ARTICLE IN PRESS

Marine Pollution Bulletin xxx (2009) xxx–xxx

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Microbiological water quality at non-human influenced reference beaches in southern California during wet weather

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ARTICLE INFO

Keywords:
Fecal indicator bacteria
Enterococcus
E. coli
Total coliform
Reference beach
Non-human

ABSTRACT

Although urban wet weather discharges may have elevated concentrations of fecal indicator bacteria impacting water quality at swimming beaches, not all of these bacteria may arise from human sources. In this study, the contribution of non-human fecal indicator bacteria was quantified by sampling coastal reference beaches in southern California. Samples were collected at beaches near stormwater discharges from undeveloped watersheds and analyzed for total coliform, *Escherichia coli*, and enterococci. Surfzone samples exceeded water quality thresholds >10 times more frequently during wet weather than dry weather. Exceedences were greatest <24 h following rainfall, then steadily declined on successive days. Early season storms exceeded thresholds more frequently, and by greater magnitude, compared to late season storms. Large storms exceeded thresholds more frequently than smaller-sized storms, partly due to the breaching of sand berms. When discharges did reach the surf zone, bacterial concentrations in the wave wash were correlated with watershed bacterial flux.

1. Introduction

Beaches in southern California are a valuable recreational resource for swimming, surfing, and other body contact activities. For example, greater than 175 million beach-goers visit southern California beaches annually, more than all other parts of the country combined (Schiff et al., 2001). This year-round activity results in tremendous economic revenue estimated at more than $9 billion annually in ocean related activities for the region (NRC, 1990).

Fecal indicator bacteria (total coliform, *Escherichia coli*/fecal coliform, and enterococci) are used to monitor the water quality of marine beaches because they have been shown to correlate with swimming related illness. For example, Cabelli (1982) demonstrated that increases in concentrations of enterococci correlated with an increase in the risk of highly credible gastrointestinal illness among swimmers on beaches in New Jersey. In Santa Monica Bay, California, Haile et al. (1999) observed an increase in the relative risk for diarrhea with blood and highly credible gastrointestinal illness in swimmers exposed to higher concentrations of enterococci.

While the water quality at most beaches in southern California meets water quality thresholds established by the State during dry weather, several beaches have impaired water quality based on routine fecal indicator bacteria monitoring. Noble et al. (2000) conducted a regional study of all southern California beaches and found that approximately 5% of the shoreline exceeded water quality thresholds for fecal indicator bacteria during the summer of 1998. This level of exceedence was not randomly distributed. More than half of the exceedences occurred near storm drains that discharge across the beach. A retrospective analysis of fecal indicator bacteria based on five years of daily beach monitoring during dry weather in Santa Monica Bay found similar results, with over half of the water quality exceedences occurring in front of storm drains (Schiff et al., 2003).

The microbial water quality of beaches in southern California drastically changes following rainstorms. Noble et al. (2003a,b) repeated their 1998 summer study, but sampled following a significant rainfall event during the winter of 1998–1999. In this case, over half of all beaches exceeded fecal indicator bacteria water quality thresholds. This frequency of impaired water quality jumped to nearly 90% when these beaches were located in front of storm drains. Similarly, Schiff et al. (2003) observed a doubling of microbial water quality exceedences between dry and wet weather, even though wet weather represented less than 10% of the year.

There are many sources of bacteria that could potentially be found in storm drains that discharge to beaches. Some of these sources may be of human origin including sewage spills, leaking sanitary sewage systems, faulty septic systems, or illicit discharges and illegal dumping (Geldreich, 1978). However, many bacteria may actually arise from natural sources. Fecal indicator bacteria

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0025-326X/$ - see front matter
doi:10.1016/j.marpolbul.2009.11.015

Please cite this article in press as: Griffith, J.F., et al. Microbiological water quality at non-human influenced reference beaches in southern California during wet weather. Mar. Pollut. Bull. (2009), doi:10.1016/j.marpolbul.2009.11.015

such as total coliform, *E. coli*/fecal coliform and enterococci are a component of the gut microflora of all warm-blooded animals, including domesticated dogs and cats, and wild birds and mammals (Grant et al., 2001; Oshiro and Fujioka, 1995). Furthermore, fecal indicator bacteria may have extended survival or even regrow in beach sediments and wrack (Valiela et al., 1991; Weiskel et al., 1996; Desmarais et al., 2002; Gruber et al., 2005; Anderson et al., 2005). Therefore, the reference condition for bacterial water quality, including those beaches that are located at the mouth of undeveloped watersheds, is likely not zero. In fact, some shoreline managers use the level of contributions from undeveloped watersheds as the benchmark for water quality from developed watersheds in the Los Angeles region (LARWQCB, 2002). Unfortunately, the contributions of fecal indicator bacteria from undeveloped watersheds to reference beaches are largely unknown, which complicates this approach for assessing public health risk or beach management. Understanding this uncertainty is paramount because current use of reference beaches for regulation are focused on a minimum number of sites.

The goal of this study was to assess the microbial water quality at reference beaches following wet weather events in southern California through measurements of fecal indicator bacteria. Reference beaches were defined as those beaches located at the mouth of undeveloped watersheds and whose bacterial contributions are minimally influenced by human activities. These data can then be used by public health agencies and beach managers for making informed decisions about the reference condition of microbial water quality during wet weather. A series of secondary objectives were also addressed during this study to enhance our ability to decipher processes that can influence reference beach water quality during wet weather. These objectives included assessments of: (1) beach water quality over time following rainfall to determine how long elevated concentrations of fecal indicator bacteria persist; (2) the influence of storm size and seasonality on beach water quality; (3) the relationship between land-based inputs and microbial water quality at reference beaches; (4) the relationship between watershed size and microbial water quality; and (5) the influence of lagoonal systems on microbial water quality at reference beaches.

2. Methods

Six coastal reference beaches in southern California were selected for assessment of water quality during wet weather. Reference beaches were selected based on four criteria: (1) each reference beach must be an open beach with breaking waves; (2) each reference beach must have a freshwater input; (3) the freshwater input must come from a watershed of similar size to nearby beaches that receive wet weather inputs from urban watersheds; and (4) the watershed discharging to the reference beach must be >93% undeveloped.

The six reference beaches were: (1) Point Mugu State Beach located at the mouth of Big Sycamore Creek in Ventura County; (2) Deer Creek Beach located at the mouth of Deer Creek in Ventura County; (3) Leo Carrillo State Beach located at the mouth of Arroyo Sequit Creek in Los Angeles County; (4) Dan Blocker Beach located at the mouth of Solstice Creek in Los Angeles County; (5) San Onofre State Beach located at the mouth of San Onofre Creek in San Diego County; and (6) San Mateo Beach located at the mouth of San Mateo Creek in San Diego County (Table 1, Fig. 1). All six reference beaches are open with breaking waves and have freshwater inputs. The six watersheds that discharge to these reference beaches range from 3 to 346 km^2, which is within the 25th and 75th interquartile range of watershed area for all of the watersheds that drain to impacted, urbanized beaches in southern California. Five of the watersheds that drained to the reference beaches were between 97% and 100% undeveloped, while one (San Mateo) was 93% developed, based on land use data compiled by the US Geological Survey and University of California Santa Barbara (Davis et al., 1998). Deer Creek was the smallest watershed and had the least amount of human activity, while San Mateo Creek was the largest watershed and had the greatest amount of human activity.

2.1. Sampling

The primary sampling location was in the ocean immediately in front of the freshwater input at the so-called "wave wash" where the watershed discharge initially mixes with the ocean waves. All samples were collected between ankle and knee depth on an incoming wave. The secondary sampling location was in the watershed discharge as it crossed the beach at the closest sample able location prior to mixing with the ocean.

Samples at the primary sampling sites were measured for fecal indicator bacteria and salinity. Samples at the secondary sampling sites were measured for fecal indicator bacteria, salinity and flow. A subset of samples at secondary sites was collected for analysis of human enteric virus to detect or rule out the presence of human contributions of fecal pollution. Samples were collected in sterile 250 ml polystyrene bottles (bacterial analysis, salinity analysis) or 4 l polyethylene carboys (enterovirus analysis) following Standard Methods 1060 protocol for aseptic sampling techniques (APHA, 1995). Samples were transported on ice to the laboratory for analysis. Flow was measured using a hand held velocity meter (Marsh-McBirney, Inc., Frederick, MD) and estimates of wetted cross-sectional area.

Sampling focused on wet weather during the Fall and Winter of 2004–2005 and 2005–2006. Wet weather sampling criteria included three or more days of antecedent dry period and predicted minimum rainfall estimates of 0.10 in. Four samples were collected per site corresponding to the day of the storm (defined as within 24 h of recorded rainfall) and the three days following recorded rainfall (four days of sampling in total). Storms were targeted based on two factors; size of storm and seasonality. Size of storm was stratified into small storm events (less than mean daily rainfall) and large storm events (greater than mean daily rainfall) based on historical rainfall at the nearest rain gage. Seasonality was stratified into early season (before December 31st) and late season (after January 1st) storm events. Storm season in southern California is defined as October 15th to April 15th. To summarize, six reference beaches were sampled over the course of four days during five different storm events for a total of 120 sampling events.

Concentrations of total coliforms, *E. coli*, and enterococci were measured using kits supplied by IDEXX Laboratories, Inc. (Westbrook, ME). Concentrations of total coliforms and *E. coli* were measured using the Colilert-18™, while enterococci was measured using Enterolert™. Samples were heat-sealed into Quanti-Tray/2000™ pouches and incubated overnight per the manufacturer's instructions and subsequently inspected for positive wells. Conversion of positive wells to a most probable number (MPN) was done following Hurley and Roscoe (1983). Samples taken at Big Sycamore Beach, Deer Creek Beach, Dan Blocker Beach and Leo Carrillo State Beach were analyzed at the City of Los Angeles laboratory facilities (El Segundo, CA). Samples collected from San Onofre State Beach and San Mateo Beach were analyzed at Weston Solutions Laboratories (Carlsbad, CA).

All discharge samples from the first day of flow were analyzed for human enterovirus. The purpose of this analysis was to reduce the chance that human sewage was a source of indicator bacteria at each site. Since these viruses only infect and multiply in humans through the oral-fecal route, their detection is a reliable marker for

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Table 1
Reference beach and watershed characteristics.

References[a] beach	Watershed	Latitude (NAD 83)	Longitude (NAD 83)	Size[b]	Open space[c]	Beach direct[d]	Beach subst[e]	Lagoon system
Point Mugu	Big Sycamore Creek	3404.255N	11900.901W	55.1	>95	SW	Sand	No
Deer Creek	Deer reek	34°03.724′N	118°59.164′W	3.1	100	SW	Sand	No
Leo Carrillo	Arroyo Sequit	34°2.671′N	118°55.950′W	28.1	100	SW	Sand	Yes
Dan Blocker	Solstice Canyon	34°01.970′N	118°44.539′W	11.5	99	SW	Sand and Cobble	No
San Onofre	San Onofre Creek	33°22.842′N	117°34.719′W	110	97	W	Sand and Cobble	Yes
San Mateo	San Mateo Creek	33°23.143′N	117°35.664′W	346	93	W	Sand and Cobble	Yes

[a] Reference beach.
[b] Watershed size in km^2.
[c] Open space in %.
[d] Beach direction.
[e] Beach substrate.

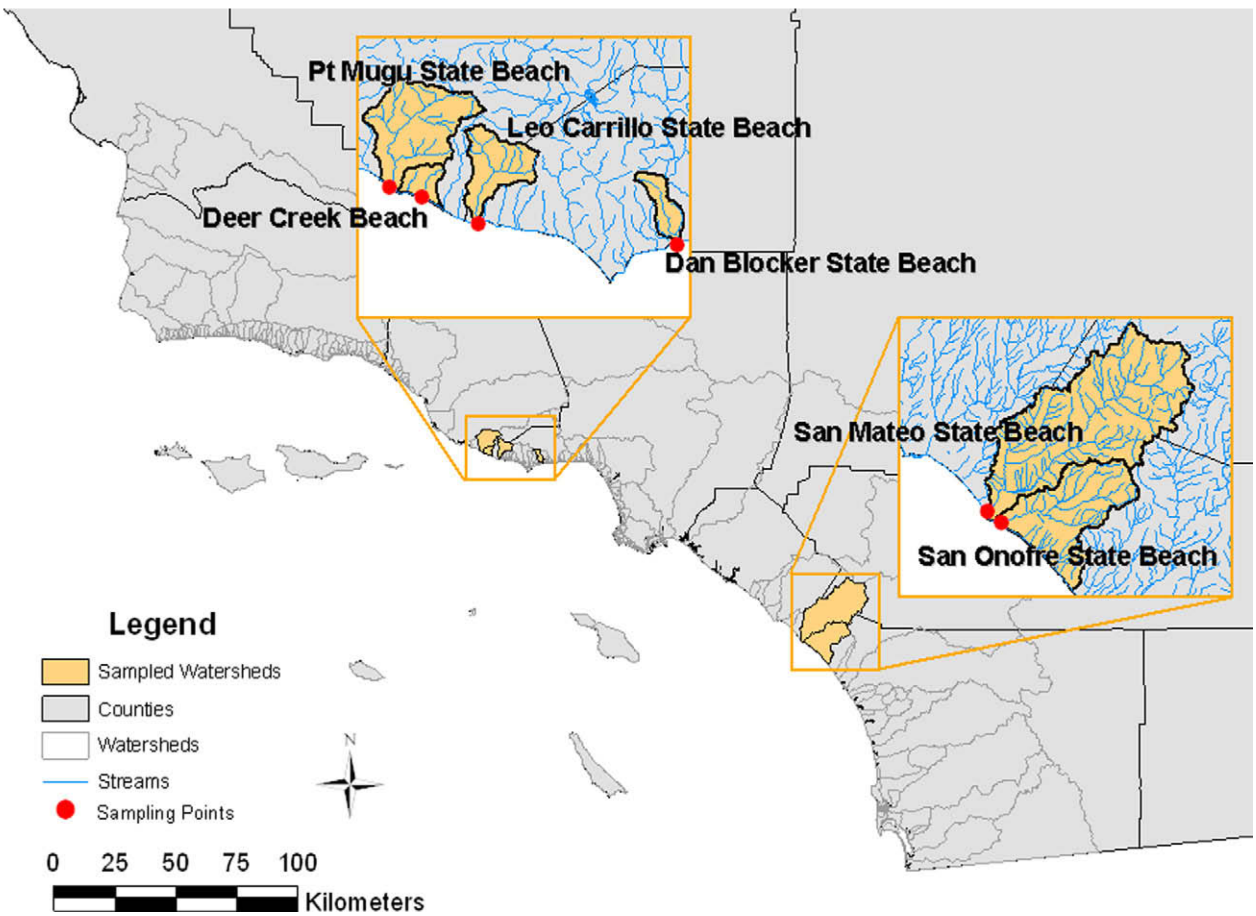

Fig. 1. Reference beaches and watersheds.

a human input of fecal contamination into the system. During the 2005–2006 sampling period, all discharge samples were analyzed for human enterovirus.

Following collection, water samples were passed through 0.45 μm pore-size 47 mm Type HA filters (Millipore, New Bedford, MA) to concentrate viruses. Volumes filtered ranged from 200 ml to 4 l depending on the turbidity and sediment load of the individual sample. In some cases several filters were required to filter the entire sample. Filters were immediately stored at −80 °C and subsequently transported on dry ice to the University of Southern California for human enterovirus analysis. Analysis for the presence of human enterovirus was accomplished following the method described by Fuhrman et al. (2005).

Data analysis focused on seven comparisons. The first compared the frequency of water quality threshold exceedences during wet weather to the frequency of exceedences during winter dry weather and summer dry weather. Wet weather was defined as the day of recorded rainfall plus the next three days. Dry weather was defined as any day greater than three days since recorded rainfall. Winter was defined as November 1–March 31 and summer was defined as April 1–October 31. Wet weather data were collected as part of this study. Winter and summer dry weather data (April 2004–March 2005) for San Onofre State Beach were supplied by the City and County of San Diego, respectively. Winter and summer dry weather data (April 2004–March 2005) for Leo Carrillo State Beach was supplied by the City of Los Angeles. Winter dry weather data (October 2004–March 2005) for Dan Blocker Beach were also supplied by the City of Los Angeles, but no summer dry weather data were available. Winter and summer dry weather data (October 2003–October 2004) for Deer Creek Beach and Point Mugu

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Beach were supplied by the Ventura County Department of Environmental Health (winter dry weather data from 2004 to 2005 at Deer Creek Beach and Point Mugu Beach were not collected by the Ventura County Health Dept.). Water quality thresholds were based on single samples compared to the State of California's AB411 public health standards for marine bathing beaches: (1) >104 enterococci/100 ml; (2) >400 fecal coliform/100 ml (we substituted *E. coli* for fecal coliform); (3) >10,000 total coliform/100 ml; and (4) >1000 total coliform/100 ml when the total coliform to fecal coliform (or *E. coli*) ratio was <10.

The second data analysis element compared the frequency of water quality exceedences among the four days that comprised wet weather. Concentrations of fecal indicator bacteria for all beaches combined were compared to the state's water quality thresholds within 24 h of rainfall and the three days following recorded rainfall.

The third data analysis element focused on comparisons among the six reference beaches. The first comparison examined the relative frequency of exceedence of the state's water quality thresholds for fecal indicator bacteria for all storms combined. The second comparison examined the magnitude of enterococcus concentrations between the four days that comprised wet weather. Mean concentrations and standard deviations were plotted against results within 24 h of rainfall and up to three days following recorded rainfall. Enterococci were chosen as the example indicator for this analysis.

The fourth data analysis element compared the frequency of water quality exceedences between small and large storms and between early and late season storms. Concentrations of fecal indicator bacteria for all beaches combined were compared to the state's water quality thresholds for large and small storms as well as early and late season storms. A subsidiary data analysis examining storm bias quantified the frequency of water quality threshold exceedences when storm flows generated watershed discharges that did not cross the beach sand berm, when storm flows were large enough to breach the sand berm, and for those watersheds that always breached the sand berm regardless of storm size. Deer Creek and Solstice Creek were two reference watersheds that always breached the sand berm during this study. Big Sycamore, Arroyo Sequit and San Onofre Creeks had watershed discharges that intermittently breached the sand berm.

The fifth data analysis element compared bacterial concentrations at each reference beach to salinity measurements and flux of bacteria into the surf zone to evaluate the impact of watershed discharges on reference beach water quality. In this case, we assumed that salinity acted as a conservative tracer of freshwater inputs. Flux was calculated as the product of bacterial concentration and flow. For this analysis, we only examined data when watershed discharges were entering the wave wash. Once again, we chose enterococci for this analysis.

The sixth data analysis element examined the incidence of exceedences of California's AB411 water quality standards for fecal indicator bacteria compared to the size of the watershed. Watersheds were broken into small (<25 km^2), medium (20–99 km^2), and large (>100 km^2), with two watersheds falling into each category.

The last data analysis element focused on the presence or absence of a lagoonal system. For purposes of this study a lagoon was defined as a persistent body of ponded water at the terminus of a creek. During most of the year, these lagoons are separated from the ocean by a sand berm and only flow when the berm is breached by high volume flow from the creek and/or by wave or tidal action. Here we compared bacterial concentrations in the wave wash during wet weather when these systems were flowing versus when they were blocked by the sand berm.

3. Results

Of the nine storm events sampled during this study (Table 2), four occurred early in the season and five occurred late in the season. Four of the storms were larger (0.87–3.07 in.) and five were smaller (0.09–0.44 in.). Antecedent dry periods ranged from 2 to 34 days, depending upon the site and storm event.

Genetic markers of human enterovirus were detected in four discharge samples. These samples were collected from the discharge across San Onofre State Beach on February 12, 2005, Leo Carillo State Beach on March 3, 2006, and Dan Blocker beach on March 13 and 15, 2006. As is the case with the fecal indicator bacteria, the source of the virus particle(s) was unknown. Therefore, all data from these sampling events (wave wash and discharge) were excluded from the following data analysis, as the detection of human enterovirus was indicative of the possible presence of human fecal bacteria, which we were trying to avoid.

The prevalence of water quality exceedences cumulatively at the nine reference beach sites was greater during wet weather than during winter dry weather or summer dry weather, regardless of fecal indicator bacteria (Table 3). About 16% of all samples exceeded water quality thresholds for at least one indicator during wet weather. This was >10 times the frequency of water quality threshold exceedences during dry weather. Although the frequency of water quality threshold exceedences in wet weather was always greater than winter dry weather or summer dry weather, the discrepancy between time periods varied among the individual fecal indicator bacteria. For example, 12% of enterococcus samples exceeded water quality thresholds during wet weather compared to 1% of the samples collected during winter dry weather and 0% of the samples collected during summer dry weather. Comparatively, 10% of the samples analyzed for *E. coli* during wet weather exceeded water quality thresholds compared to 1% of samples during winter dry weather and <1% during summer dry weather. Water quality thresholds for total coliforms exceeded water quality thresholds <1% during dry weather while total coliform to fecal coliform ratio only exceeded water quality thresholds during wet weather.

San Onofre State Beach and San Mateo Beach had the greatest frequency of water quality threshold exceedences during wet weather compared to the other four beaches sampled during this study (Table 3). Almost one-third of the samples at these sites exceeded water quality thresholds for at least one indicator during wet weather. Exceedences occurred at about half this frequency in wet weather at Dan Blocker and Leo Carillo Beaches, with 15% and 17% of the samples exceeding water quality thresholds for at least one indicator during wet weather, respectively. In contrast, only 5% of samples exceeded thresholds for any indicator at Point Mugu State Beach during wet weather, and Deer Creek Beach had none.

Consistent with the frequency of exceedence, the enterococci geometric mean concentration during wet weather was double the geometric mean concentration observed during summer dry weather (Table 4). Across all beaches, maximum enterococci concentrations were one to two orders of magnitude greater during wet weather compared to summer dry weather. This relationship persisted across five of the six reference beaches. Finally, summer dry weather had 30% more non-detectable samples than wet weather conditions.

The greatest frequency of water quality threshold exceedences occurred within 24 h of rainfall and steadily decreased for the next three days (Fig. 2). Twenty-seven percent of all samples collected <24 h of rainfall exceeded water quality thresholds for at least one indicator. This frequency of water quality threshold exceedences decreased to 21% of samples collected 1 day following

Table 2
Precipitation (inches) during nine storm events at six reference beaches during the 2004–2005 and 2005–2006 wet seasons.

Storm date	Site					
	Point Mugu[b]	Deer Creek[a,b]	Leo Carillo[a,b]	Dan Blocker[a]	San Mateo[c]	San Onofre[c]
10/27–10/30/04	–	1.31	1.31	1.31	–	3.07
12/5–12/8/04	–	0.41	0.41	0.41	–	0.39
1/29–2/1/04	–	0.44	0.44	0.44	–	0.16
2/12–2/15/05	–	2.04	2.04	2.04	–	2.44
10/18–10/21/05	1.02	–	1.02	–	1.97	–
1/1–1/4/06	1.94	–	1.94	–	0.87	–
2/19–2/22/06	0.8	–	0.8	–	0.31	–
2/28–3/3/06	1.87	–	1.87	–	0.87	–
3/12–3/15/06	0.11	0.11	0.11	0.09	0.35	0.35

[a] Malibu Big Rock rain gage.
[b] Leo Carillo rain gage.
[c] San Onofre rain gage.

Table 3
Frequency of water quality threshold exceedences for fecal indicator bacteria: Total Coliform (Total), *E. coli*, *Enterococci* (Entero), Total Coliform:*E. coli* (TC:FC), and Any Indicator (Any). Expressed as% Days at reference beaches during Wet, Winter Dry, and Summer Dry weather – see text for Dry Weather data sources.

Reference beaches	Weather type	Total	*E. coli*	Entero	TC:FC	Any
Point Mugu State Beach	Wet[a]	5.0	0	5.0	0	5.0
	Winter dry[b]	0	0	0	0	0
	Summer dry[c]	<1	0	0	0	<1
Deer Creek Beach	Wet	0	0	0	0	0
	Winter dry	0	0	0	0	0
	Summer dry	0	0	0	0	0
Leo Carrillo State Beach	Wet	5.6	8.3	11.1	8.3	16.7
	Winter dry	0	0	0	0	0
	Summer dry	0	0	0	0	0
Dan Blocker Beach	Wet	5.0	10.0	10.0	0	15.0
	Winter dry	0	2.8	1.4	0	2.8
	Summer dry	–[d]	–	–	–	–
San Mateo State Beach	Wet	0	25.0	20.0	15.0	30.0
	Winter dry	10	10	10	0	20
	Summer dry	1.9	1.9	9.3	0	9.3
San Onofre State Beach	Wet	25.0	15.0	25.0	0	30.0
	Winter dry	0	6.7	6.7	0	6.7
	Summer dry	0	0	0	0	0
All Beaches	Wet	6.6	9.6	11.8	4.4	16.2
	Winter dry	0	1.4	1.4	0	1.4
	Summer dry	<1	<1	<1	0	<1

[a] Wet weather (<3 days after rainfall, this study).
[b] Winter dry weather (>3 days after rainfall, November to March).
[c] Summer dry weather (>3 days after rainfall, April to October).
[d] No data.

recorded rainfall, then 15% 2 days following recorded rainfall and ultimately declined to 3% of samples 3 days following recorded rainfall. This pattern of water quality threshold exceedences was repeated by virtually every bacterial indicator, but at varying levels of frequency. Enterococci exhibited the greatest rate of water threshold exceedences <24 h following recorded rainfall and the greatest persistence 3 days following a rain event. For example, the frequency of water quality threshold exceedences for total coliform, *E. coli*, enterococci, and total coliform:fecal coliform ratio within 24 h of recorded rainfall was 13%, 20%, 20%, and 7% of all samples, respectively, but enterococci was responsible for all of the exceedences recorded on day 3.

Exceedences of water quality thresholds for fecal indicator bacteria in wet weather occurred more than twice as frequently in large (>100 km^2) watersheds than in medium (25–100 km^2) watersheds, and more than four times as frequently than in small (<25 km^2) watersheds (Fig. 3). More than any other indicator, concentrations of enterococci were responsible for the majority of water quality threshold exceedences across all three watershed size categories, exceeding thresholds 22% of the time for large-sized watersheds, 9% for medium-sized watersheds and 5% for small-sized watersheds. Although total coliform and *E. coli* concentrations did not exceed water quality thresholds as often as did enterococci, they followed the same trend in terms of watershed size.

Early season storms resulted in a greater number of water quality threshold exceedences than late season storms (Fig. 4A). After combining all wet weather samples at all creeks, 18% of the samples from early season storms exceeded water quality thresholds for at least one indicator, while 15% of the samples from late season storms exceeded water quality thresholds for at least one indicator. Early season storms also had a greater frequency of exceedence of more than one threshold compared to late season storms. In fact, 63% of the samples that exceeded water quality thresholds during early season storms exceeded more than one threshold (i.e. *E. coli* and enterococci). In contrast, 67% of the samples that exceeded water quality thresholds during late season storms exceeded only one threshold.

Table 4
Enterococcus concentrations at reference beaches during wet, winter dry, and summer dry weather.

Reference beaches	Weather type	N	Non-detectable (%)	Maximum (per 100 ml)	Geomean (per 100 ml)
Point Mugu State Beach	Wet[a]	20	75	195	13.6
	Winter dry[b]	17	76	31	10.7
	Summer dry[c]	33	94	31	10.3
Deer Creek Beach	Wet	20	70	100	14.8
	Winter dry	16	75	1091	14.9
	Summer dry	32	84	10	10
Leo Carrillo State Beach	Wet	35	57	5460	17.2
	Winter dry	9	44	771	28.7
	Summer dry	26	73	30	10.7
Dan Blocker Beach	Wet	18	33	1400	24.2
	Winter dry	16	31	53	14.3
	Summer dry	–[d]	–	–	–
San Mateo State Beach	Wet	20	35	882	35.8
	Winter dry	13	8	158	29.4
	Summer dry	14	79	20	10.5
San Onofre State Beach	Wet	19	42	4884	37.6
	Winter dry	12	33	63	14.4
	Summer dry	14	79	64	11.4
All Beaches	Wet	132	53	5460	21.3
	Winter dry	83	47	1091	16.4
	Summer dry	119	83	64	10.5

[a] Wet weather (<3 days after rainfall, this study).
[b] Winter dry weather (>3 days after rainfall, November to March).
[c] Summer dry weather (>3 days after rainfall, April to October).
[d] No data.

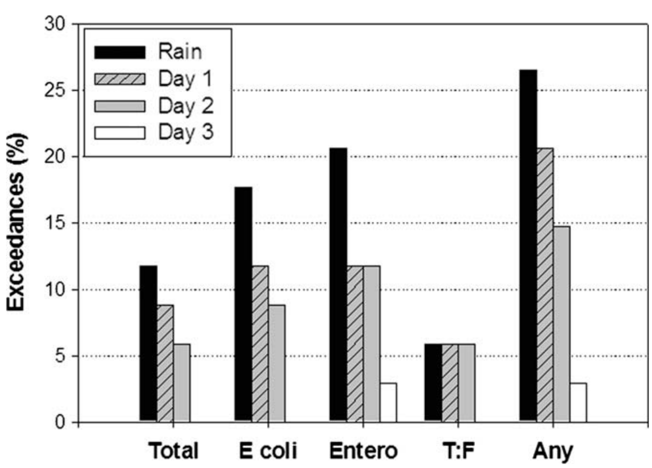

Fig. 2. Frequency of water quality threshold exceedences for fecal indicator bacteria: total coliform (Total), *E. coli*, enterococci (Entero), total coliform:*E. coli* (TC:FC), and any indicator (Any) within 24 h (rain), 24–48 h (day 1), 48–72 h (day 2), and 72–96 h (day 3) following rainfall at six reference beaches during the 2004–2005 and 2005–2006 storm seasons.

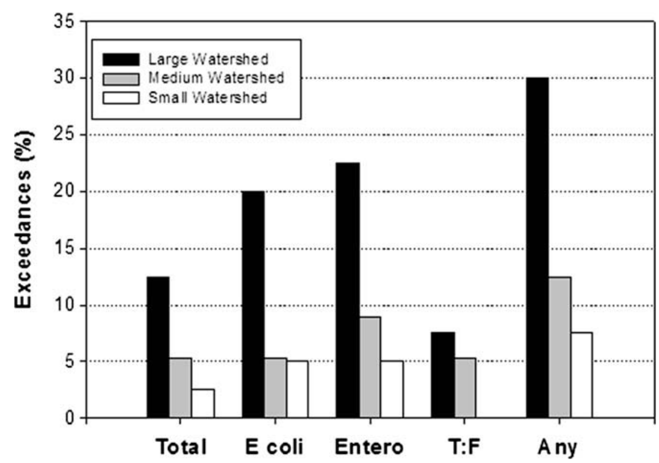

Fig. 3. Comparison of water quality threshold exceedences for fecal indicator bacteria: total coliform (Total), *E. coli*, enterococci (Entero), total coliform:*E. coli* (TC:FC), and any indicator (Any), in the wave wash with watershed size (small: 3–12 km^2, medium: 28–56 km^2, large: 110–346 km^2).

Larger storms resulted in a greater number of water quality threshold exceedences than small storms (Fig. 4B). After combining all wet weather samples at all creeks, 21% exceeded water quality thresholds for at least one indicator during large storms, compared to 12% of wet weather samples in small storms. This discrepancy between large and small storms was similar, or greater, for total coliform and enterococci thresholds and slightly lower for *E. coli*. For example, 16% of the enterococcus samples exceeded water quality thresholds following large-sized rainfall events compared to 7% during smaller-sized rainfall events. In contrast, the total coliform-to-fecal coliform ratio exhibited the opposite trend, exceeding water quality thresholds only 1% of the time after large storms and 7% after small storms.

One factor that accounted for the differences in water quality threshold exceedences observed between large and small-sized rainfall events was the ability to breach the sand berm and discharge across the reference beach (Fig. 5). Storms that were capable of producing sufficient flows to breach the sand berm were more than four times more likely to exceed water quality thresholds when flowing to the ocean compared to storms where the sand berm blocked flow across the beach. For example, almost 40% of the wet weather samples exceeded water quality thresholds for at least one indicator when the sand berm was breached compared to 12% of the samples when it had not breached. Similar patterns of threshold exceedence frequency were observed for each of the individual bacterial indicators.

At reference beaches that always breached the sand berm, the frequency of water quality threshold exceedences was low and

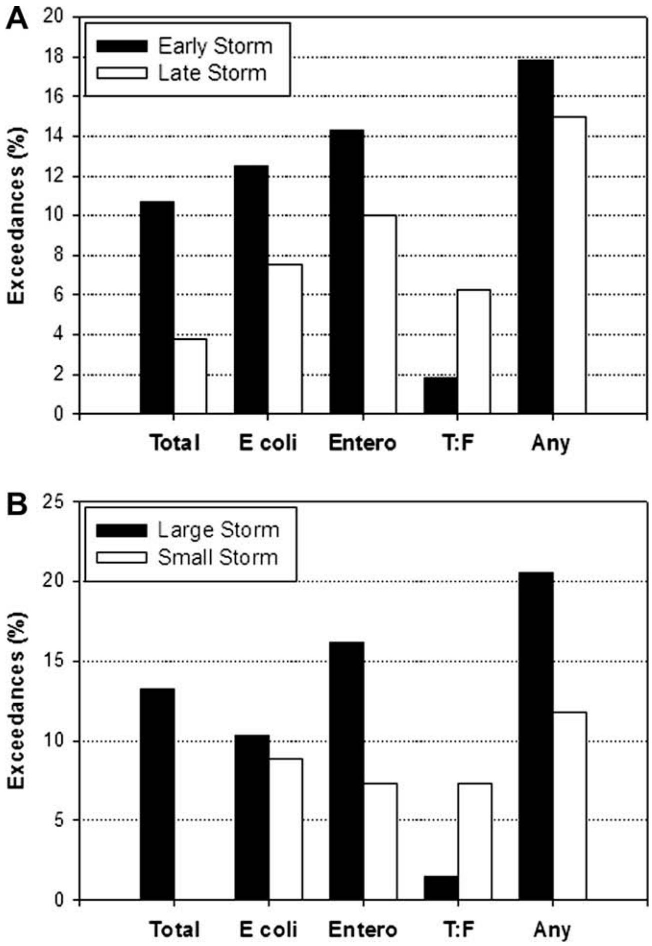

Fig. 4. Comparison of water quality threshold exceedences for fecal indicator bacteria: total coliform (Total), *E. coli*, enterococci (Entero), total coliform:*E. coli* (TC:FC), and any indicator (Any), <3 days rainfall at four reference beaches. (A) Early and late storm events. (B) Small and large storm events during the 2004–2005 and 2005–2006 storm seasons.

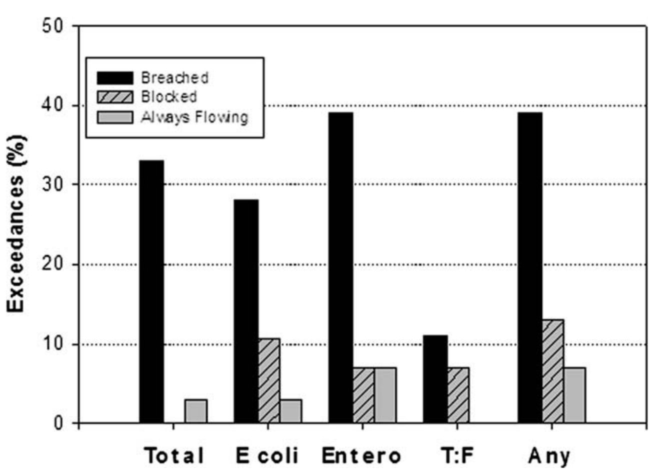

Fig. 5. Comparison of water quality threshold exceedences for fecal indicator bacteria: total coliform (Total), *E. coli*, enterococci (Entero), total coliform:*E. coli* (TC:FC), and any indicator (Any) at reference beaches when creeks behind the beach are always flowing or blocked behind a sand berm, and when the and berm is temporarily breached.

similar to when the sand berm had not been breached at the more intermittent beaches (Fig. 5). For example, 8% of the enterococcus samples exceeded water quality thresholds both at sites where the

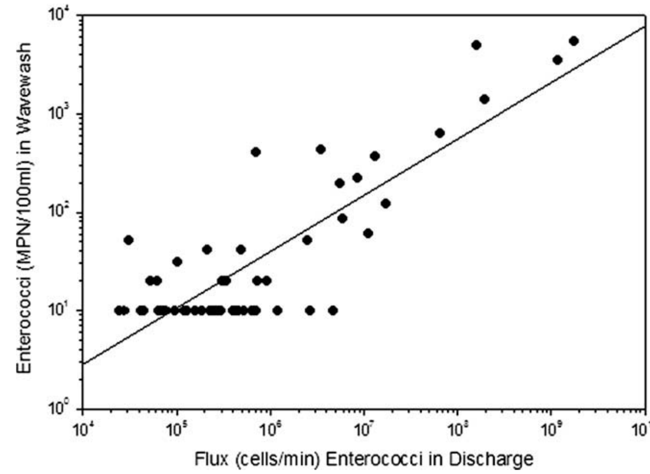

Fig. 6. Enterococci concentrations in the wave wash compared to flux from undeveloped watersheds discharging to reference beaches.

berm was always breached (i.e. Deer Creek and Dan Blocker Beaches) and at sites when the berm was not breached (i.e. Leo Carrillo and San Onofre State Beaches). Beaches that always breached were characterized as relatively small and lacked lagoon systems at their termini.

Discharges from reference watersheds appeared to be the predominant source of fecal indicator bacteria at reference beaches during wet weather. For example, concentrations of enterococci in the wave wash were positively correlated to the flux of enterococci in the discharge from their respective undeveloped watersheds (Fig. 6). The flux of enterococci from undeveloped watersheds could explain roughly 73% of the variation observed in concentrations of this indicator in the wave wash ($r^2 = 0.73$). This suggests that land-based sources are likely the major contributor to concentrations of enterococci in the wave wash when creeks are flowing.

In cases where there was a terminal lagoon, the watershed, not the lagoon, appeared to be the predominant source of fecal indicator bacteria when sand berms were breached (Fig. 7). The relationship between concentrations of fecal indicator bacteria in the discharge across the beach and in creek above the lagoon was near unity. Concentrations in the creek could explain between 93% and 99% of the variability for each of the three fecal indicator bacteria in the discharge ($r^2 = 0.99$, 0.99, and 0.93 for enterococci, *E. coli*, and total coliform, respectively). The relationship between concentrations of fecal indicator bacteria in the discharge across the reference beach and in the lagoon above the beach was also near unity. Concentrations in the lagoon could explain between 96% and 99% of the variability for each of the three fecal indicator bacteria in the discharge ($r^2 = 0.98$, 0.99, and 0.96 for enterococci, *E. coli*, and total coliform, respectively). The similarity of fecal indicator bacteria concentrations between the creek, the lagoon, and the discharge demonstrated that the lagoon had little influence on inputs to the ocean and was essentially a conduit for the creek during wet weather.

It appears that factors other than flow may be responsible for water quality exceedences at reference beaches with intact sand berms when storms are insufficient to breach berms (Table 4). For example, San Mateo Creek never breached its sand berm during the sampling period yet this reference beach had a similar frequency of bacterial water quality threshold exceedences as those of adjacent San Onofre Creek when its sand berm was breached. A possible reason for the large number of exceedences at this non-breached site was the large number of Western Gulls observed feeding on the beach during wet weather sampling (Table 4).

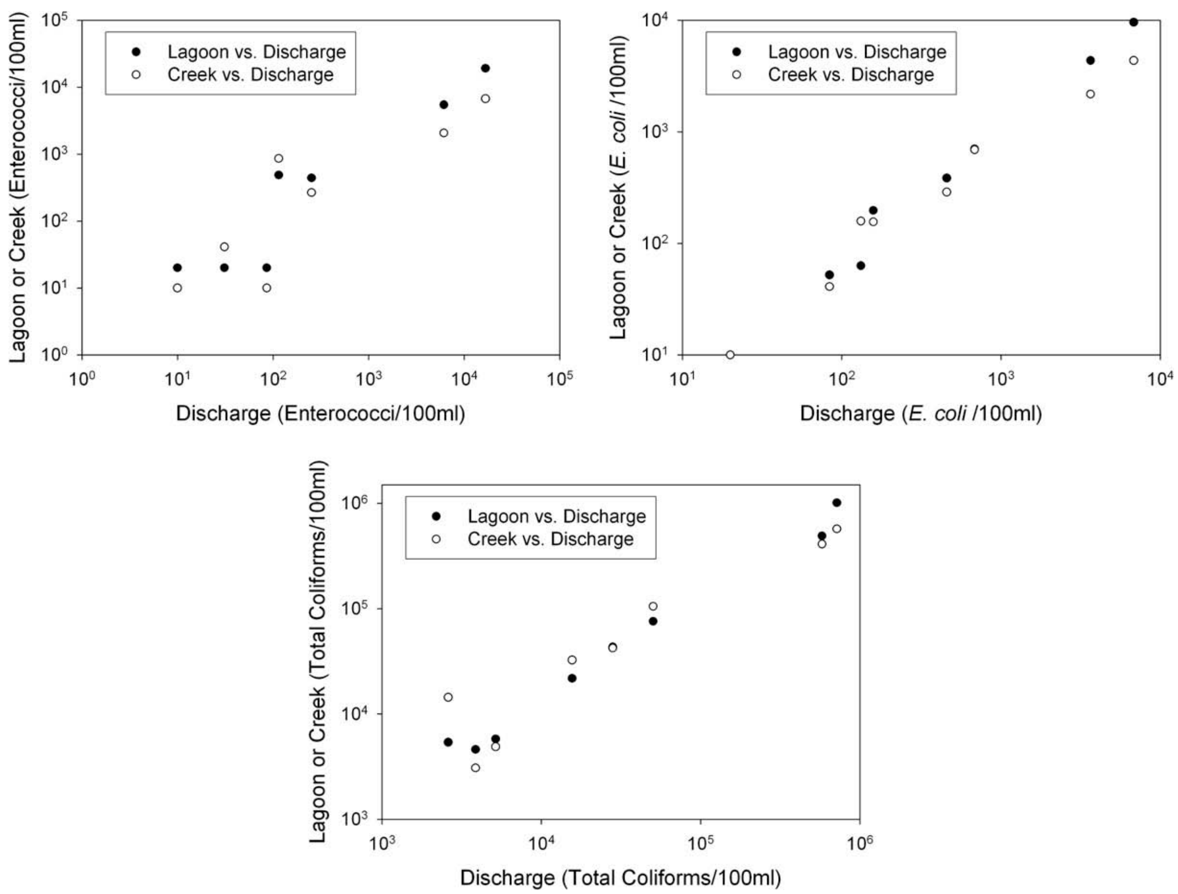

Fig. 7. Comparison of fecal indicator bacteria concentration in the discharge across San Onofre Beach to concentrations in San Onofre Creek and the San Onofre Lagoon.

4. Discussion

This study demonstrated that natural contributions of fecal indicator bacteria at beaches with minimal or no known human influence are sufficient to generate exceedences of the State of California water quality thresholds during wet weather. On average, one-fifth of all samples collected within three days of rainfall exceeded water quality thresholds for at least one bacterial indicator and these exceedences were observed at three-quarters of the reference beaches sampled. Concentrations of enterococci and *E. coli* led to exceedences of water quality thresholds most frequently, while total coliform and total coliform to fecal coliform ratios led to the least number of exceedences Table 5.

Wet weather discharges from undeveloped watersheds generally contributed to higher concentrations of fecal indicator bacteria along reference beaches relative to other times of the year. Moreover, concentrations of fecal indicator bacteria at the reference beaches were positively correlated with flux of indicator bacteria in the discharge draining from the undeveloped watersheds. Similar to this study, Schiff and Kinney (2001) found a large quantity of fecal indicator bacteria in wet weather discharges in similar-sized, almost entirely undeveloped watersheds, from inland San Diego County with no human activity.

Table 5
Average number of birds observed when water quality standards for enterococci were exceeded when lagoon was breached versus not breached.

	Lagoon breached		Lagoon not breached	
	# Exceedences	Avg. # Birds	# Exceedences	Avg. # Birds
Leo Carillo	4	24	–	–
San Onofre	4	<1	1	0
San Mateo	–	–	4	131

There were a number of interrelated factors that appeared to affect the flux of indicator bacteria from undeveloped watersheds and the resulting frequency of water quality threshold exceedences at reference beaches during wet weather. These included watershed size, storm size, and early vs. late season storms. Watershed size and storm size relate to a function of source strength and transport. Larger watersheds and larger storms both have the capability to generate and mobilize more bacteria from within the watershed. In fact, the largest storms at the largest watersheds generated the greatest frequency of water quality exceedences and for multiple fecal indicator bacteria thresholds. Smaller storms and/or smaller watersheds generated lesser bacterial flux and fewer beach exceedences resulted. Beach regulators could use this information to adaptively manage varying expectations for exceedence days at impaired beaches compared to the current regulatory approach of using long-term averages to set benchmarks.

A third interrelated factor was the presence of a lagoon and sand berm at the terminus of the creek. A significant increase in the frequency of water quality exceedences occurred when stable beach berms blocking lagoons were breached. This occurred consistently during large storm events. Conversely, when rainstorms were insufficiently large to break through stable beach berms, the frequency of water quality exceedences was reduced. The presence of the lagoon appeared to have little effect on the flux of indicator bacteria when the sand berm was breached; concentrations in the discharge across the beach were nearly identical to concentrations in the creek above the lagoon. However, the presence of the lagoon did appear to have an affect on water quality threshold

Please cite this article in press as: Griffith, J.F., et al. Microbiological water quality at non-human influenced reference beaches in southern California during wet weather. Mar. Pollut. Bull. (2009), doi:10.1016/j.marpolbul.2009.11.015

exceedences at the reference beach when storms were insufficiently large to breach sand berms. In this case, an increase in seabirds roosting on the beach near lagoons was observed with a concomitant increase in water quality exceedences. Birds have been implicated in bacterial water quality exceedences at other locations (Choi et al., 2003; Abdulreesh et al., 2004; Grant et al., 2001) and it is possible, at least in this case, the freshwater lagoon (particularly at San Mateo Creek) acts as a bird attractant, drawing birds to the beach where their dropping may be resuspended by wave and tidal action.

Seasonality also affected reference beach microbial water quality. Early season storms had a greater frequency of water quality exceedences compared to late season storm events, possibly from a "first flush" effect, which may have served to bring large amounts of accumulated debris and associated bacteria down to the beach from the upper reaches of watersheds. Additionally, early season storms had a greater magnitude of water quality threshold exceedences, exceeding by more than one indicator in the majority of the wet weather samples collected. In contrast, the vast majority of water quality exceedences in late season storms exceeded for only a single indicator.

One last factor affecting our ability to adequately disentangle factors contributing to concentrations of fecal indicator bacteria at references beaches is the detection of human enterovirus markers at San Onofre and Leo Carillo State Beaches and at Dan Blocker Beach. While virus was detected during a very small number of events that were excluded from our calculations, it cast a shadow of doubt regarding human contributions over the remaining storms at each of these sites. All of these watersheds were characterized by very little development (<3%), but virtually all of the watersheds in our study have some human trespass. Ultimately, the effects of non-human sources in lagoon systems, dispersed throughout large and small watersheds, and potential human contributions should be addressed before a complete understanding of natural source contributions will be known. A complete accounting of sources at these sites may not be forthcoming until more accurate technology for identifying and quantifying fecal sources is available.

The risk associated with wet weather discharges of non-human sources of fecal indicator bacteria, as well as with the detection of genetic markers for human enterovirus, is uncertain. Several epidemiology studies have examined the effect of increased fecal indicator bacteria on the risk of swimming-related illnesses (see Wade et al. (2003) for a review). Cabelli et al. (1982) found a relationship between enterococci and health effects at a marine bathing beach in New Jersey, but this beach was impacted by known point sources of human fecal pollution. Haile et al. (1999) found a relationship between indicator bacteria concentrations and health effects in those who swam near storm drains in Santa Monica Bay, but these drains were also known to contain human sources of fecal pollution. Colford et al. (2007) found no relationship between largely non-human sources of fecal indicator bacteria or genetic markers for human enterovirus and health effects in Mission Bay, a marine bathing beach in San Diego, but only examined dry weather. In this study, we quantified non-human sources of bacteria from non-point sources during wet weather, but we did not examine health risks. Epidemiological studies during wet weather need to be conducted in order to estimate the risk of swimming-related illnesses at reference beaches like those examined in this study.

Acknowledgements

We wish to acknowledge Stan Asato and Ioannice Lee at the City of Los Angeles, and Larissa Aumand and Rosabel Diaz at Weston Solutions, Inc., for their assistance with sample collection and analysis. Partial funding for this study was provided by the Los Angeles Regional Water Quality Control Board.

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