Tidal forcing of enterococci at marine recreational beaches at fortnightly and semi-diurnal frequencies

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ABSTRACT

Marine beach water quality is typically monitored in early morning once a week without respect to tidal condition. To assess the effect of tide on this public health warning systems, we analyzed enterococci (ENT) data from 60 southern California marine beaches with differing geomorphology, orientation and proximity to runoff sources. ENT concentrations during spring tides were significantly higher ($p < 0.1$) than those during neap tides at 50 of the beaches (83%); and at over half of them, water samples were more likely to be out of compliance with the ENT single sample standard during spring tides compared to neap. Tide stage had a smaller effect; ENT concentrations varied according to tide stage at 27% of the beaches. When tide range (spring/neap) and tide stage (ebb/flood) conditions were considered together, spring-ebb tides yielded the highest ENT concentrations and the greatest chance of exceeding the single-sample standard at the majority of beaches. Proximity to a terrestrial runoff source, slope of the runoff source, slope of the beach and orientation of the beach had minimal influence on tidal modulation of ENT concentrations. The presence of spring and spring-ebb tide signals at such a great percentage of beaches suggests that tide should be considered in design and interpretation of beach monitoring program data. It also suggests that ENT delivered by tidally-forced mechanisms other than terrestrial surficial runoff are widespread. Possibilities include ENT-laden groundwater (saline and fresh) from the beach aquifer, as well as ENT-enriched sands, decaying wrack, and bird feces near the high water line.

INTRODUCTION

Marine recreational waters in the United States and much of the world are routinely monitored for fecal indicator bacteria (FIB) to assess health risk for swimmers (Schiff *et al.* 2002). Epidemiology studies have demonstrated correlation between FIB concentrations and increased risk of acquiring gastrointestinal illness and other ailments in bathers (Wade *et al.* 2004). The FIB most commonly used as indices of water quality are total coliform (TC), fecal coliform (FC), *Escherichia coli* (EC) (a subset of fecal coliform), and enterococci (ENT). Most marine monitoring takes place early in the morning on a daily to weekly basis. Water samples are collected at ankle to waist depth and taken to a laboratory where target organisms are quantified. After a 24- to 48-hour incubation period, results are delivered to a government agency that posts the beach as unfit for swimming if it does not conform to local marine bathing water standards.

One problem with the present monitoring protocol is FIB concentrations change at frequencies that surpass those at which posting decisions can be made. At Huntington State Beach, CA, for example, FIB levels can change dramatically over just 10 minutes (Boehm *et al.* 2002). Thus, it is difficult to accurately judge beach water quality and swimmer health risk from a daily or weekly water sample. Elucidating physical and biological mechanisms that modulate FIB levels in the marine environment may aid beach managers in interpreting water quality measurements, identifying FIB sources for remediation, and designing monitoring programs.

A number of physical and biological factors have been linked to FIB fate and transport in marine waters: rain, sunlight, tides, waves, and temperature (physical) and protozoa, birds, swimmers, and wrack (biological; Boehm *et al.* In press). While rainfall has been studied extensively at beaches around the US (Boehm *et al.* 2002,Curriero *et al.* 2001, Mallin *et al.* 2001, Schiff *et al.* 2003, Lipp *et al.* 2001), the remaining factors have been studied at only a few recreational beaches. The present study explores the impact of astronomical tides on daily FIB levels at an array of beaches in southern California with the goal of elucidating how knowledge of tides may be used to predict beach water quality (e.g., through the

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use of models), and deduce information about the location of FIB sources at a particular beach. We hypothesize that tides exert wide-spread influence on FIB concentrations based on observations at marine beaches in the United Kingdom (Crowther *et al.* 2001) and Huntington State Beach, California (Boehm *et al.* 2002, Grant *et al.* 2001, Boehm et al 2004a) that show tides affect FIB levels to various extents.

There are numerous mechanisms whereby tides might influence shoreline FIB concentrations. Flooding tides can dilute nearshore FIB sources and reduce bacterial concentrations (Coehlo *et al.* 1999). Ebbing tides allow water to drain from land to sea from tidally-influenced wetlands (Grant *et al.* 2001) and beach aquifers (Urish and McKenna 2004, Boehm *et al.* 2004). Higher than average spring tides provide a hydrologic connection between the sea and fecal sources at the high water line and upper reaches of the tidal prism in tidal wetlands and subterranean estuaries within the beach aquifer. Tidally-modulated nearshore currents are capable of moving FIB from a source to a distant beach (Boehm *et al.* 2002, Kim *et al.* 200).

Historical records of ENT from 60 marine beaches with diverse physiography (orientation, slope, proximity to streams or drains) are utilized to investigate the impact of tides. We focus our analyses on ENT because it correlates better than TC, FC, or EC to risk of gastrointestinal illness during swimming in marine waters (Wade *et al.* 2004). The impact of both tide range and stage on ENT levels in the surf zone is determined. Tide range refers to the difference between the daily highest and lowest tides, which varies fortnightly in phase with the moon (spring and neap tides). Tide stage refers to whether the tide level is ebbing or flooding.

METHODS

Enterococci, season, and tide data

ENT data were obtained from monitoring programs in three regions of southern California spanning 120 km: Huntington Beach, Whites Point, and Santa Monica Bay (Figure 1). Data from Huntington Beach were collected from 17 sites between 1 June 1998 and 30 August 2001 at a frequency of five days per week during summer and three days per week during winter. Data from Whites Point were collected from 8 sites between 1 December 1991 and 28 December 1999 daily to weekly. Data from Santa Monica Bay were collected from 35 sites, 17 of which were sampled daily between 1 September 1987 and 4 July 1994, while the remaining 18 sites were sampled weekly between 5 July 1994 and 31 December 1999. A description of the sites, including proximity to a watershed outlet, slope of the input from the watershed outlet, beach slope, and beach direction is given in Table 1. The 60 sites represent a wide array of beach physiography with differing proximity to streams and drains, allowing us to assess if beach-specific factors influence tidal effects on ENT concentration.

Water samples at all sites were obtained from ankle deep water on the incoming wave in the morning by local monitoring agencies (Orange County Sanitation District, the City of Los Angeles and the Los Angeles County Sanitation Districts). Sampling time was recorded by the monitoring agency at each station, which typically fell between 700 and 1000 hours, though some samples were collected as late as 1400 hours. ENT were quantified using either the Standard Method 9230C or EPA method 1600, depending on the sampling agency. Interlaboratory comparison studies have demonstrated consistency between these laboratory methods and among these organizations (Noble *et al.* 2004).

Southern California experiences a Mediterranean climate with distinct wet and dry seasons. The wet season typically falls between 1 November and 30 March and the dry between 1 April and 31 October (Santa Ana Watershed Project Authority). To determine if freshwater inputs to the coast affect the manner in which tide influences ENT concentrations, we classified each sample as *wet* or *dry* based on the season in which they were collected.

We used the actual recorded time of sample collection, rounded to the closest hour and converted to

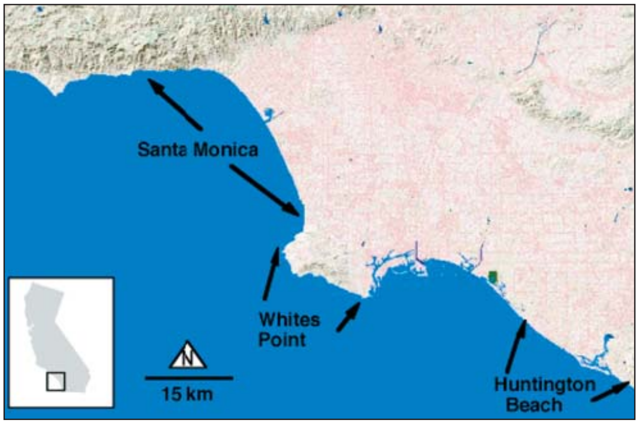

Figure 1. Map showing regions included in the study. The background is taken from the United States Geological Service seamless database.

Table 1. Summary table for all months[a].

ALL MONTHS					Tide Range Comparison				Tide Stage Comparison				Tide Range-Tide Stage Comparison							
Station	Physiography Description	GM	Range	CV (%)	S (GM)	N (GM)	S (% >104)	N (% >104)	E (GM)	F (GM)	E (% >104)	F (% >104)	S-E (GM)	S-F (GM)	N-E (GM)	N-F (GM)	S-E (%>104)	S-F (%>104)	N-E (% >104)	N-F (% >104)
S1_pre94	S-3/-	8.6	1-4100	68	12.4*	6.0*	6*	4*	7.3#	9.3#	6*	4*	13.8	11.8	6.7	5.1	8*	5*	5*	1*
S2_pre94	S-3/in-5	6.4	1-8300	86	8.7*	4.7*	6*	4*	5.8	6.7	6*	3*	11.5*	8.0*	5.2*	4.4*	8*	4*	6*	2*
S3_pre94	SW-5/in-5	13.3	1-6300	55	17.1*	10.4*	9*	5*	12.7	13.5	7	6	21.9*	15.7*	11.8*	9.1*	10*	7*	7*	4*
S4_pre94	W-1/in-3	9.1	1-10000	68	11.6*	7.2*	7*	4*	9.1	9.2	6*	4*	24.1*	10.3*	7.9*	6.9*	18*	5*	4*	4*
S5_pre94	W-1/in-3	9.3	1-25000	69	12.5*	7.0*	8*	5*	8.6	9.5	8*	5*	30.1*	10.6*	7.0*	7.2*	20*	6*	6*	4*
S6_pre94	W-1/in-3	9.6	1-6400	68	13.3*	7.0*	9*	5*	8.5	10.0	7	6	28.3*	11.1*	6.8*	8.0*	21*	6*	5*	5*
S7_pre94	W-1/-	6.1	1-6000	88	10*	3.8*	9*	3*	5.5	6.3	6	6	22.4*	7.8*	3.9*	4.0*	16*	7*	4*	3*
S8_pre94	W-1/-	6.0	1-6600	96	8.1*	4.5*	8*	5*	6.9*	5.6*	9*	6*	18.5*	6.4*	5.1*	4.4*	15*	6*	7*	5*
S9_pre94	W-1/-	5.3	1-6800	97	6.8*	4.2*	6	5	5.4	5.3	6	5	8.2*	6.2*	4.9*	3.6*	6	5	6	4
S10_pre94	W-1/-	4.2	1-16000	104	5.9*	3.0*	5*	2*	3.9	4.4	3	4	7.8*	5.0*	3.1*	3.2*	9*	4*	2*	3*
S11_pre94	W-1/-	3.7	1-3000	107	4.5*	3.0*	3*	2*	3.9	3.5	3	3	7.1*	3.8*	3.4*	2.8*	5	3	2	2
S12_pre94	W-1/-	3.0	1-6000	126	4.1*	2.3*	3*	2*	3.2	2.8	2	2	5.5*	3.4*	2.5*	2.1*	3	2	1	2
S13_pre94	W-2/-	3.3	1-3900	120	4.5*	2.4*	3*	1*	3.6*	3*	2	2	6.6*	3.5*	2.8*	2.2*	3	3	2	1
S14_pre94	W-2/-	3.9	1-23000	112	5.3*	3.0*	5*	2*	4.1	3.8	4	3	6.6*	4.4*	3.2*	3*	6*	4*	3*	2*
S15_pre94	W-3/-	8.5	1-4800	73	10.5*	6.9*	8*	4*	9.2	8.3	7*	5*	11.5	10.0	8.1	6.3	12*	6*	5*	4*
S16_pre94	W-3/in-3	4.7	1-6700	104	6.5*	3.5*	6*	3*	4.7	4.8	5	4	6.7	6.0	3.8	3.5	7*	5*	4*	3*
S17_pre94	W-5/in-3	4.2	1-4600	105	5.6*	3.2*	5*	2*	4.8*	3.8*	4	3	8.0*	4.2*	3.4*	3.4*	8*	4*	2*	3*
S1_post94	S-3/in-1	39.2	1-6100	53	38.7	39.7	32	36	46.9	35.6	40	32	56.4	34.8	41.9	36.7	44	29	38	36
S2_post94	S-3/in-5	31.4	1-7800	50	45.4*	21.7*	28*	14*	46.0*	23.5*	31*	13*	81.7*	33.4*	28.8*	16.4*	44*	20*	21*	6*
S3_post94	W-1/in-4	17.5	1-4500	57	21.9*	13.9*	13	12	20.4	16.4	17*	10*	34.9*	17.6*	15.2*	14.7*	24*	8*	13*	14*
S4_post94	W-1/in-0	53.5	1-7700	39	52.3	54.7	25	30	56.1	51.2	30	27	68.6	48.2	51.6	55.7	28	26	30	30
S5_post94	W-1/in-3	25.7	1-6000	42	33.2*	20.1*	15*	5*	25.8	25.6	14*	6*	46.7	31.5	20.0	18.2	31*	10*	7*	0*
S6_post94	W-1/in-0	24.0	1-6000	62	29.2	19.9	25	24	29.2	19.3	33*	17*	56.7	20.1	22.9	18.0	47*	15*	28*	22*
S7_post94	W-1/in-3	12.5	1-6000	67	14.9	10.6	10	11	15.2	12.0	15*	9*	28.4*	11.4*	11.4*	13*	20	7	13	11
S8_post94	W-1/in-	10.8	1-4400	68	16.2*	7.4*	13*	4*	10.8	8.9	6	6	23.5*	10.7*	8.3*	6.5*	14	8	4	4
S9_post94	SE-0/-	22.5	1-15000	57	22.9	22.2	16	16	28.5	19.9	21*	12*	33.2	20.9	27.1	18.1	34*	11*	17*	15*
S10_post94	W-1/in-3	19.7	1-9000	54	27.3*	14.6*	14	9	15.5	21.7	9	11	24.8	24.1	14.5	16.6	13	11	9	11
S11_post94	W-1/-	11.8	1-7300	75	14.5	9.7	13	11	10.4	13.1	13	12	12.7	15.4	10.0	9.0	12	14	13	8
S12_post94	W-1/in-	5.9	1-660	83	6.5	5.5	4	3	7.2	5.0	5	3	10.3	5.6	6.6	4.0	10	4	3	2
S13_post94	W-2/-	2.7	1-340	126	3.3*	2.2*	0#	2#	3.4	2.5	2	1	5.8*	2.7*	2.6*	2.1*	0	0	2	4
S14_post94	W-2/-	4.0	1-2400	109	6.3*	2.6*	7*	1*	4.5	3.4	5	2	10.2*	4.3*	2.8*	2.4*	10*	3*	1*	0*
S15_post94	W-2/-	5.1	1-5100	99	7.9*	3.3*	7	4	5.5	4.0	6	3	11.9*	4.7*	3.5*	3.2*	9	2	3	5
S16_post94	W-4/in-3	21.6	1-6300	45	27.9*	17.1*	16*	6*	20.8	20.8	12*	6*	31.0	26.9	16.9	15.9	22*	8*	7*	4*
S17_post94	W-3/in-0	5.7	1-2800	95	8.2*	4.0*	9*	3*	6.6	4.9	8	4	11.6	6.2	4.6	3.9	12	4	5	3
S18_post94	W-5/in-0	4.0	1-930	101	5.0*	3.2*	3	4	4.1	3.6	3	2	4.3	4.7	3.9	2.9	3	0	2	4
SM_WP	NW-1/in-3	5.9	1-16000	76	7.4*	4.7*	4	3	6.6	5.0	5	3	12.2*	4.9*	4.7*	5.1*	8	3	4	3
SB_WP	NW-3/in-3	2.6	1-110	84	3.1*	2.1*	1	0	2.4	2.6	1	0	3.4	3.0	2.0	2.2	2	0	0	0
S1_WP	NW-3/in-	2.8	1-18000	118	3.0	2.7	3	3	3.3*	2.4*	4*	2*	4.2*	2.3*	2.9*	2.5*	4*	2*	4*	1*
S2_WP	SW-3/in-3	3.3	1-6600	105	4.2*	2.7*	4*	2*	3.9*	3*	4*	2*	6.4*	3.2*	2.8*	2.6*	7*	3*	2*	2*
S3_WP	SW-1/in-1	4.1	1-7200	88	5.4*	3.2*	3*	1*	4.4	3.9	3*	1*	7.6*	4.3*	3.2*	3.5*	6*	2*	2*	1*
S5_WP	SW-3/in-3	4.7	1-2600	95	7.1*	3.2*	7*	2*	6.9*	3.1*	7*	2*	11.6*	3.1*	3.6*	3*	11*	2*	3*	2*
S6_WP	SW-3/in-3	3.8	1-5200	100	5.1*	2.9*	5*	3*	4.1	3.6	5*	2*	8.8*	3.7*	2.9*	3.4*	10*	1*	3*	4*
S7_WP	SW-1/in-5	5.1	1-9600	88	6.9*	3.8*	6*	3*	4.9	4.9	6*	3*	13.9*	5.6*	4.1*	3.5*	19*	3*	3*	2*
39N_HB	SW-3/-	5.4	2-646	73	6.6*	4.6*	4	2	3.5#	7.4#	1#	5#	4.4	6.9	3.5	9.5	0	5	1	5
33N_HB	SW-3/-	5.5	2-400	65	6.5*	4.8*	3	2	4.6#	6.5#	2	3	12.7	6.5	4.3	6.1	10	3	2	3
27N_HB	SW-1/-	6.5	2-840	65	7.6*	5.7*	3	2	5.3#	7.5#	2	3	5.4	7.7	5.3	6.9	0	3	2	3
21N_HB	SW-1/-	6.5	2-400	65	7.8*	5.5*	3	2	5.1#	7.8#	1	3	5.4	7.8	5.0	7.5	0	3	1	1
15N_HB	SW-1/-	8.9	2-780	59	11.5*	7*	5*	2*	6.3#	11.1#	2#	5#	10.4	11.2	6.0	10.8	0	6	2	4
9N_HB	SW-5/-	14.6	2-930	58	22.8*	9.6*	22*	8*	8.7#	21.1#	4#	22#	25.4	22.0	7.7	18.7	15*	22*	3*	22*
6N_HB	SW-5/-	14.7	2-1050	57	23.6*	9.5*	19*	7*	9.1#	19.1#	7#	17#	16.3	24.5	8.3	10.1	16*	21*	5*	7*
3N_HB	SW-5/-	15.3	2-600	55	22.4*	10.9*	16*	8*	10.5#	18.8#	8#	14#	44.6*	19.9*	9*	15.6*	32*	14*	5*	15*
0N_HB	SW-1/in-2	8.0	1-400	64	8.4	7.8	6	4	8.7	7.5	4	5	14.8	7.8	8.3	6.6	0	6	5	3
3S_HB	SW-3/-	5.3	2-400	71	5.7	5.0	2	3	6.0	4.8	4	2	14.0*	5.0*	5.4*	4.3*	11*	1*	3*	3*
6S_HB	W-5/-	4.3	2-400	73	5.2*	3.7*	2	1	4.3	4.3	2	1	14.0*	4.6*	3.6*	3.6*	8*	2*	1*	0*
9S_HB	W-5/-	4.4	2-460	74	5.2*	3.7*	2	2	4.2	4.5	1	2	11*	4.7*	3.6*	4.2*	4	2	1	3
15S_HB	S-5/-	4.7	2-400	75	6.5*	3.5*	4*	1*	5.0	4.5	5*	0*	20*	4.9*	3.5*	3.7*	19*	1*	2*	0*
21S_HB	S-5/-	4.1	2-400	74	4.9*	3.4*	3*	1*	4.4	3.8	2	1	8.6*	3.9*	3.6*	3.6*	9*	1*	0*	2*
27S_HB	S-5/in-	2.9	2-400	76	3.4*	2.6*	1	1	2.9	2.9	1	1	3.8	3.1	2.7	2.6	4	1	1	1
29S_HB	S-5/in-1	5.0	2-384	71	6.9*	3.7*	3*	1*	5.4	4.5	1	2	8.4*	5.2*	4.1*	3.8*	2	1	1	3
39S_HB	S-5/-	3.0	2-252	78	3.6*	2.5*	1*	0*	3.1	2.8	0	1	4.0	3.2	2.5	2.5	0	2	0	0

[a] The station names are given in the first column. Rows are organized by location from north to south; Santa Monica (pre 1994) stations are listed first, followed by Santa Monica (post 1994) stations, WhitesPoint stations, and Huntington Beach stations. The station designations used by the monitoring agencies are preserved. The physiography and characteristics of ENT for each site is shown in columns 2 - 5. Physiography is given as X-i/Y-jwhere Xis the direction the beach faces, idenotes the slope of the beach (very slight, slight, slight to moderate, moderate, moderate to steep, and 5 steep), Y is “in” if the beach is near terrestrial runoff source, and if Y) in, then jis the slope of the input (0 - 5, as indicated previously for beach slope). The GM of ENT during spring (S(GM)) versus neap (N(GM)) andthe percent of samples over 104 MPN/100 ml collected during each tidal condition (S (% >104) and N (% >104)) is compared in columns 6 - 9; similar comparisons are made between ebb and flood

(columns 10 - 13), and spring-ebb, spring-flood, neap-ebb, and neap-flood (columns 14 - 21). For the tide range and tide stage comparisons, the GMs are followed by * if the spring (or ebb) is significantly higher (p <0.1) than theneap (or flood); the GMs are followed by # if the neap (or flood) is significantly higher than the spring (or ebb); the % > 104 are followed by if the number of samples in exceedance of 104 MPN/100 mL is significantly(p <0.1) biased toward spring (or ebb) tides over neap (or flood) tides; the 104 are followed by if the number of samples in exceedance of 104 MPN/100 ml is biased toward neap (or flood) tides over spring(or ebb) tides. Finally, in the tide range-tide stage comparisons (columns 14 - 21), GMs are followed by if the spring-ebb GM is significantly (0.1) higher than the GM of other tidal conditions; 104 are followed by if the number of samples in exceedance of 104 MPN/100 ml is significantly (0.1) biased toward at least one of the four compared tidal conditions. All GMs are in units of MPN/100 ml.

Pacific Standard Time (PST), to determine tide level, and subsequently, tide stage. Tide level data referenced to PST were compiled using the NASA tide calculator with harmonic constants for Newport Beach, CA (IERS). Samples were classified as having been collected during an ebb, flood, or transition stage based on the tide level an hour before and after the sample was collected. A sample was classified as a *transition* if the tide stage changed during the two-hour window surrounding its collection, *ebb* if tide level was falling, or *flood* if the tide level was rising. Tide level data for Newport Beach were used to determine tide stage at all the beaches analyzed in this study. Given the short time lag (5 to 10 minutes) between tide level at the most southern and northern beaches during which tide level differs by at most 10 cm (data not shown), this decision should not affect our conclusions.

Tide range for each sample collection day was classified as *spring* or *neap* based on the phase of the moon as follows. Days 0 - 3, 12 - 18, and 26 - 28 following the full moon were classified as spring tides, with the remaining days classified as neap.

Statistical analyses

To determine if season, tide range, and/or tide stage explained day-to-day variations in ENT at the 60 stations, analyses of variance (ANOVAs) were performed (Matlab, Mathworks, Natick, MA). Daily log-transformed ENT concentration served as the dependent variable. A combination of season (wet or dry), tide range (spring or neap), tide stage (ebb, flood, or transition), and up to three-way interaction terms were included as factors. The best ANOVA model was fit to log-ENT from each station by including only terms that explained a significant ($p < 0.1$) portion of the total variance. The relative importance of a factor was determined by comparing the total number of stations where it was included in the model, and the range in the percent of the total log-ENT variance the factor explained. The latter was calculated for the factors included in each model as $R^2 = 100(SS_F/SS_T)$ where R^2 is the squared multiple correlation coefficient, SS_F is the sum of squares for the factor, and SS_T is the total sum of squares.

Post hoc comparisons were conducted to quantify precisely how tide range and stage affected ENT levels. We compared the geometric means (GMs) and 90% confidence intervals of ENT during ebb versus flood tides, and spring versus neap tides, respectively considering the entire year (both wet and dry seasons) and the two seasons individually. The difference in ENT under the compared tidal conditions was calculated using the following equations:

$$\Delta_{a,ef} = 100 \times \frac{GM_{a,e} - GM_{a,f}}{GM_a} \tag{1a}$$

$$\Delta_{a,sn} = 100 \times \frac{GM_{a,s} - GM_{a,n}}{GM_a} \tag{1b}$$

where $\Delta_{a,ef}$ and $\Delta_{a,sn}$ are the percent differences between ENT concentrations at station *a* during ebb and flood (*ef*), and spring and neap (*sn*) tides, respectively, relative to the GM of ENT at station a during season(s) examined (GM_a). The $\Delta_{a,ij}$ was deemed significant if the 90% confidence intervals for the two compared GMs ($GM_{a,i}$ and $GM_{a,j}$) did not overlap.

The synergy between tide range and stage was quantified by binning ENT data from each station according to the tide stage and range (spring-ebb, spring-flood, neap-ebb, and neap-flood) during which they were collected, and calculating and comparing the GMs and 90% confidence intervals. The analysis was repeated for samples collected in the dry and wet seasons exclusively.

To determine if beach warnings are more likely to be issued during certain tidal conditions, we computed the number of ENT measurements made under different tidal conditions in excess of the California single-sample ENT (104 most probable number (MPN)/100 ml) and compared it to the number of measurements below the standard. Significant ($p < 0.1$) differences between outcomes were assessed using a contingency table and chi-square test. The results are presented as the percent of samples under each compared condition in excess of the standard. The analysis was repeated for samples collected in the dry and wet seasons exclusively. It should be noted that beach warnings are issued for exceedances of standards in addition to the ENT standard considered here.

The *N-way* ANOVAs were performed using $\Delta_{a,ij}$ or percent of samples over 104 MPN/100 ml as dependent variables, and beach physiography (presence of an inlet or watershed outlet, slope of the beach, slope of input, and beach direction) as factors to determine if physical properties of the beach controlled the degree to which tide influenced beaches.

RESULTS

The GMs among stations ranged from 2 to 54 MPN/100 ml, while the coefficient of variation (CV, 100 x standard deviation of the log-transformed ENT time series/log-mean) ranged from 39% to 126%, indicating there are large fluctuations about the GMs (Table 1). The GMs and CVs were inversely correlated (r = -0.8, *p* <0.1), indicating that there was more variation associated with lower GMs. Figure 2, Panels A and B illustrate this variation by showing time series of ENT, in addition to tide range, and tide stage during sample collection at a single, representative station (S5pre94 in Santa Monica Bay, Table 1).

ANOVA

The results of the ANOVA are summarized in Figure 3. The total number of beaches where each factor, or interaction term, (*x*-axis) was included in the model is given as *n*. The range in the percent of log-ENT variance explained by each factor at beaches where it was included in the ANOVA is illustrated with a box and whisker. Overall, season and tide range were included in models at more stations than other terms, and they explained a greater percent of log-ENT variance compared to tide stage or any of the interaction terms.

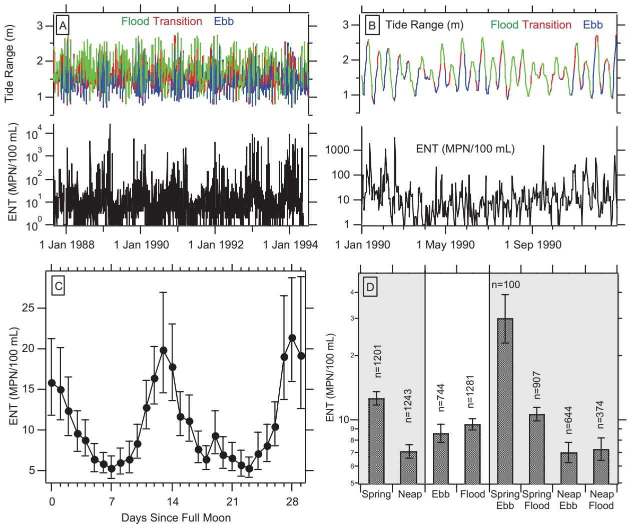

Figure 2. The time series of ENT, tide range, and tide stage for a single representative station located in Santa Monica (S5pre94), and the tide stage at the time of sampling is indicated by the color of the tide range data series (Panel A). The time series from Panel A expanded for one year. The ENT time series from Panel plotted as function of day since the full moon, day 0 (Panel B). The GM and 90% confidence intervals for ENT on each day of the lunar month is shown (Panel C). A graphical comparison of the GM of ENT from panel during spring vs neap, ebb vs flood, and spring-ebb, spring-flood, neap-ebb, vs neap-flood (Panel D).

Season, tide range, and tide stage explained a significant percent of the variance at 52 (87%), 52 (87%), and 22 (37%) of the 60 stations, respectively. Where included in the model, season explained on average 9% of the variance (maximum 33%, minimum 1.2%) at 52 stations, tide range explained on average 4% (maximum 10%, minimum 0.3%) at 52 stations, while tide stage explained an average 1% of the variance (maximum 4%, minimum 0.2%) at 22 stations.

The interaction terms explained a small percentage of the total log-ENT variance even though they were significant factors at a subset of stations. Their necessary inclusion in the models indicates at some stations, a factor's influence on log-ENT variability depended on the state of the other factors. The interaction between tide range and season was important at 21 (35%) stations, tide stage and season at 29 (50%) stations, tide stage and tide range at 28 (47%) stations, and the three-way interaction between tide range stage and season at 10 (17%) stations. On average, each of these interaction terms did not account for more than 1% of the log-ENT variance (Figure 3).

The tides, and interaction terms involving them, affected ENT concentrations at 58 of the 60 beaches (97%), and together they explained, on average, approximately 9% of the variability in log-ENT concentrations. The observation that tides impact ENT at nearly all of the stations we examined is significant because besides rainfall, no other factor has been identified as an important predictor of day-to-day ENT at physically and geographically distinct marine beaches. While 9% of the variation may seem small, and the average amount of variance explained by individual tide-related factors even smaller, the variability explained by tides is enough to significantly impact average concentrations and the percent of samples over the single-sample standard for ENT at many beaches, explained next. Identifying even this seemingly small explanation for variability is also meaningful because the variation of ENT in marine waters has proven notoriously difficult to explain, because of our lack of understanding of physical and biological processes that influence its fate (Fischer *et al.* 1979).

Post hoc comparisons

The results from the ANOVA confirm that tides are responsible for variation in log-ENT at a majori-

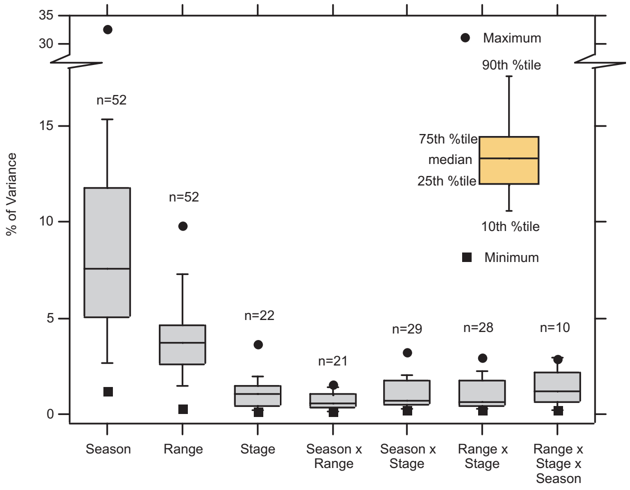

Figure 3. Box and whisker plot showing percent variance in log-ENT concentrations explained by factors in three-way ANOVA. The number of stations whose best model required inclusion of the factor is given near the factor box. As illustrated in the legend, the box delineates the 25th and 75th percentiles, the median is denoted by the horizontal bar in the middle of box, and the whiskers show the 90th and 10th percentiles. The circles and squares indicate the maximum and minimum observed, respectively. Note that there is break in the y axis.

ty (97%) of the 60 tested beaches. The significance of the interaction terms at a subset of beaches implies that the effects of tide range (or stage) on ENT may vary as a function of season and tide stage (or range). *Post hoc* analyses quantified the differences between ENT concentrations measured during various tide conditions and season.

Spring versus neap tide comparisons

A spring-neap cycle was evident (based on significant differences between spring and neap GMs) in ENT at 50 of the 60 stations when all months were considered (52 and 34 stations if only dry or wet months were considered, respectively). A representative cycle is displayed in Figure 2, panel C where the GM of ENT is shown as a function of day since the full moon. The phase of the cycle is consistent between stations; the highest ENT concentrations occur during spring tides (days 0 and 14 - 15 since the full moon) and lowest during neap.

The GM of ENT during spring vs. neap tides at each of the 60 stations is reported in Table 1 for all months (Appendix I and Appendix II show results for dry and wet months exclusively). ENT concentrations were never statistically higher during neap compared to spring tides, regardless of the months considered in the analysis. Differences in GMs were compared using Δ_{sn} (Figure 4, panel A). Significant Δ_{sn} were typically 40% to 80% regardless of season(s) and ranged from 24% to 122%.

The *N-way* ANOVA between Δ_{sn} and beach physiography indicated that only during dry months could the magnitude of Δ_{sn} be modeled as a function of beach attributes. The analysis revealed the presence or absence of an inlet, beach slope and direction, and input slope accounted for a total of 87% of the variability in Δ_{sn} ($p < 0.1$). Slight input slopes, SW and W facing beaches with moderate to steep slopes, and absence of an inlet gave rise to higher Δ_{sn}. Samples were significantly more likely to contain ENT in excess of 104 MPN/100 ml when they were collected during spring tides compared to neap tides at 36 stations when all months were considered (when dry or wet months were considered exclusively, this number dropped to 20 and 28, respectively). Table 1 (Appendix I and Appendix II for dry and wet months) shows the percent of samples collected during spring and neap tides in excess of the standard. For the example beach featured in Figure 2, 15% of the samples collected during spring tides were over 104 MPN/100 ml, compared to just 5% during neap tides. ENT over the standard were not more common during neap tides compared to spring tides at any station when all months were considered. There was no discernable relation between beach physiography and the fortnightly tidal results.

Ebb versus flood comparisons

The ENT GMs during ebb and flood tides are shown in Tables 1, Appendix I, and Appendix II for all, dry and wet months, respectively. Figure 2, panel D shows the tide stage comparison graphically for one representative station where as was true for most of the beaches, there was no significant difference between ENT during ebb versus flood tides at this beach. However, for some beaches, there was a significant difference between ENT concentrations measured during different tide stage conditions; specifically there were significant differences between ENT at 16, 33, and 5 stations when all, dry, and wet months, respectively, were examined. Figure 4, panel B shows the distribution of Δ_{ef} from the analyses. In contrast to the results of the tide-range comparison, there are fewer stations with significant Δ_{ef}, and there are marked differences in the sign and magnitude of Δ_{ef} between beaches and seasons. The latter indicates that both flood and ebb tide-induced processes modulate ENT at various beaches.

When all seasons are considered, Δ_{ef} ranged from -85% to 82% with 9 of the 16 significant Δ_{ef} less than 0 (indicating ENT concentrations are elevated during flood tides). Most of the negative Δ_{ef} (8 of 9) are located in northern Huntington Beach, away from a nearby terrestrial watershed outlet. The flood tide signal at this beach could be caused by tidal-currents transporting ENT from a distant source to the site during flood tide conditions. On the other hand, beaches where Δ_{ef} was positive (indicating ebb tides had higher ENT than flood) were almost all located near a watershed inlet (5 of 7) though many other beaches near inlets did not exhibit any significant tide stage effects.

During dry months, ENT concentrations measured during flood tides were significantly higher than ENT measured during ebb tides at a majority of beaches (33 of 60). No beach showed the converse. This is illustrated in Figure 4, panel B where the distribution of significant Δ_{ef} are all less than 0, ranging from -108% to -22%. We believe this is partly a result of a sampling bias because in the dry season, on average 87% of the spring tide samples were collected during flood tides. Indeed, all of the stations with significant (negative) Δ_{ef} during the dry season also had significant, positive Δ_{ef} during the dry season. We elaborate on this finding in the next section where interactions between tide stage and tide range are explored.

In the wet season, all the beaches that had significantly different ENT between the two tide stages exhibited higher ENT during ebb tides compared to flood tides (5 of 5). Figure 4, panel B shows the distribution for all significant Δ_{ef}: Δ_{ef} were greater than 0, ranging from 48% to 95%. Sites with significant Δ_{ef} were in close proximity to watershed outlets, suggesting that during wet months, ebb flow may enhance transport of ENT from input sources to the beach. However, many other sites in close proximity to watershed outlets did not have significant wet weather Δ_{ef}.

The percent of ebb versus flood measurements in excess of 104 MPN/100 ml is displayed in Tables 1, Appendix I, and Appendix II for all, dry and wet months, respectively. The comparative results mostly mirror results from the GM comparisons. When all months were examined, 20 sites were more likely to exceed standards during ebb tide, while only 5 were more likely to exceed standards on ebb tide. Most of the 20 sites (15 beaches) where exceedances were more probable during an ebb tide are located near terrestrial inputs. However, many other beaches with inlets did not show a similar relationship. The 5 beaches where exceedances were more common in floods compared to ebbs are amongst the same beaches in northern Huntington Beach where ENT GMs were higher during flood compared to ebb tides. At the sample beach used in Figure 2, 8% of ebb tide measurements resulted in exceedance of the single-sample standard compared to 5% during flood

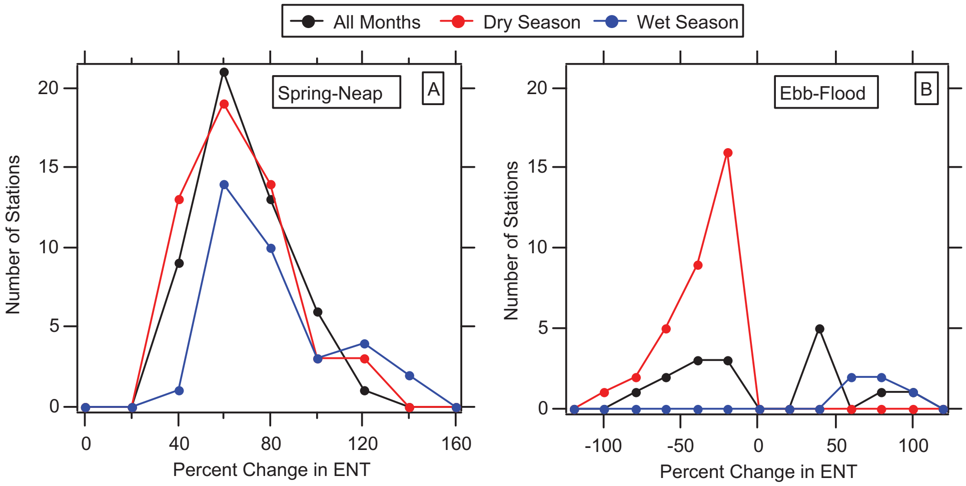

Figure 4. Frequency distribution illustrating the difference between the ENT concentrations during spring and neap tides (Δ_{sn} panel A) and ebb and flood tides (Δ_{ef} panel B). Only significant differences are included in the distributions. Results from all (black), dry (red), and wet (blue) months are shown. The bins used to create the distribution are 20% wide, and the marker is located at the highest level of each bin.

tide measurements. This distribution indicates a bias for exceedances during ebb tides based on the chi-squared test.

During the dry season, there were 10 stations where exceedances were biased towards a specific tide stage; at all 10 stations, exceedances were more common during flood tides than during ebb tides (Appendix I). The wet season analysis revealed that there were 8 stations where exceedances were biased based on when they were sampled during the tide stage, and all of those were biased to occur during ebb tides (Appendix II). Seven of these beaches were located in close proximity to watershed outlet. During both seasons, the observed biases resulted in exceedances typically over twice as likely during the favored tidal condition.

Tide range and tide stage comparison

The tide-range comparisons showed that ENT concentrations during spring tides were consistently higher than neap tides at the great majority of stations (50 of 60 from the all month analysis). Results from the tide-stage comparison were less straightforward; fewer stations exhibited significant differences between the compared conditions, and one condition did not consistently have higher ENT between seasons and beaches. To obtain further insight into the effect of tide stage on ENT levels, we separated the ebb and flood tides according to the tide range conditions under which they were collected.

The ENT GMs and percent of samples greater than 104 MPN/100 ml measured during the four conditions (spring-ebb, spring-flood, neap-ebb, and neap-flood) are shown in Table 1 for all months. GMs were highest during spring-ebb tides at 53 stations, and 35 of these GMs were significantly higher than GMs calculated for the other three tidal conditions. No other tidal condition was significantly important. At 33 stations, the number of samples in exceedance of the single-sample standard was significantly biased by tidal condition and at all but three beaches, the bias was towards the spring-ebb tide. Thus, the effect of tide-stage became more straightforward when tide-range was included in the analyses: ENT concentrations were highest during ebb flow of spring tides.

The trends for wet months were similar to those for all months, although the effects of tides are a bit muted, probably due to the passage of winter storms that cause storm runoff to enter the ocean regardless of tide condition. GMs of ENT were highest during spring-ebb tides at 46 stations and 11 of these were significantly higher than GMs calculated for the other three tidal conditions. Exceedances were biased to occur during spring-ebb tides conditions at 19 beaches (Appendix II).

During dry months, the spring-ebb tide was under-sampled, with on average 87% of the spring tide samples collected during the flood tide. Only two beaches had significantly higher ENT GMs during one tidal condition compared to the others, and these had highest ENT during spring-ebb tides (Appendix I). Exceedances of the single-sample standard were biased towards a particular set of tidal conditions at 12 beaches, and at 7 of these, that condition was spring-ebb. While it appears that the spring-ebb did not have as consistent an influence on ENT during dry months compared to other months examined, the result should be interpreted cautiously because the spring-ebb was consistently under-sampled, resulting in larger confidence bounds for estimates of GMs and relatively small contributions to the chi-square for estimates of exceedance bias.

The *N-way* ANOVAs were used to explore the influence of beach physiography on the results from the tide range and tide stage comparisons. Beach physiography did not account for any of the variation between site GMs or percent of samples in exceedance of 104 MPN/100 ml, regardless of season examined.

DISCUSSION

A spring-neap signal like that in Figure 2, panel C was found amongst the apparent noise (Figure 2, panel A) at almost every beach examined regardless of its physiography. At over half of the beaches, ENT in excess of the single-sample standard was more likely to occur during spring tides compared to neap. The spring-neap ENT signal was muted somewhat during the wet season, probably due to rainfall events that might have provided a large influx of ENT at random times during the fortnightly tidal cycle. These results suggest that in general, the higher and lower than average tides that accompany spring tides mobilize and allow flushing of, respectively, pollutants to the sea, or provide enhanced conditions for ENT persistence in seawater. Hydrologic studies have confirmed that spring tides typically provide the greatest exchange between terrestrial and coastal waters at shallow watershed outlets like those at our study sites (Fischer *et al.* 1979), and between pore waters and coastal waters in beach aquifers (Taniguchi 2002, Kim and Hwang 2002, Carls *et al.* 2003). If such mechanisms are indeed responsible for the observed spring tide signal, it implies that a source of ENT, or a "nutrient" that allows ENT growth or persistence is present in the upper reaches of the tidal prism or subterranean estuary (Moore 1999), or the high water line of the beach. This is consistent with the growing body of evidence that ENT is present in the subsurface of beach aquifers (Boehm *et al.* 2003, Kinnetic Laboratories, Inc. 2004), on marine sands (Boehm *et al.* 2003, Kinnetic Laboratories, Inc. 2004, Nix *et al.* 1994, Oshiro and Fujioka 1995, Obiri-Danso and Jones 2000, Desmarais *et al.* 2002), wrack (Anderson *et al.* 1997) and bird feces (Choi *et al.* 2003) at the high water line.

An ebb-flood signal was not wide-spread (i.e., it was not present at the majority of beaches), nor was the phasing of the signal consistent between beaches like the spring-neap signal described above (Figure 4, panel B). Nevertheless, it was important at some of the sites investigated. We found that if the ebb-flood was examined exclusively during spring tides, ENT levels were higher during ebb compared to flood tides, both in terms of the GMs and the percent of samples in exceedance of the single-sample standard. This could imply that when the tide range is large, ENT are most effectively flushed by ebb tides from land-based sources. The exception to this observation was the analysis for the dry months when tide stage appeared to have little impact of ENT levels once tide range was accounted for. This might result from the limited number of spring-ebb observations in the data set.

Overall, beach physiography, including the presence of an input, beach slope, input slope, and beach direction, had little bearing on the degree to which tides influenced ENT concentrations at specific sites. Terrestrial runoff is a well-documented source of ENT to beaches in southern California where the storm drain system is independent from the sewage treatment system (Dojiri *et al.* 2004). The momentum of flow from these inputs is typically small owing to low seasonal rainfall, so ebbing and flooding tides easily modulate the input flow. Given this well understood process, we expected to find ENT concentrations at the 31 beaches in close proximity to terrestrial runoff sources to be highly affected by tides, and beaches further away relatively unaffected. Our results suggest this was not necessarily the case. The lack of tidal signals at a subset of beaches near watershed outlets suggests that factors such as dilution induced by rip currents, direction of littoral drift, or ENT concentration and momentum of the discharge may confound a tidal signal. The occurrence of tidal signals at locations away from input sources suggests that interactions between the tide, and beach sands or aquifers may drive a tidal relationship.

The ANOVA analysis revealed that by using season and tides, we could account for between 0 and 45% of log-ENT variance at the 60 beaches. While tide range, tide stage, and various interaction terms accounted together for on average only 9% of the log-ENT variance, they influenced ENT levels such that GMs and the number of exceedances of the single-sample standard were significantly higher during specific tide conditions. Importantly we have identified a mechanism that modulates ENT at a majority of physically and geographically distinct beaches. Future work should focus on determining other mechanisms that modulate ENT at recreational beaches, so that all the variance in log-ENT concentrations (as in Figure 2, panel A) can be accounted for. Possibilities include wave height and direction, water temperature, and wind.

The strength and ubiquitous nature of the tidal effects we observed suggest that tide should be considered in beach water quality monitoring program design. Most beach sampling in the US is conducted only once per week. The goal of such sporadic monitoring is to identify problems if they exist. Our results suggest that in southern California, weekly monitoring would be best conducted during spring-ebb tides. Monitoring data should to be interpreted in context of when samples were collected within the tidal cycle. New efforts to model bacterial conditions on freshwater beaches as a function of environmental influences provide an opportunity to enhance interpretation of such data (Olyphant and Whitman 2004). Our study results suggest that tidal conditions need to be an important part of such models when they are developed for the marine environment.

The finding that spring tides and the spring-ebb tide synergy give rise to elevated ENT at the majority of beaches, even those away from watershed outlets, suggests tidally-forced sources other than land-based surficial runoff are widespread. Therefore, sand, bird feces, and wrack near the high water line, as well as water within the beach aquifer, should be considered in bacterial source identification investigations.

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Appendix I. Physiography, water quality, and tidal comparisons for the dry months of April through October.

DRY MONTHS					Tide Range Comparison				Tide Stage Comparison				Tide Range-Tide Stage Comparison							
Station	Physiography Description	GM	Range	CV (%)	S (GM)	N (GM)	S (% >104)	N (% >104)	**E (GM)**	**F (GM)**	**E (% >104)**	**F (% >104)**	S-E (GM)	S-F (GM)	N-E (GM)	N-F (GM)	S-E (%>104)	S-F (%>104)	N-E (%>104)	N-F (%>104)
S1_pre94	S-3/-	6.4	1-1200	67	10.3*	4.0*	2*	0*	**4.4#**	**7.9#**	**1**	**1**	10.1	10.6	4.0	3.7	0	2	1	0
S2_pre94	S-3/in-5	4.3	1-800	88	6.4*	2.9*	2*	1*	**3.1#**	**5.1#**	**0#**	**1#**	5.9	6.3	2.9	3.0	0	1	0	1
S3_pre94	SW-5/in-5	9.6	1-3400	53	13.2*	7.0*	4*	1*	**7#**	**11.1#**	**2**	**3**	11.1	13.3	6.8	6.8	0*	4*	2*	1*
S4_pre94	W-1/in-3	6.1	1-6200	70	7.6*	4.9*	2	2	**4.6#**	**7.1#**	**1**	**2**	6.5	7.9	4.5	5.5	0	2	1	2
S5_pre94	W-1/in-3	6.3	1-6400	68	7.9*	5*	3	2	**4.1#**	**7.2#**	**2**	**2**	10.3	7.8	3.9	5.9	13*	2*	2*	2*
S6_pre94	W-1/in-3	6.4	1-6400	72	8.3*	4.9*	4*	2*	**4#**	**7.7#**	**2**	**3**	6.6	8.4	3.9	6.3	0	4	2	2
S7_pre94	W-1/-	3.9	1-6000	99	6.0*	2.6*	4*	2*	**2.4#**	**4.8#**	**2#**	**4#**	5.9	5.9	2.3	2.9	9*	4*	1*	2*
S8_pre94	W-1/-	3.7	1-6600	106	5.0*	2.7*	3	2	**2.9#**	**4.2#**	**3**	**3**	5.4	4.9	2.8	2.8	0	4	3	2
S9_pre94	W-1/-	3.4	1-6800	111	4.4*	2.6*	2	2	**2.7#**	**3.8#**	**2**	**2**	4.0	4.5	2.6	2.5	0	2	2	3
S10_pre94	W-1/-	3.2	1-16000	111	4.4*	2.3*	3*	1*	**2.2#**	**3.8#**	**1**	**2**	4.0	4.3	2.1	2.9	6*	2*	0*	3*
S11_pre94	W-1/-	2.3	1-1200	126	2.8*	2.0*	1	1	**1.8#**	**2.5#**	**0#**	**1#**	3.1	2.7	1.8	2.2	0*	0*	0*	2*
S12_pre94	W-1/-	2.2	1-5500	142	2.8*	1.7*	1	0	**1.9#**	**2.3#**	**0#**	**1#**	3.1	2.6	1.7	1.8	0	1	0	0
S13_pre94	W-2/-	2.1	1-1200	148	2.7*	1.6*	1*	0*	**1.7#**	**2.2#**	**1**	**1**	2.5	2.5	1.6	1.7	1	1	0	0
S14_pre94	W-2/-	2.9	1-23000	121	3.7*	2.3*	2*	1*	**2.3#**	**3.3#**	**1**	**2**	3.5	3.6	2.0	2.7	2	2	1	1
S15_pre94	W-3/-	6.1	1-2400	76	7.1*	5.3*	3	2	**5.1#**	**7#**	**2**	**3**	5.5	7.7	4.9	5.9	5	3	1	3
S16_pre94	W-3/in-3	3.7	1-3800	113	5.2*	2.6*	4*	2*	**2.9#**	**4.1#**	**3**	**3**	4.1	5.0	2.5	2.9	6	3	2	3
S17_pre94	W-5/in-3	2.9	1-1400	122	3.5*	2.3*	2	2	**2.7**	**3.1**	**2**	**2**	4.0	3.3	2.2	2.7	3	2	1	3
S1_post94	S-3/in-1	23.8	1-3700	59	27.3	20.8	25	24	**24.4**	**24.4**	**28**	**25**	19.9	32.8	26.6	14.5	20	29	31	17
S2_post94	S-3/in-5	17.1	1-1600	55	24.5*	12.5*	15	9	**20.4**	**15.8**	**16**	**9**	36.3	25.2	15.2	9.5	26*	16*	11*	2*
S3_post94	W-1/in-4	10.2	1-940	53	12.9*	8.0*	3	3	**10.3**	**11.0**	**5**	**3**	15.8	13.1	8.8	8.1	6	3	5	3
S4_post94	W-1/in-0	49.6	1-7500	41	44.6	54.8	21#	35#	**44.3**	**50.9**	**31**	**27**	42.1	43.4	44.9	63.1	19	22	34	35
S5_post94	W-1/in-3	17.9	1-6000	43	20.9	15.5	6	4	**13.8**	**21.2**	**5**	**5**	15.5	24.5	13.3	16.7	7	8	4	0
S6_post94	W-1/in-0	10.6	1-3600	71	14.9*	7.7*	15	10	**10.0**	**10.8**	**18**	**10**	23.3	15.1	7.6	5.7	33*	13*	13*	5*
S7_post94	W-1/in-3	8.8	1-5100	72	11.5*	6.8*	8	4	**7.3**	**10.2**	**6**	**7**	13.9	10.8	5.9	9.3	10	8	5	6
S8_post94	W-1/in-	5.6	1-1800	73	8*	4*	2	1	**4.4**	**5.8**	**2**	**1**	4.8	7.4	4.4	3.9	0	2	2	0
S9_post94	SE-0/-	13.5	1-1700	59	13.7	13.2	8	7	**14.4**	**13.2**	**8**	**5**	6.5	14.1	16.6	11.6	0	5	10	5
S10_post94	W-1/in-3	11.8	1-6200	53	16.9*	8.5*	6	2	**8#**	**15.3#**	**0#**	**6#**	8.2	17.3	8.0	10.9	0	6	0	3
S11_post94	W-1/-	6.8	1-5600	81	8.9*	5.3*	5	4	**4.5#**	**8.9#**	**6**	**5**	3.8	9.8	4.5	7.2	0	5	6	3
S12_post94	W-1/in-	4.2	1-600	97	4.7	3.8	3	2	**4.7**	**3.9**	**2**	**3**	5.7	4.4	4.6	3.0	0	3	2	3
S13_post94	W-2/-	1.9	1-120	150	2.4*	1.5*	0	1	**1.8**	**2.1**	**2**	**0**	2.2	2.5	1.7	1.3	0	0	2	0
S14_post94	W-2/-	2.4	1-1000	135	3.2*	1.8*	2	0	**2.0**	**2.6**	**1**	**1**	3.4	3.1	1.6	2.0	6	2	0	0
S15_post94	W-2/-	3.2	1-480	109	4.5*	2.2*	4	1	**2.6**	**3.2**	**2**	**1**	3.9	4.0	2.2	2.2	0	2	2	0
S16_post94	W-4/in-3	15.5	1-1300	47	18.0	13.4	5	5	**12.2**	**17.1**	**4**	**5**	13.6	21.3	11.6	13.5	10	4	2	6
S17_post94	W-3/in-0	3.3	1-2800	104	5.1*	2.2*	3*	0*	**3.3**	**3.2**	**1**	**1**	5.4	5.0	2.5	2.1	4	2	0	0
S18_post94	W-5/in-0	2.6	1-530	123	3.4*	2.1*	1	2	**2.3**	**2.9**	**1**	**1**	2.6	4.1	2.2	2.0	3	0	0	2
SM_WP	NW-1/in-3	4.2	1-62	65	4.6	3.8	0	0	**4.2**	**4.0**	**0**	**0**	5.6	4.1	3.8	3.9	0	0	0	0
SB_WP	NW-3/in-3	2.5	1-57	83	2.9*	2.2*	0	0	**2.1#**	**2.7#**	**0**	**0**	1.9	3.0	2.1	2.2	0	0	0	0
S1_WP	NW-3/in-	2.1	1-560	79	2.2	2.1	1*	0*	**2.2**	**2.0**	**0**	**1**	2.7*	2.0*	2.1*	2.0*	2	1	0	0
S2_WP	SW-3/in-3	2.5	1-1200	95	3.0*	2.1*	1*	0*	**2.3**	**2.6**	**0**	**1**	3.0	3.0	2.1	2.1	2	1	0	0
S3_WP	SW-1/in-1	3.0	1-7200	88	3.9*	2.4*	1*	0*	**2.4#**	**3.5#**	**0**	**1**	3.7	3.9	2.2	2.8	0	1	0	1
S5_WP	SW-3/in-3	2.6	1-1200	101	3.2*	2.2*	1	1	**2.8**	**2.5**	**1**	**1**	4.0*	2.8*	2.1*	2.3*	1	2	1	0
S6_WP	SW-3/in-3	3.0	1-5200	101	3.5*	2.6*	1	2	**2.4#**	**3.5#**	**2**	**2**	2.5	3.6	2.4	3.3	0	1	2	3
S7_WP	SW-1/in-5	3.6	1-1000	87	4.8*	2.7*	2	1	**2.6#**	**4.1#**	**0**	**1**	4.7	4.6	2.5	2.9	0	1	0	2
39N_HB	SW-3/-	5.8	2-646	70	7.2*	4.6*	5*	1*	**3.4#**	**8.6#**	**0#**	**5#**	4.3	8.0	3.3	11.0	0*	6*	0*	2*
33N_HB	SW-3/-	5.8	2-400	61	6.9*	4.7*	3	1	**5#**	**6.9#**	**2**	**2**	13.2	7.4	4.7	5.6	12	2	2	2
27N_HB	SW-1/-	6.3	2-840	60	7.4*	5.2*	2*	0*	**5.3#**	**7.4#**	**1**	**1**	5.4	7.9	5.3	6.0	0	2	1	0
21N_HB	SW-1/-	6.3	2-400	60	7.7*	4.8*	2*	0*	**4.7#**	**8.1#**	**1**	**2**	5.9	8.6	4.6	7.0	0	2	1	0
15N_HB	SW-1/-	9.2	2-780	56	12.3*	6.7*	4	2	**6.2#**	**12.4#**	**2**	**5**	7.8	12.9	6.0	11.3	0	5	2	4
9N_HB	SW-5/-	18.6	2-930	55	29.7*	10.4*	29*	10*	**9.7#**	**29.8#**	**5#**	**29#**	29.2	33.0	8.3	22.4	19*	30*	4*	27*
6N_HB	SW-5/-	16.5	2-1050	57	28.2*	9.2*	23*	8*	**9.5#**	**22.9#**	**8#**	**21#**	19.1	32.2	8.5	9.9	22*	26*	5*	8*
3N_HB	SW-5/-	13.2	2-600	58	20.6*	9*	14*	6*	**7.7#**	**17.6#**	**3#**	**14#**	46.0	18.8	7.1	13.9	33*	13*	2*	15*
0N_HB	SW-1/in-2	6.6	1-400	66	7.5*	5.7*	6*	1*	**6.0**	**7.3**	**2#**	**6#**	10.0	8.2	5.9	4.8	0	7	3	0
3S_HB	SW-3/-	3.8	2-262	69	4.5*	3.4*	1	0	**3.3**	**4.2**	**0**	**1**	3.8	4.5	3.3	3.2	0	1	0	0
6S_HB	W-5/-	3.4	2-176	70	4.2*	2.9*	1	0	**2.8#**	**3.7#**	**1**	**1**	6.8	4.1	2.7	2.8	17*	1*	0*	0*
9S_HB	W-5/-	3.5	2-460	75	4.3*	3.1*	1	1	**3#**	**4#**	**1**	**2**	4.5	4.1	2.9	3.7	0	1	1	4
15S_HB	S-5/-	3.6	2-400	67	4.9*	3*	0	0	**3#**	**4#**	**1**	**0**	5.4	4.5	2.8	3.0	0	0	1	0
21S_HB	S-5/-	3.4	2-154	69	4.1*	3*	0	0	**3.0**	**3.6**	**0**	**0**	3.9	3.7	2.9	3.2	0	0	0	1
27S_HB	S-5/in-	2.7	2-106	69	3.1*	2.4*	0	0	**2.7**	**2.8**	**1**	**0**	3.6	3.0	2.6	2.4	0	0	1	0
29S_HB	S-5/in-1	4.3	2-384	70	5.9*	3.3*	2	1	**3.8**	**4.5**	**0**	**2**	5.0	5.1	3.4	3.7	0	1	0	2
39S_HB	S-5/-	3.0	2-252	79	3.8*	2.4*	1	0	**3.1**	**2.9**	**0**	**1**	4.8	3.3	2.5	2.4	0	2	0	0

Appendix II. Physiography, water quality, and tidal comparisons for the wet months of November through March.

WET MONTHS					Tide Range Comparison				Tide Stage Comparison								Tide Range-Tide Stage Comparison			
Station	Physiography Description	GM	Range	CV (%)	S (GM)	N (GM)	S (% >104)	N (% >104)	E (GM)	F (GM)	E (% >104)	F (% >104)	S-E (GM)	S-F (GM)	N-E (GM)	N-F (GM)	S-E (%>104)	S-F (%>104)	N-E (%>104)	N-F (%>104)
S1_pre94	S-3/-	12.7	1-4100	64	15.9*	10.2*	12*	8*	11.1	12.5	10	7	15.8	14.2	10.5	9.1	12*	10*	9*	2*
S2_pre94	S-3/in-5	10.6	1-8300	76	13.2*	8.5*	11	9	9.4	10.9	10	7	15.0	12.0	8.6	8.7	11	8	10	4
S3_pre94	SW-5/in-5	20.4	1-6300	53	24*	17.4*	16*	10*	19.8	19.2	11	12	25.0*	21.4*	18.8*	14.7*	13	13	11	8
S4_pre94	W-1/in-3	15.4	1-10000	59	20.3*	11.8*	13*	7*	15.2	14.4	9	9	30.7*	16.7*	12.8*	10.2*	21*	10*	6*	7*
S5_pre94	W-1/in-3	15.7	1-25000	63	22.8*	10.9*	15*	9*	15.0	15.3	12	11	37.0*	18.5*	11.9*	9.9*	21*	12*	10*	7*
S6_pre94	W-1/in-3	16.4	1-4700	58	24.3*	11.2*	16*	8*	15.1	15.9	12	11	38.4*	18.6*	11.4*	11.5*	25*	12*	8*	9*
S7_pre94	W-1/-	11.0	1-6000	71	19.3*	6.4*	14*	6*	10.0	10.4	9	10	28.3*	13.9*	6.7*	6.3*	17*	13*	6*	5*
S8_pre94	W-1/-	11.4	1-6000	78	15.1*	8.6*	15*	9*	12.7	9.8	13	12	23.4	11.2	9.4	8.0	17	13	10	10
S9_pre94	W-1/-	9.7	1-6800	78	12.1*	7.8*	10	8	8.8	9.5	8	9	9.7	11.7	8.4	6.5	7	11	9	5
S10_pre94	W-1/-	6.0	1-3500	92	8.8*	4.1*	8*	3*	5.7	5.7	5	6	9.1	7.4	4.4	3.9	9*	7*	3*	3*
S11_pre94	W-1/-	6.6	1-3000	82	8.5*	5.1*	7*	4*	6.6	6.5	5	6	8.3	8.3	6.0	4.2	6	7	4	3
S12_pre94	W-1/-	4.6	1-6000	105	6.7*	3.2*	6*	3*	4.6	4.2	3	5	6.6	6.1	3.7	2.6	4*	6*	2*	4*
S13_pre94	W-2/-	5.9	1-3900	89	9*	3.9*	6*	3*	6.3	5.2	3	5	9.4	7.9	4.8	3.0	4*	7*	3*	2*
S14_pre94	W-2/-	5.8	1-4900	98	8.4*	4.1*	9*	4*	6.2	5.2	6	7	8.4	7.5	5.0	3.4	8*	10*	5*	4*
S15_pre94	W-3/-	13.1	1-4800	65	17.5*	9.9*	15*	7*	14.4	11.5	11	10	16.0	19.3	13.4	6.8	15*	14*	8*	6*
S16_pre94	W-3/in-3	6.7	1-6700	93	8.9*	5*	9*	5*	6.8	6.6	7	7	8.5	9.5	5.7	4.7	8*	10*	6*	4*
S17_pre94	W-5/in-3	6.9	1-4600	85	10.2*	4.7*	9*	3*	7.5	6.0	6	6	11.1	8.4	5.2	4.6	10*	8*	3*	4*
S1_post94	S-3/in-1	101.2	2-6100	38	74.1	140.9	45*	60*	116.3	85.5	57	47	134.3	41.7	100.6	179.6	63*	28*	50*	68*
S2_post94	S-3/in-5	75.6	1-7800	36	99.1	55.0	44*	24*	99.3	48.9	46*	20*	130.2	58.4	70.8	41.5	55*	27*	34*	13*
S3_post94	W-1/in-4	38.0	1-4500	51	49.5	29.6	28	23	35.8	44.6	27	29	54.1	43.1	26.8	46.2	34	23	22	35
S4_post94	W-1/in-0	62.0	1-7700	36	71.2	54.6	32	21	73.4	52.2	28	27	91.7	64.0	63.3	39.0	33	37	24	14
S5_post94	W-1/in-3	43.2	3-2800	36	64*	29.5*	28*	7*	46.1	36.7	22*	9*	92.9	50.8	31.2	21.5	46*	15*	9*	0*
S6_post94	W-1/in-0	78.3	1-6000	39	75.6	81.1	39	44	91.7	54.7	50*	30*	124.5	37.1	80.8	87.9	59*	18*	46*	44*
S7_post94	W-1/in-3	25.4	1-6000	53	24.5	26.4	14	23	39.9	18.2	27*	12*	49.3	13.1	34.3	29.9	27*	3*	27*	24*
S8_post94	W-1/in-	27.7	1-4400	48	39.7*	19*	27*	8*	25.6	21.5	10	17	43.1	23.3	19.1	18.6	19	20	5	12
S9_post94	SE-0/-	47.9	1-15000	48	49.0	46.9	29	30	53.5	52.7	33	30	69.4	57.1	47.5	46.2	50	26	25	37
S10_post94	W-1/in-3	41.6	1-9000	47	54.2	32.5	25	21	31.5	39.8	19	21	43.2	43.4	29.4	32.3	20	20	19	22
S11_post94	W-1/-	25.9	1-7300	61	29.7	22.7	26	20	23.9	24.5	20	25	20.9	33.2	24.8	12.9	17	30	21	14
S12_post94	W-1/in-	9.8	1-660	64	10.2	9.4	6	6	12.0	7.5	8	3	16.2	8.4	10.9	6.2	17	5	5	0
S13_post94	W-2/-	4.6	1-340	96	5.4	3.9	0*	4*	6.0	3.5	2	4	9.6	3.4	4.4	3.8	0	0	3	10
S14_post94	W-2/-	8.4	1-2400	77	14.8*	4.6*	13*	3*	11.3	5.7	8	2	19.7	8.2	6.8	3.3	13	4	3	0
S15_post94	W-2/-	10.5	1-5100	77	18.4*	6*	13	9	10.7	6.9	9	9	22.2	7.6	5.7	6.4	15	5	5	13
S16_post94	W-4/in-3	35.3	1-6300	39	52.2*	24.4*	31*	7*	36.4	32.5	20	9	61.6	45.5	26.4	22.9	32*	18*	12*	0*
S17_post94	W-3/in-0	12.6	1-2500	74	16.7	9.8	17	8	13.5	10.7	14	8	24.3	9.5	9.1	11.9	19	9	11	8
S18_post94	W-5/in-0	7.3	1-930	75	9.0	6.0	5	6	7.2	5.4	4	4	7.0	6.5	7.3	4.9	3	0	5	7
SM_WP	NW-1/in-3	9.3	1-16000	74	14.1*	6.3*	11	7	10.2	7.5	10	9	16.8*	8.0*	6.2*	7.1*	12	11	9	7
SB_WP	NW-3/in-3	2.7	1-110	86	3.6*	2*	2	0	2.9	2.3	2	0	4.2	2.8	1.9	2.1	3	0	0	0
S1_WP	NW-3/in-	3.9	1-18000	118	4.2	3.6	4	6	4.4	3.3	6	4	4.7	3.6	4.1	3.2	5	6	8	2
S2_WP	SW-3/in-3	4.9	1-6600	98	6.6*	3.7*	8*	4*	5.7	3.9	7	5	8.2*	4.6*	4*	3.5*	8	9	5	3
S3_WP	SW-1/in-1	5.7	1-2400	79	7.6*	4.3*	6*	2*	6.4	4.8	5*	2*	8.7	5.9	4.8	4.2	8*	5*	3*	1*
S5_WP	SW-3/in-3	8.8	1-2600	75	16.6*	4.8*	14*	4*	12.9*	4.4*	12*	3*	20.8*	5.8*	5.9*	4.3*	16*	4*	5*	3*
S6_WP	SW-3/in-3	5.5	1-2600	91	8.9*	3.5*	10*	4*	6.4*	3.8*	8*	4*	12.1*	3.9*	3.6*	3.7*	13*	3*	4*	5*
S7_WP	SW-1/in-5	8.2	1-9600	78	11.4*	6*	12*	6*	8.4	6.9	10	6	16.3	8.4	6.8	4.5	21*	7*	7*	3*
39N_HB	SW-3/-	4.5	2-400	80	4.8	4.3	1	5	3.9	4.9	4	4	4.9	4.6	3.8	6.2	0	2	4	12
33N_HB	SW-3/-	4.9	2-400	75	5.2	4.5	3	2	3.7	5.3	2	4	11.0	4.8	3.6	7.9	0	3	2	6
27N_HB	SW-1/-	7.0	2-400	74	7.7	6.4	6	5	5.3	7.8	4	7	n.a.	7.1	5.3	11.0	n.a.	6	4	11
21N_HB	SW-1/-	7.1	2-400	73	6.9	7.4	6	5	6.1	7.0	2	6	2.0	6.4	6.2	10.0	0	6	2	6
15N_HB	SW-1/-	8.0	2-400	67	9.3	7.0	8*	2*	6.7	8.2	2	7	43.2*	8.0*	6.0*	9.2*	0	7	2	6
9N_HB	SW-5/-	7.8	2-400	61	9.0	6.8	4	2	6.8	8.5	2	4	14.5	8.2	6.4	10.0	0	3	2	6
6N_HB	SW-5/-	10.8	2-400	53	12.8	9.3	8	6	8.2	11.5	5	6	10.7	11.7	7.9	10.6	0	7	6	5
3N_HB	SW-5/-	22.9	2-400	48	30.9*	17.5*	23	15	18.4	23.1	16	15	44.0	24.2	15.0	20.5	31	16	13	14
0N_HB	SW-1/in-2	13.3	2-400	56	10.2	17.0	6	11	17.5*	8.4*	7	4	17.4	6.7	17.5	13.9	0	2	9	9
3S_HB	SW-3/-	12.2	2-400	55	10.6	13.9	6	10	16.2*	7.7*	10	4	18.1	7.5	15.7	8.2	13	2	9	9
6S_HB	W-5/-	7.9	2-400	63	9.0	7.0	4	5	8.5	7.0	4	3	17.5	7.3	6.6	6.4	5	5	4	0
9S_HB	W-5/-	7.6	2-400	61	9.6*	6.2*	4	2	7.4	6.9	1	3	14.8	7.8	5.6	5.5	5	5	0	0
15S_HB	S-5/-	9.2	2-400	67	16.2*	5.5*	14*	3*	10.7	7.1	12*	2*	33.7*	8.2*	5.5*	6.0*	27*	3*	4*	0*
21S_HB	S-5/-	6.3	2-400	71	8.5*	4.9*	9*	1*	7.5	4.9	5	3	12.4	5.1	5.5	4.8	12*	4*	0*	3*
27S_HB	S-5/in-	3.6	2-400	82	4.2	3.1	4	1	3.3	3.7	2	3	3.9	4.1	2.9	3.4	6	4	0	3
29S_HB	S-5/in-1	7.2	2-170	68	11.9*	4.6*	5	2	8.8*	4.6*	3	4	13.1	6.4	6.0	3.9	4	6	2	3
39S_HB	S-5/-	3.0	2-100	76	3.3	2.7	0	0	3.0	2.7	0	0	3.4	2.6	2.6	2.7	0	0	0	0