TC and FC concentrations (solid and open symbols, respectively, in B) to the AB411 single sample standards* at stations 15S–21N for the 4th intensive sampling period are plotted together with sampling times at station 0 (pink dots), Los Angeles sea level (red line), and temperature 0.5 m above bottom at M01 (blue line). Only ENT samples with ratios exceeding 1, and coliform samples with ratios exceeding 0.5 are shown here. A local time reference is used; the period between sunset and sunrise is shaded gray. *Note that not all samples with TC >1000 MPN/100 ml exceed AB411 standards, as the TC/FC ratio may not be <10.

coliform values near the time of low tide is evident however. The temporal patterns are similar for the other five intensive sampling periods not shown in Fig. 7.

Figs. 8–10 show the concentration of all three FIB at all stations 15S–21N for all hourly data from the six intensive sampling periods plotted as a function of time of day, sea level, and time since the previous higher high water, respectively. ENT values rebounded as soon as the sun set, while coliform values did not rise until later in the evening, and did not reach values as high as seen in the early morning (see Fig. 8). Coliform values were highest (with a few exceptions) when sea level was low, whereas ENT had no obvious relationship to sea level (see Fig. 9). The TC peak that was seen 5–10 h after higher high water (HHW) at station 0 also occurred north of the SAR (represented by station 6N here), while the weaker peak 15–20 h after HHW only appeared at station 0 (see Fig. 10). Fecal coliform showed a pronounced peak at station 6N, but not at station 0, 6–10 h after HHW. The ENT pattern was quite different from total and fecal coliform.

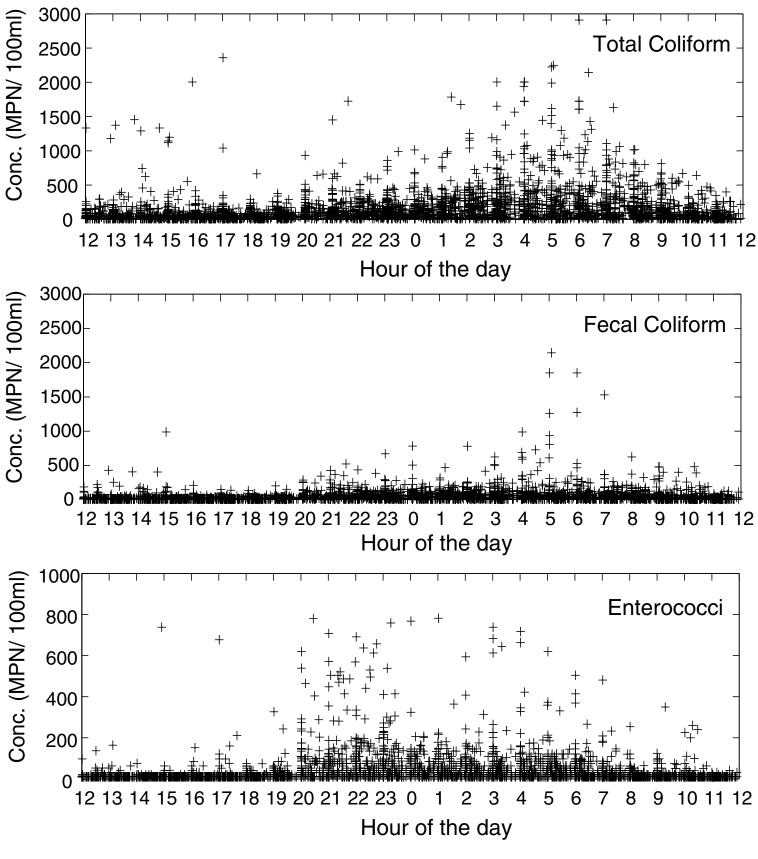

Fig. 8. Concentrations of fecal indicator bacteria at all stations 15S–21N for all hourly data from the six cruise periods are plotted versus time of day using a 24-h clock. Three total coliform, one fecal coliform, and nine enterococci samples had concentrations greater than the maximum values plotted in this figure.

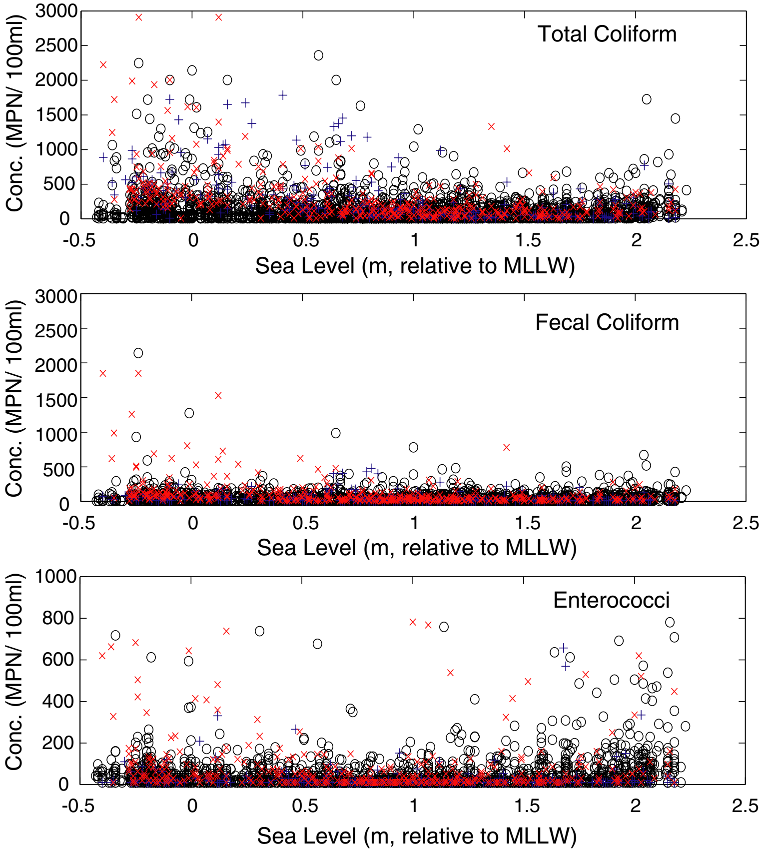

Fig. 9. The same surf zone bacterial data as shown in figure 8 is plotted versus sea level measured in Los Angeles. Values measured at station 6N are shown as red xs, those measured at station 0 as blue +s, all other stations are black os.

4. Discussion

4.1. Statistics and sampling bias

As has been previously noted by Noble et al. (2003b), Grant et al. (2000) and others, we found that ENT exceeded AB411 single sample standards in many more samples than total and fecal coliform did. However, the analyses presented demonstrate that, due to the fact that samples from many stations have ENT exceedances on the same day, the number of beach postings or closures in this area are as likely to be due to high coliform levels as to high ENT levels.

Since the measurements of FIB concentrations are not continuous in time, it is important to consider how representative these data are, given the sample schedule used to obtain them. Using five years of daily sampling at 24 Los Angeles area sites, Leecaster and Weisberg (2001) estimated that 70% of AB411 single sample exceedances last only one day, and less than 10% last more than three days. Assuming similar temporal variabil-

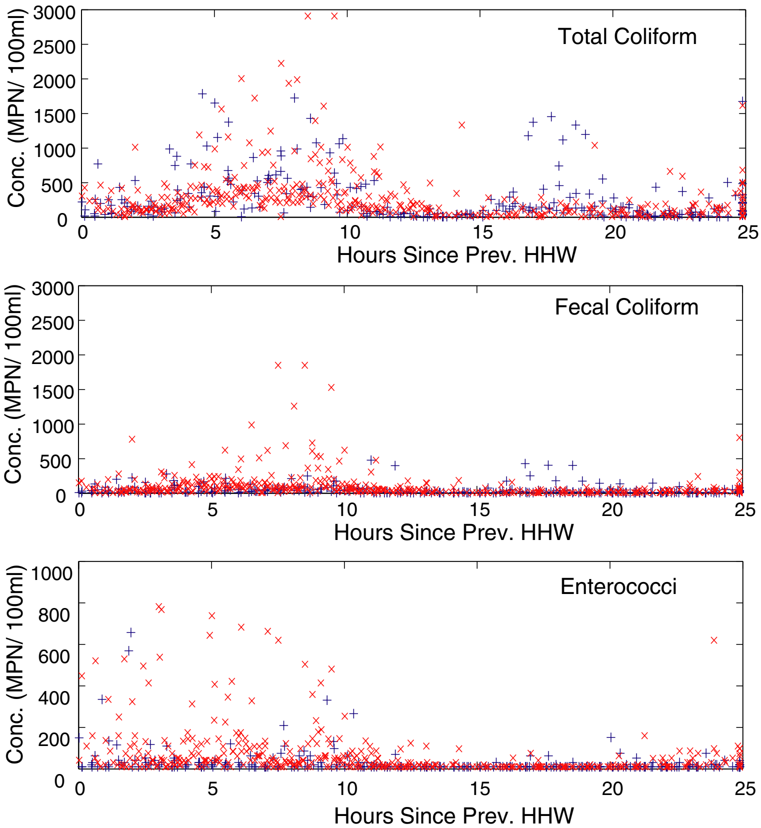

Fig. 10. Concentrations of fecal indicator bacteria at stations 0 (blue +s) and 6N (red xs) for all hourly data from the six cruise periods are plotted versus time since the previous higher high water as measured at Los Angeles. Two total coliform, no fecal coliform and three enterococci samples had concentrations greater than the maximum values plotted in the figure.

ity, the five times per week sampling OCSD did during the summers and the last half of 2001 may have missed about 20% of the total and fecal coliform exceedances. Based on two weeks of hourly sampling at four stations during May 2000 and 12 h of sampling every 10-min at six stations (3N–12N) during September 2001, Boehm et al. (2002a) estimated that more than 70% of single sample exceedances last less than 1 h, so the likelihood is that many more days on which exceedances exist, at least fleetingly, are also missed. This means the five times/week summertime sampling and the ~12 days worth of hourly sampling analyzed here should be representative of the spatial and temporal patterns of summertime variability with time scales greater than 2 h.

4.2. Spring–neap cycle and internal tidal pulses

The incidence of high concentrations of bacteria confirm a previously identified relationship with the lunar cycle (MEC, 2000; Grant et al., 2000). The larger the tidal range (or equivalently, the lower the daily lower low water, or the higher the daily higher high water), the higher the probability of a contamination event (see Fig. 3). Our results (Section 3.1) indicate that bacterial contamination events were most likely to occur on the day of the largest tidal range and that 50% of the events occurred within ±2 days of the spring tide. Based on summer 1999 Huntington Beach surf zone samples, Kim and Grant (2004) found that the error rate for beach postings would have been substantially reduced if they had been based on ENT concentrations predicted from daily tidal range, rather than on measured concentrations. This is because the correlation between ENT concentration and daily tidal range often exceeded that between the concentration in the current sample and the one preceding it; and the time between the collection of a sample and posting a beach based on that sample's concentration usually equals or exceeds the time interval between sample collections.

While it is clear that the surf zone was most contaminated near the time of spring tides, the reasons for this are not as clear. The tidal variations in sea level are primarily due to the barotropic, or depth-independent (neglecting bottom friction) component of the tidal signal, also known as the surface tide. In stratified water however, the tidal period isotherm displacements and currents may be much more heavily influenced by the depth-dependent, or baroclinic, component of the tidal signal, known as the internal tide. At the latitude of Huntington Beach, freely propagating internal waves can exist at the semi-diurnal, but not the diurnal, period. A detailed analysis, description, and discussion of the internal tide off HB can be found in Noble and Hamilton (2004) and is the focus of a paper in preparation by Noble et al.

As has been found in many other coastal areas, Boehm et al. (2002b) identified intermittent pulses of cold water near shore, and attributed them in part to cross-shore advection by internal tides. They could not rule out the possibility that this phenomenon, which we will refer to as internal tidal pulses, could transport FIB in high concentrations from the OCSD effluent plume into the surf zone, the hypothesis that had been proposed by Grant et al. (2000). If the internal tide were phase-locked to the surface tide (i.e., the largest internal tides occurred during spring tides), and if the internal tidal pulses transported high concentrations of FIB to the surf zone, then this mechanism would help explain the fortnightly variability observed in the FIB concentrations. However, the largest internal tidal pulses during HB PIII occurred during July 23–26, not coincident with a spring tide (the previous spring tide occurred on July 20), and the only exceedance of the AB411 single sample standards in the Huntington Beach area on those days was a single sample taken at 3N on July 23 with a measured ENT concentration of 110 MPN/100 ml. The timing of the cold pulses and the surf zone sampling at 3N–12N (see Table 1) was such that the samples could have captured high bacterial concentrations if they were brought in to shore together with the cold water.

Table 1
The timing of the cold surges, defined as the 13° isotherm being shoreward of the 20 m isobath, are shown together with Huntington Beach surf zone sample times

Date	Cold surge time (PST)	Stn 3N–12N sample times (PST)
7/23/01	02:00–07:00	07:25–07:55
7/24/01	01:00–09:00	06:35–07:10
7/25/01	03:00–06:00	06:30–07:05
7/26/01	02:00–07:00	06:30–07:05

We also considered whether the fact that the sampling times for each station vary very little over the 3.5 year record, in combination with the change in time of the low tides each day, could result in the effects of the timing of the sample relative to low tide being misinterpreted as spring tide effects. If the tidal cycle were due only to the largest constituent, M_2 with a period of 12.42 h; and the spring tides were exactly 14.77 d apart (which they are not based on our determination of the largest sea level ranges from measured tidal heights), and the sample was taken at exactly the same time each day, then the sample time relative to low tide would be the same on all spring tide days. For example, if the samples at station 9N were always collected an hour after low tide on days when the spring tide occurred, then it would be impossible to tell if the preferential occurrence of high bacterial concentrations on those days was due to the large tidal range, or the timing of the sample relative to the stage of the tide. This would be particularly problematic for the coliform bacteria data which, based on the hourly sampling, show a relationship to the stage of the tide.

We examined the timing of when the bacteria samples were taken at station 9N relative to the time of the previous low water at Los Angeles, and found that on summertime spring tide days, samples were always taken between 0 and 6 h after the previous low water (i.e., generally on the rising tide). During the winter, spring tide sampling occasionally occurred more than 6 h after the previous low water; but sampling frequency was less in the winter than the summer. The fact that the number of hours after low tide that the samples were taken on spring tide days are relatively evenly distributed between 0 and 6 h, and that on many non-spring tide days samples were also taken 0–6 h after low tide, lends credence to the hypothesis that the increased bacterial concentrations at spring tide are due to larger tidal ranges, rather than the timing of the sample collection relative to the phase of the tide. However, with the given sampling scheme, it is not possible to unequivocally separate out those two effects. To get an even distribution of samples on falling versus rising tides on spring tide days, one would have to collect half the samples in the evening, which would then introduce another set of issues concerning the diel cycle.

As other potential tidally related mechanisms are ruled out, increasingly it appears that the larger land area flushed by seawater during the extreme high tides may be responsible for the fortnightly variability. This mechanism would increase FIB contributions from beach areas where dog feces, for instance, might be a significant source as was found in the San Diego area (MEC, 2003), as well as from the TM where bird droppings have been implicated as a source of ENT (Grant et al., 2001), and from the SAR (Kim et al., 2004).

4.3. Spatial patterns and sources; tidal current and surface wave direction

Increased levels of all three FIB were found more frequently in the surf zone north of the SAR than south of it (Figs. 2 and 4; and Grant et al., 2000), though high concentrations of ENT were found throughout the range on a number of occasions. Excessive levels of total and fecal coliform were generally confined to the 0–15N and 3N–9N regions, respectively. There was some indication that a local source of bacterial contamination, particularly high in FC, existed near 6N.

The highest values of TC were found preferentially near low tide at station 0 (next to the mouth of the SAR) and nearby stations to the north of it. Hourly TC data also indicate that there was upcoast (northwestward) propagation from station 0, with a speed of about 30 cm s^{-1} (Fig. 6). Based on measurements made just outside the surf zone during May 2000, Kim et al. (2004) state that the alongshore currents during flood tides are directed upcoast, which is consistent with results from the HB PIII studies (Noble, personal communication), and hypothesize that they distribute the FIB that entered the coastal ocean from the SAR and TM on the previous ebb tide preferentially to the north of the SAR. A mass budget analysis for July 5–7, 2001 which included measurements at the outlets of TM and SAR, in addition to the surf zone data used here, concluded that SAR contributed more TC than did TM (Kim et al., 2004). It should be noted, however, that the subtidal currents often exceed the tidal currents, so that there may be no change in the sign of the alongshore flow over the course of several days (Hamilton, 2004).

Earlier work by Grant et al. (2001), using May 2000 data, identified TM as a net source of ENT. Confirming results presented here, recent modeling of mass and momentum flux in the surf zone are consistent with TM and SAR being the primary source for the TC, but not the FC and ENT, found in the Huntington Beach region (Grant et al., 2005).

Kim et al. (2004) have suggested that the predominance of high bacterial concentrations north of the SAR may be due in part to northwestward alongshore currents in the surf zone resulting from southerly swell. Grant et al. (2005, 2001) found that dye introduced into TM on two ebb tides in May 2000 subsequently moved upcoast or downcoast in the surf zone at ~30 cm s^{-1}, depending on whether surface waves were out of the south or west, respectively. Boehm et al. (2002a) noted propagation of an ENT pulse from 6N to 9N, also at 30 cm s^{-1}, in 10-min data collected on September 15, 2001, also during southerly wave conditions. The results presented here indicate that bacterial contamination events in the Huntington Beach region show no preference for days with southerly swell versus days without them. Southerly swell was present on some occasions when upcoast (northwestward) propagation of high TC concentrations from the SAR was observed, and not on others. For instance, there were only westerly wind waves during July 19–20 when upcoast propagation of high TC concentrations was observed (see Fig. 6).

4.4. Diurnal and semidiurnal variability

Consistent with conclusions drawn by Grant et al. (2000) and the results of Boehm et al. (2002a) for data from May 2000, all three FIB showed a day–night cycle, with the highest values occurring at night (see Figs. 6–8). The hourly data revealed no relationship between ENT concentration and sea level (see Fig. 9). That, and the fact that the rapid increase in ENT concentration preceded both high water and the sudden drop in near-bottom nearshore temperature (see Fig. 7a), suggests that the day–night cycle in ENT is more strongly influenced by sunlight-induced die-off than by tidal influence on either a landward or seaward source, since the former would be expected to commence with the start of the ebb tide and the latter to be coincident with the cooler temperatures which have an offshore source. In contrast, high coliform values occurred predominantly near low tide (see Figs. 7b and 9). The high TC levels found near station 0 near the end of the larger nighttime ebb tide were also found at stations to the north (see Fig. 10), with evidence of 30 cm/s^{-1} propagation speeds (see Fig. 6); suggesting that they may enter the coastal ocean from a landward source and then be advected alongshore. The smaller TC peak at station 0 associated with the daytime ebb tide did not affect station 6N, perhaps indicating die-off or dilution to background levels before the source waters were advected past station 6N. There was a peak in FC concentration at 6N, but not at station 0, associated with the nighttime ebb tide only (see Fig. 10).

Noble et al. (2003b) proposed that ENT have a higher rate of failing the AB411 standards because, as suggested by earlier studies, ENT survives longer in seawater than TC or FC. However, recent work by the same author (Noble et al., 2004b), using sewage as an inoculant, and environmental conditions similar to those found off HB, demonstrates that while ENT die off more slowly than FC under dark conditions, ENT are more susceptible than FC to sunlight inactivation, which is consistent with our results (Fig. 8) and with Boehm et al. (2002a) who noted that ENT falls below detection limits earlier in the day than total and fecal coliform. Sinton (2004) found that the relative inactivation rates of ENT and FC are different for raw sewage versus the effluent from waste stabilization ponds, with ENT having higher survival rates than FC over the course of one day in the former, while the reverse was true for the latter. The T_{90} for ENT in temperature and sunlight conditions common in southern California coastal waters was only 8–10 h (Noble et al., 2004b), indicating that these bacteria are very unlikely to last from one day to the next. It has also been suggested (Chamberlain and Mitchell, 1978) that photochemically produced oxidants, such as peroxide, may play a role in the daytime die-off of FIB. Boehm et al. (2002a) measured increasing concentrations of peroxide over the course of a day in a sunlight exposed tank filled with water from the Huntington Beach surf zone.

Though the results presented in Section 3.3 indicate that TC levels were controlled more by the phase of the semidiurnal tidal cycle, and ENT more by the diurnal light cycle, the fact that all the hourly sampling in this study was separated by about two weeks means that we cannot definitively separate the two effects since the time of low tide varied so little among the six intensive sampling periods, and the larger ebb tide always fell at night. Grant et al. (2001), using May 2000 data, characterized the temporal variability of ENT concentration in terms of flood versus ebb tides, noting that TM was a source of ENT to the surf zone during ebb tides, but they did not look at the influence of time of day.

The temporal and spatial variability in FIB concentrations is due not just to temporal and spatial variability in their sources, and advection and dispersion once they enter the ocean, but also to the fact that bacteria do not behave in a conservative fashion. Also, different types of bacteria die off at different rates, and those rates vary as a function of environmental factors such as temperature, salinity, nutrient concentration, predation, and the presence or absence of bacterial toxins, in addition to solar radiation. Furthermore, coagulation, flocculation, adsorption on particles, and sinking, all impact the ultimate fate of the bacteria. The survival rate of FIB under the prevailing environmental conditions is not well enough known for us to be able to say with any certainty how the temporal patterns were influenced by survival rate.

It is possible that the effects of sunlight in combination with the timing of the flood/ebb cycle could contribute to the predominance of high bacteria levels near summertime spring tides. In a mixed, predominantly semidiurnal tidal regime, such as is found off southern California, the nearly twice daily tidal cycles are of unequal value. This is known as the diurnal inequality of the semidiurnal tide. The larger of the two ebb tides (higher high water to lower low water) falls at night during the summertime spring tides, with the higher high tide at 8–10 p.m. local time. During the summertime neap tides, the larger of the two daily ebb tides is smaller than during spring tides, obviously, but much of it also falls during daylight hours.

5. Conclusions

The TC, FC and ENT concentrations measured in the surf zone off Huntington Beach between July 1, 1998 and December 31, 2001, including 5-day per week summertime sampling, and 12 days of hourly sampling during 2001 summertime spring tides, were analyzed with respect to their spatial and temporal variability on time scales from fortnightly to hourly. Most samples had FIB concentrations below detection limits; only a small percentage exceeded AB411 single sample standards.

Areas where coliform bacteria exceeded AB411 standards were generally localized in the region within 15,000 ft (4.6 km) to the north of the SAR. The data do not support the hypothesis (Kim et al., 2004) that surface wave-driven alongshore flow is responsible for this distribution, as these events did not occur preferentially during times of southerly swell. The ENT exceedances covered a broader area both to the north and south of SAR and tended to show up at many surf zone stations on the same day. Hence, even though more ENT samples than coliform samples exceeded AB411 standards, Huntington Beach closures were as likely to be due to coliform as to ENT.

Higher bacteria concentrations were associated with maximum tidal ranges, i.e., spring tides. Fifty percent of the FIB exceedance events (defined as either coliform or ENT exceedances local to the Huntington Beach area, or widespread ENT exceedances) occurred within ± 2 days of the spring tide. The data predict that on any given spring tide day there is a 60% chance of an AB411 single sample standard being exceeded in the Huntington Beach surf zone. A companion paper (Noble et al., accepted) found that the fortnightly variability continued through 2003, even after OCSD fully implemented disinfection of its effluent in October 2002. In southern California, the largest spring tides fall in the summer (May–August) and winter (December–February). The timing of the largest spring tides relative to the annual cycle does not change year to year. Hence, the probability of beach contamination will remain high in the summer for contaminants related to the spring–neap cycle. Large internal tidal pulses were not coincident with spring tides, and were not associated with high bacterial concentrations in the surf zone.

All three FIB exhibited a day–night cycle, with the highest values occurring at night. This pattern was very pronounced for ENT, which rebounded to high nighttime values almost as soon as the sun went down. High coliform counts appeared preferentially at low sea level heights, particularly after the larger ebb tide. Since the larger ebb tide always occurred at night during the six hourly sampling periods, separated by two weeks, we cannot definitively separate the effect of the diurnal inequality in the semidiurnal tide from the day–night cycle. However, we suggest that total and fecal coliform levels are controlled principally by the phase of the tide, whereas ENT levels are controlled more by the day–night cycle.

The widespread nature of the high levels of ENT, combined with the fact that it dies off very quickly during the day (Noble et al., 2004b), would seem to indicate there may be multiple sources. Boehm et al. (2002a) suggested that the most likely answer to the question "Why is the surf zone so rapidly re-supplied with indicator bacteria after the sun goes down?" is that there is a continuous supply of indicator bacteria to the surf zone. These data would support that suggestion for ENT.

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References

Boehm, A.B., Grant, S.B., Kim, J.H., Mowbray, S.L., McGee, C.D., Clark, C.D., Foley, D.M., Wellman, D.E., 2002a. Decadal and shorter period variability of surf zone water quality at Huntington Beach, California. Environmental Science and Technology 36, 3885–3892.

Boehm, A.B., Sanders, B.F., Winant, C.D., 2002b. Cross-shelf transport at Huntington Beach. Implications for the fate of sewage discharged through an offshore ocean outfall. Environmental Science and Technology 36, 1899–1906.

Cabelli, V., Dufour, A.P., McCabe, L.J., Levin, M.A., 1982. Swimming-associated gastroenteritis and water quality. American Journal of Epidemiology 115, 606–616.

Chamberlain, C.E., Mitchell, R., 1978. A decay model for enteric bacteria in natural waters. In: Mitchell, R. (Ed.), Water Pollution Microbiology. Wiley, NY.

Eaton, A.D., Clesceri, L.S., Greenberg, A.E. (Eds.), 1995. Standard Methods for the Examination of Water and Wastewater, 19th ed. American Water Works Association, Washington, DC.

Flesisher, J.M., Jones, F., Kay, D., Stanwell-Smith, R., Wyer, M., Morano, R., 1993. Water and non-water-related risk factors for gastroenteritis among bathers exposed to sewage-contaminated marine waters. International Journal of Epidemiology 22, 698–708.

Grant, S.B., Web, C., Sanders, B.F., Jones, B., Boehm, A., Kim, J.H., Redman, J., Chu, A., Mrse, R., Gardiner, N., Brown, A., 2000. Huntington Beach Water Quality Investigation Phase II: An analysis of ocean, surf zone, watershed, sediment, and groundwater data collected from June 1998 to September 2000. Technical Report for the National Water Research Institute and the City of Huntington Beach, 2000.

Grant, S.B., Sanders, B.F., Boehm, A.B., Redman, J.A., Kim, J.H., Mrse, R.D., Chu, A.K., Gouldin, M., McGee, C.D., Gardiner, N.A., Jones, B.H., Svejkovsky, J., Leipzig, G.V., Brown, A., 2001. Generation of *Enterococci* bacteria in a coastal saltwater marsh and its impact on surf zone water quality. Environmental Science and Technology 35, 2407–2416.

Grant, S.B., Kim, J.H., Jones, S.A., Jenkins, S.A., Wasyl, J., Cudaback, C., 2005. Surf zone entrainment, along-shore transport, and human health implications of pollution from tidal outlets. Journal of Geophysical Research 110, C10025. doi:10.1029/2004JC002401.

Haile, R.W., Witte, J.S., Gold, M., Cressey, R., McGee, C., Millikan, R.C., Glasser, A., Harawa, N., Ervin, C., Harmon, P., Harper, J., Dermand, J., Alamillo, J., Barrett, K., Nides, M., Wang, G., 1999. The health effects of swimming in ocean water contaminated by storm drain runoff. Epidemiology 10, 355–363.

Hamilton, P., 2004. Chapter 4: Subtidal circulation pathways. In: Noble, M., Xu, J., Huntington Beach Shoreline Contamination Investigation, Phase III, Final Report, Coastal Circulation and Transport Patterns: The Likelihood of OCSD's Plume Impacting Huntington Beach Shoreline, USGS Open-File Report 2004-1019, Vers. 1.0. Available from: <http://pubs.usgs.gov/of/2004/1019>.

Hamilton, P., Jones, B., Largier, J., Noble, M., Rosenfeld, L., Xu, J., 2004. Chapter 2: Methodology. In: Noble, M., Xu, J., Huntington Beach Shoreline Contamination Investigation, Phase III, Final Report, Coastal Circulation and Transport Patterns: The Likelihood of OCSD's Plume Impacting Huntington Beach Shoreline, USGS Open-File Report 2004-1019, Vers. 1.0. Available from: <http://pubs.usgs.gov/of/2004/1019>.

Kim, J.H., Grant, S.B., 2004. Public mis-notification of coast water quality: a probabilistic evaluation of posting errors at Huntington Beach, California. Environmental Science and Technology 38, 2497–2504.

Kim, J.H., Grant, S.B., McGee, C.D., Sanders, B.F., Largier, J.L., 2004. Locating sources of surf zone pollution: a mass budget analysis of fecal indicator bacteria at Huntington State Beach, California. Environmental Science and Technology 38, 2626–2636.

Leecaster, M.K., Weisberg, S.B., 2001. Effect of sampling frequency on shoreline microbiology assessments. Marine Pollution Bulletin 42, 1150–1154.

Lygre, A., Krogstad, H.E., 1986. Maximum entropy estimation of the directional distribution in ocean wave spectra. Journal of Physical Oceanography 16, 2052–2060.

MEC Analytical Systems, Incorporated (2000). Huntington Beach closure: relationships between high counts of bacteria on Huntington Beaches and potential sources. Final Report.

MEC Analytical Systems, Incorporated (2003). San Diego River–Ocean Beach Water Quality Improvement Project. San Diego river sampling and source identification investigations. Phase I – Final Report.

Noble, M., Hamilton, P., 2004. Chapter 7: Tidal transport pathways. In: Noble, M., Xu, J., Huntington Beach Shoreline Contamination Investigation, Phase III, Final Report, Coastal Circulation and Transport Patterns: The Likelihood of OCSD's Plume Impacting Huntington Beach Shoreline, USGS Open-File Report 2004-1019, Vers. 1.0. Available from: <http://pubs.usgs.gov/of/2004/1019>.

Noble, M., Xu, J., Rosenfeld, L., Largier, J., Hamilton, P., Jones, B., Robertson, G., 2003a. Huntington Beach Shoreline Contamination Investigation, Phase III. Executive Summary, USGS Open-File Report 03-62.

Noble, R.T., Moore, D.F., Leecaster, M.K., McGee, C.D., Weisberg, S.B., 2003b. Comparison of total coliform, fecal coliform, and enterococcus bacterial indicator response for ocean recreational water quality testing. Water Research 37, 1637–1643.

Noble, M., Jones, B., Xu, J., Rosenfeld, L., Hamilton, P., Robertson, G., Largier, J., 2004a. Non-linear internal tides move cool sub-surface waters from the mid-shelf to the beach. EOS Transactions AGU, 85, Fall Meeting Supplement, Abstract OS32B-05.

Noble, R.T., Lee, I.M., Schiff, K.C., 2004b. Inactivation of indicator bacteria from various sources of fecal contamination in seawater and freshwater. Journal of Applied Microbiology 96, 464–472.

Noble, M.A., Xu, J.P., Robertson, G.L., Rosenfeld, L.K. Distribution and sources of surf zone bacteria at Huntington Beach before and after disinfection on an ocean outfall – a frequency domain analysis. Marine Environmental Research (accepted), doi:10.1016/j.marenvres.2006.02.006.

[OCSD] Orange County Sanitation District, 2001. Marine Monitoring Annual Report FY 2000-01.

Reeves, R.L., Grant, S.B., Mrse, R.D., Copil Oancea, C.M., Sanders, B.F., Boehm, A.B., 2004. Scaling and management of fecal indicator bacteria in runoff from a coastal urban watershed in southern California. Environmental Science and Technology 38, 2637–2648.

Rosenfeld, L., 2004. Chapter 3: Surfzone bacteria patterns. In: Noble, M., Xu, J. Huntington Beach Shoreline Contamination Investigation, Phase III, Final Report, Coastal Circulation and Transport Patterns: The Likelihood of OCSD's Plume Impacting Huntington Beach Shoreline, USGS Open-File Report 2004-1019, Vers. 1.0. Available from: <http://pubs.usgs.gov/of/2004/1019>.

Sinton, L.W., 2004. Dynamics of pathogens in marine systems. ASLO/TOS Ocean Research Conference, Honolulu, HI, Abs. SS9.06.