Influence of Variable Precipitation on Coastal Water Quality in Southern California

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ABSTRACT:

Objectives: To examine the consequences of changing precipitation levels on southern California's recreational coastal water quality, and compare the responses of watersheds with differing levels of urban development.

Methods: The geo-temporal relationship for six years (2000–2005) of precipitation levels, discharge rates for the ten primary waterways, and coastal water bacteria concentrations at seventy-eight southern California beaches were examined.

Results: Precipitation levels, river-creek discharge rates, and coastal water bacteria concentrations were significantly correlated ($p < 0.01$) for all ten watersheds investigated. Water bacteria concentrations significantly increased with higher levels of precipitation across 95% of the seventy-eight beaches investigated. A heavily developed watershed had significantly higher median bacteria concentrations (186 cfu) in the adjoining coastal waters compared to an undeveloped watershed (10 cfu) of similar size.

Conclusions: Precipitation and ensuing runoff strongly control the rate of polluted water delivered to most beaches in southern California. Variable precipitation generates a greater response in coastal water bacteria concentrations in developed watersheds compared to undeveloped areas. Projected declines in regional precipitation as a consequence of climate change may result in less contaminated water delivered to coastal waters, thus decreasing risk of water associated illnesses during winter months. *Water Environ. Res.*, **83,** 2121 (2011).

KEYWORDS: coastal water quality, indicator bacteria, precipitation, recreational marine bathing, urban runoff, climate change.

doi:10.2175/106143011X12928814444574

Introduction

Changing precipitation patterns as a consequence of climate change present a global and national public health concern (Epstein, 2005; Patz, 2000). One major concern is that increases in precipitation may lead to greater contaminant loads delivered to surface and recreational waters (Grum, 2006; Rose, 2001). As a result, regions predicted to have increased precipitation are expected to experience a greater health burden of waterborne diseases (Curriero, 2001; Greenough, 2001; Hunter, 2003; Patz, 2008; Schijven, 2005). An important public health concern is how climate change will impact the recreational coastal waters of southern California's 350 km coastline. This region has some of the world's most popular beaches that entertain more than 129 million beach visits annually, accounting for almost 60% of all beach visitations in the U.S. (Dwight, 2007).

Land-use patterns in watersheds have a direct impact on the quality of receiving waters. Population density, level and type of development, impervious surface area, and septic system prevalence, have all been found to be strongly associated with the quality of surface and recreational waters (Arnold, 1996; Field, 1993; Kay, 2008; Klein, 1979; Mallin, 2000; Selvakumar, 2006; Young, 1999). Given that southern California is one of the most highly urbanized and densely populated regions in the United States, with over twenty million residents, the anthropogenic influence on coastal water quality is substantial.

Pollution generated in southern California's watersheds is transported to coastal waters by urban (dry weather) runoff, discharged treated wastewater, and storm water runoff. Urban runoff is comprised of water that has passed over a developed landscape, and accumulated contaminants from a variety of residential and industrial sources. The sources of contamination in urban runoff vary among and within watersheds, but include permitted discharges, undetected sewage leaks, runoff from lawn and turf irrigation, car washings, illegally dumped chemical contaminants (pesticides, oil, paint, etc.), pet excrement, and numerous other factors in an urbanized landscape. The daily activities of millions of people in the region generate millions of gallons of contaminated leachate every day. The consequences of contaminated urban runoff on southern California's coastal water quality have been the focus of several investigations (Ackerman, 2003; Dwight, 2002; Noble, 2000; Reeves, 2004; Schiff, 2003).

Southern California beach water quality is also impacted by treated wastewater; more than 1.5 billion gallons per day are discharged into rivers and coastal waters. Despite efforts to eliminate risk from this waste stream via treatment, significant amounts of pathogens are released into recreational waters. The daily contributions of contaminants from urban runoff and wastewater discharges have a persistent, year-round influence on coastal water quality at some beaches.

The greatest fraction of Southern California's annual coastal water contaminate load is transported by storm water runoff during the winter months. Large portions of the landscape are covered by impervious surfaces (such as roadways, parking lots

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Table 1—Southern California Coastal Watersheds.

Watershed	Land Use	Urban	Size	Discharge		*Enterococcus*	
Los Angeles	Urban	61%	871	5,478	High	27	Medium
San Gabriel	Urban	38%	640	2,605	High	186	High
San Diego	Urban	19%	440	253	Medium	35	Medium
Santa Ana	Urban	14%	2800	26	Low	31	Low
Tijuana	Urban	na	1750	2	Low	52	High
San Juan	Mixed	4%	176	50	Low	3240	High
San Mateo	Undeveloped	0%	139	7	Low	23	Low
San Onofre	Undeveloped	0%	42	0	Low	4	Low
Santa Margarita	Undeveloped	0%	750	405	Medium	10	Low
San Luis Rey	Undeveloped	0%	558	287	Medium	47	Medium

Watersheds listed by level of urbanization.
Percent Urban (data source: USGS, 2001).
Watershed size (square miles).
Monthly Median Discharge (cubic feet per second): Low: 0–50 cfs; Medium: 51–500 cfs; High: >500 cfs.
Monthly Median *Enterococcus* Concentrations (colony forming units): Low: <25 cfu; Medium: 26–50 cfu; High: >50 cfu.

and rooftops), that deflect storm water to drains and channels. Runoff from precipitation events is not the source of pollution, rather it transports dissolved and suspended contaminates into storm drains, creeks and rivers, which ultimately discharge untreated near recreational beaches. Winter rain events wash the urban landscape, resulting in high levels of coastal water contamination at most beaches that far exceed the health standard. Storm water discharges during winter rain events differ from urban runoff during dry periods because the significantly higher volumes of discharge result in almost full coastal contamination prompting health officials to post mandatory health warnings at all beaches for three days following rain events. Precipitation's influence on coastal water quality has been shown in earlier studies for southern California (Ackerman, 2003; Digiacomo, 2004; Dwight, 2002; He, 2008; Noble, 2003; Schiff, 2003; Washburn, 2003), and other locations globally (Brownell, 2007; Crowther, 2001; Haramoto, 2006; Heijs, 2002; Hsu, 2008; McCarthy, 2007; Neumann, 2006; Soyeux, 2007).

Both storm water and dry weather runoff from urban landscapes can contain a range of toxic and pathogenic contaminants (Bay, 1996; Gaffield, 2003; Gold, 1991). Viruses, bacteria and protozoa in recreational waters have been associated with negative health outcomes in exposed swimmers. Epidemiology studies conducted globally have found statistically significant relationships between water bacteria concentrations and incidences of acute gastroenteritis in swimmers (Prüss, 1998; Saliba, 1990; Wade, 2003; Zmirou, 2003). Epidemiology studies conducted at open ocean beaches in southern California have also reported associations between illnesses in exposed subjects and water bacteria concentrations (Colford, 2009; Dwight, 2004; Haile, 1999). Several other illnesses are also associated with waterborne pathogens including respiratory, eye, ear, and skin infections. Serious diseases such as meningitis and septicemia are rare but do occur.

The public health burden from recreational water associated illnesses is considerable. A worldwide estimate of 120 million gastrointestinal illnesses and 50 million respiratory illnesses annually may result from swimming in polluted coastal waters (Shuval, 2003). In southern California, an estimated 1.4 million gastrointestinal and respiratory illnesses result every year due to swimming in contaminated recreational waters (Brinks, 2008). Accurate health burden measures are not available because surveillance of recreational water related illnesses is voluntary and passive, and is in need of a coherent regulatory framework for better beach management and protection of public health (Turbow, 2009).

Contamination of recreational waters is a current public health concern that is expected to increase in some regions as a result of climate change. To prepare for potential consequences of climate change in regards to recreational waters, it is imperative that factors influencing water quality be identified, their contribution quantified and potential interacting variables be evaluated. Previous studies have described the associations between precipitation, runoff and coastal water quality; and other investigations have reported watershed development levels to be associated with recreational water quality. The objective of this study was to investigate these associations over longer time periods, under different levels of precipitation, and for the entire southern California region with varying levels of watershed development being represented. Six years of variable climate condition data for the large geographic region provided the information to quantify the range of influence precipitation has on runoff and coastal water quality in the region.

Methods

Study Area. Southern California's coastal waters receive discharge from ten primary rivers and creeks, as well as several smaller creeks and numerous storm drain outlets. This investigation covered all the primary rivers and creeks for which discharge data were available (Table 1, Figure 1). This study also covered all recreational beaches which water quality data were available. Coastal southern California has a Mediterranean climate that is characterized by dry, warm weather for the majority of the year and a short wet season in the winter, punctuated by a few storm events. The region typically receives 55 cm (22 in.) in total rainfall. During the six-year period of this study the region experienced a range of winter weather with record precipitation in one year (2005), severe drought (2002), and years with more typical precipitation levels.

Southern California's coastal watersheds have a wide range of land-use practices within them. In the northern and far southern parts of the region are five highly developed watersheds—*Los*

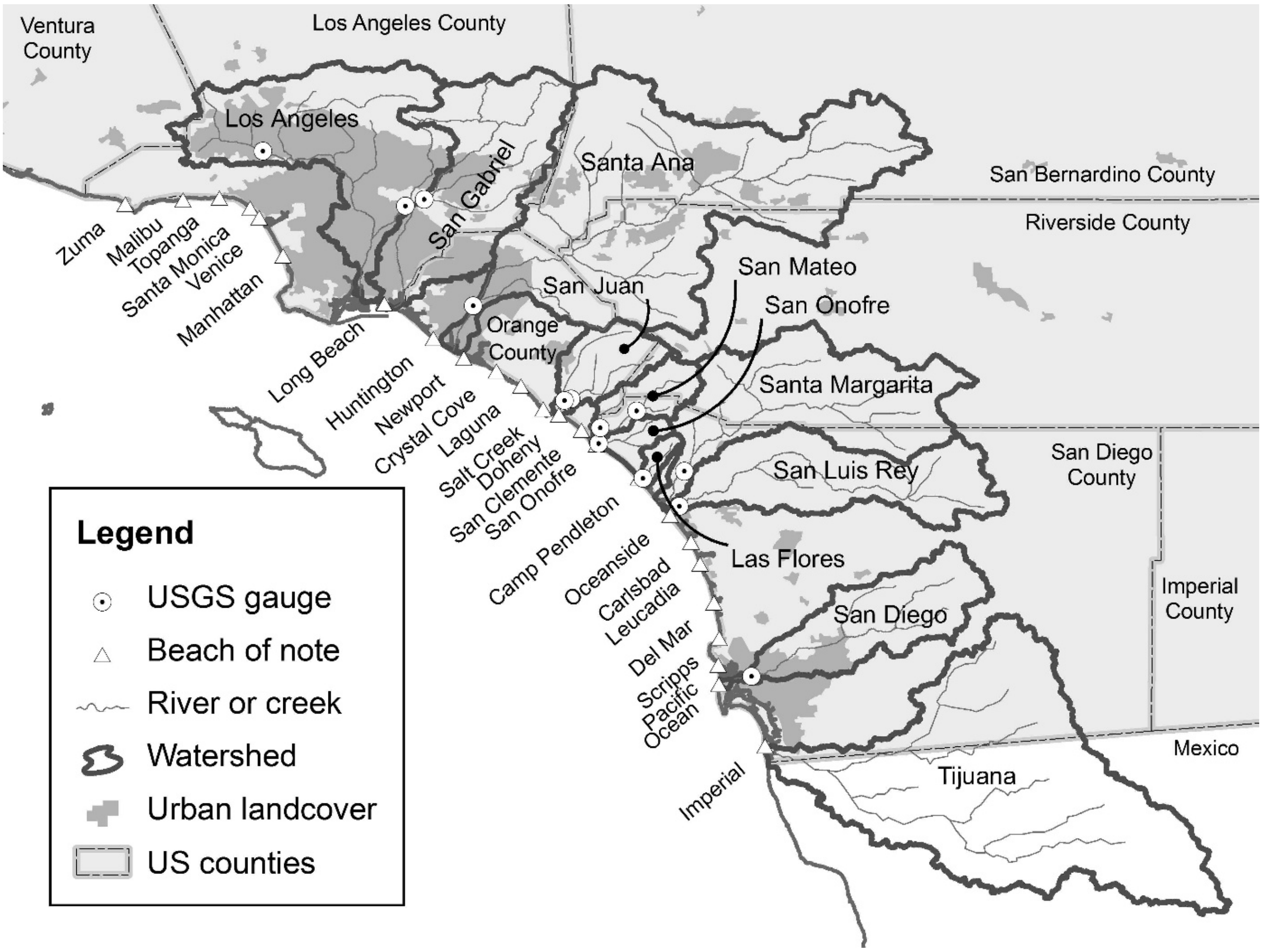

Figure 1—Southern California: Counties; Rivers and Creeks; Watershed Boundaries; Urbanization; and Select Beaches.
Image generated with USGS data: http://coastalmap.marine.usgs.gov/GISdata/basemaps/usa/urban/urbanap020.htm

Angeles, San Gabriel, Santa Ana, San Diego and *Tijuana* (Table 1; Figure 1). These five large urban watersheds have diverse land-use types, including intensive residential, commercial, industrial, military, and transportation (Anderson, 1976). Some of the developed watersheds also contain agricultural lands including crop, orchard, and confined feeding operations for cattle. The waterways in these watersheds have been channelized, dammed, and otherwise modified for flood control, water extraction, and groundwater replenishment. For the larger waterways water flow is regulated by reservoir releases and permitted discharges. For the two largest rivers (*Los Angeles* and *San Gabriel*), tertiary treated sewage is the primary source (80%) of dry weather flow, which provides a year-round base-flow level not experienced in the small water systems (SCCWRP, 2004). In the central part of the study area a military base, Camp Pendleton (506 km^2, extending along 27 km of coastline), has served as a restriction on urban development. The base includes the *San Mateo, San Onofre, Las Flores,* and *Santa Margarita* watersheds that are covered predominantly by shrub and brush range land (Table 1; Figure 1). These systems are used in this study as reference sites for comparison to the developed watersheds, except *Las Flores* watershed because there was no water quality monitoring station at a beach near the mouth. The uncontrolled rivers and creeks in southern California do not have perennial water sources, so flow is completely dependent on rain events and anthropogenic discharges.

Data Collection. Time series data on precipitation, river discharge (flow), and coastal water bacteria concentrations covering the six-year span from 1 January 2000 through 31 December 2005 ($n = 72$ months) were compiled. Precipitation data for the individual watersheds came from regional agencies responsible for rain surveillance (measured in fractions of an inch). River and creek discharge data (measured in cubic feet per second, or cfs) were collected for the ten watersheds identified in Figure 1. Daily discharge rates were taken from the U.S. Geological Survey surface water database with the exception of *Tijuana River*, which was available through San Diego State University. The *Los Angeles River* and *Santa Margarita River* were missing data for the first seven and twenty-one months, respectively; these periods were excluded from subsequent analyses.

California monitors its recreational marine water quality using a few different fecal indicator bacteria dependent on the discretion of local public health officials, and as dictated by state law. In 1999, California adopted recreational water criteria that standardized testing of coastal waters for indicator bacteria using approved methods. *Enterococcus* are the only fecal indicator bacteria to show a consistent relationship with health risk in recreational marine waters (Prüss, 1998; Saliba, 1990; Wade, 2003; Zmirou, 2003), and it is also the only indicator recognized as valid by the U.S. EPA and the World Health Organization.

Coastal *Enterococcus* concentrations were collected from 285 monitoring stations at seventy-two open ocean beaches and six embayments (harbors) in Los Angeles, Orange and San Diego counties (Figure 1). This data set covers all primary and secondary beaches on the coastline; water quality is not monitored at a few secluded beaches. Data were provided by county public health agencies as single sample values measured in colony forming units (cfu) per 100 ml of sampled seawater. Data were not available for all days; sampling intervals ranged from one to five times per week. Most beaches had one monitoring station while larger beaches had several stations (e.g., Santa Monica, Long Beach, Huntington, Newport, Laguna, Doheny, Oceanside, and Imperial beaches). All embayments had several monitoring stations. The mean value across all monitoring stations at each beach for each date was used in subsequent analyses.

Data Analyses. The strength of association between precipitation, flow, and *Enterococcus* concentrations were analyzed with correlation analyses ($\alpha = 0.05$). Kendall's tau coefficient was selected because the datasets were not normally distributed. Monthly sums for precipitation and river discharge, and monthly mean concentrations for *Enterococcus* concentrations at the beach closest to the river's mouth were used for statistical analyses ($n = 72$). To explore the influence of seasonality on the strength of association between variables, the dataset was stratified into wet months (≥ 25 mm) and dry months (< 25 mm) (Dwight, 2002). Correlations were evaluated for wet months, for dry months, and for the dataset in total.

To determine whether level of development influenced the strength of association between precipitation, river discharge, and bacteria concentrations in coastal waters, median monthly values of each variable were compared between two watersheds of similar size and different levels of urbanization (*San Gabriel* and *Santa Margarita*) using a paired Mann-Whitney test ($\alpha = 0.05$).

Annual means of precipitation, flow, and *Enterococcus* concentrations at beaches near outlets were compared among the ten watersheds investigated. Annual means of bacteria concentrations for all seventy-two beaches and six embayments were analyzed to investigate the influence of variable precipitation on coastal water quality. All statistical analyses were conducted using R. 2.7 or SPSS 12 statistical software.

Results

Overall Results. Simultaneous peaks in precipitation levels, river discharge rates, and coastal water bacteria concentrations occurred during the winter months across all study sites. Precipitation levels were similar across all watersheds over the six-year study period. Figure 2a shows the high level of similarity in precipitation for a watershed in the north of the study region, and one from the south. Although median discharge rates ranged widely for the rivers and creeks (Table 1), peak flows occurred simultaneously across sites and were tightly coupled to rain events (Figure 2b). Water quality also varied across the region by location (Table 1), though peak bacteria concentrations in recreational waters consistently occurred during high discharge periods in concert with rain events (Figure 2c).

Precipitation's association with Discharge. Precipitation and river and creek discharge rates were significantly correlated ($p < 0.001$) for all ten rivers and creeks investigated (Table 2). The correlations remained significant when stratified by months with high and low precipitation.

Discharge's association with Coastal Water Quality. River and creek discharge and coastal water bacteria concentrations were significantly correlated ($p < 0.01$) for the ten locations investigated (Table 2). Significant correlations were maintained for seven of the ten waterways during high precipitation months. There was no relationship between discharge rates and bacteria concentrations for the *Los Angeles*, *San Gabriel*, and *San Juan* during high and low precipitation months. The time series data for these three sites showed peaks in bacteria concentrations that did not correspond with increased discharge rates. The *Los Angeles* and *San Gabriel Rivers* are both regulated waterways with high inputs of treated sewage. The *San Juan Creek* watershed is unique to the region because it is small and relatively undeveloped (4% urbanized) (Table 1). Results for both high and low precipitation months found no association between creek discharge rates and bacteria concentrations at the beach nearest its outlet (Doheny beach). *San Juan Creek* had little to no discharge during either dry or wet months, yet Doheny beach experienced the highest levels of coastal water bacteria making it an outlier in this study.

Precipitation's association with Coastal Water Quality. Precipitation and water bacteria concentrations were significantly correlated ($p < 0.001$) for all ten beaches investigated near river mouths (Table 2). High precipitation months maintained strong correlations ($p < 0.05$) for seven of the ten locations. In wet months the correlations were strongest for the undeveloped watersheds and weaker for the developed watersheds. There was no significant relationship in wet months for three waterways; *Los Angeles*, *San Gabriel*, and *San Juan*, reflecting the fact that all three locations experienced increased bacteria concentrations that were not accompanied by precipitation events. Low precipitation months had weak associations for in *Los Angeles, Santa Ana, San Mateo*, and *San Onofre* watersheds. The two large urbanized watersheds (*Los Angeles* and *Santa Ana*) experienced large peaks in water bacteria concentrations that were not accompanied by precipitation events. This would imply other significant sources of pollution exist for these sites during the majority of the year. In contrast, the two creeks that drain undeveloped watersheds (*San Mateo* and *San Onofre*) had small peaks in precipitation that did not generate spikes in bacteria concentrations. This may have been because rainfall was retained within the watershed and produced no measurable flow.

Variable Precipitation and Coastal Water Quality. Over the six study years, southern California experienced a wide range in precipitation levels, which directly influenced the amount of runoff to the coastal waters and the levels of bacteria measured at beaches. Data plots from three representative years visually demonstrate the effect of variable precipitation on coastal water quality: a drought year with 23 cm of rain (2002); a typical

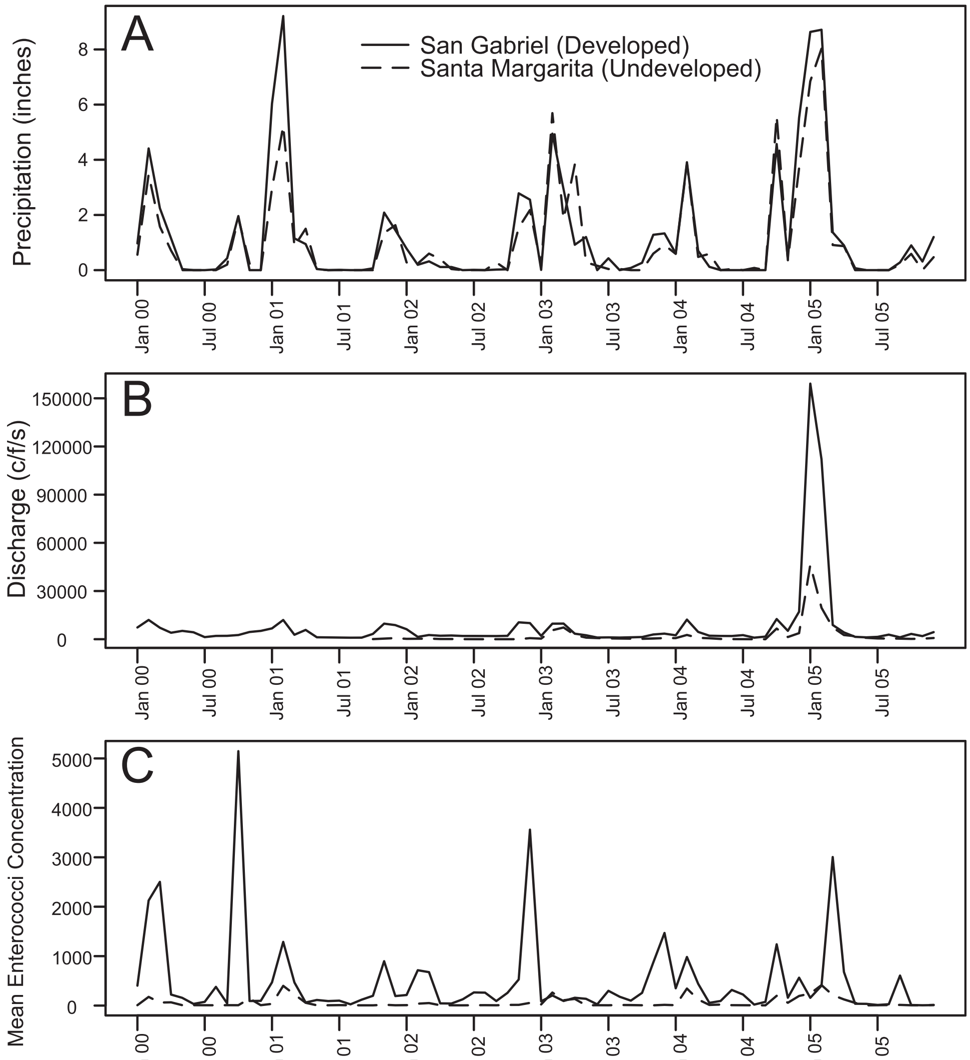

Figure 2—Developed and Undeveloped Watersheds of Comparable Size: A) Precipitation; B) Discharge; C) *Enterococcus* Concentrations at the Beach.

rainfall year with 41 cm (2001); and a high precipitation year with 79 cm of precipitation (2005), (Figure 3). The overlapping bars in Figure 3 (lowest value in foreground and highest value in back) represent annual mean bacteria concentrations for each beach in the representative years. The black bars correspond to the mean bacteria levels during a drought year, and tend to be the lowest. The grey bars represent mean water quality during a typical year of precipitation, and tend to be higher than the black bars. The white bars represent the mean water quality during a year with high precipitation levels, and tend to be the highest. The pattern is most consistent in San Diego County beaches (right side of Figure 3).

Variation in annual rainfall resulted in a wide range of mean water quality across different beaches, but the water quality was generally driven by precipitation across the region. Increasing precipitation was significantly associated with increased bacterial concentrations ($p < 0.01$) for 74 of the 78 beaches investigated (95%). However, a few beaches (22%) had consistently low bacteria levels regardless of the amount of rainfall in any given year: clean beaches remained clean despite variability in precipitation (center of Figure 3). A small number of beaches (e.g., Doheny) had consistently high bacteria levels regardless of changes in precipitation (center right of Figure 3). Precipitation's weak association with water bacteria concentrations at the consistently polluted sites implies that those sites are impacted by sources other than storm water runoff.

The lowest bacteria concentrations were observed during the drought year when 44 of 78 beaches (56%) had relatively low ($<$ 50 *cfu*.) annual mean bacterial concentrations (black bars, Figure 3). In the year with moderate precipitation (gray bars) only 26% of beaches maintained bacterial concentrations below 50 cfu; while in the year with record rainfall (white bars), only 13% of beaches had that level of water quality.

Level of Development and Coastal Water Quality. Winter rains resulted in the largest peaks in coastal bacteria concentrations across all ten beaches at the mouths of rivers and creeks investigated, regardless of the land-use within the watershed. However, the magnitude of peaks in bacteria concentrations

Table 2—Southern California 2000–2005: Kendall tau correlations coefficients (*r*) for data: Precipitation; Discharge Rates; and Bacteria Concentrations at the Beach.

Precipitation and Discharge

Rivers / Creeks	Total	High	Low
Los Angeles	0.660***	0.654***	0.373**
San Gabriel	0.606***	0.631***	0.354**
Santa Ana	0.743***	0.556**	0.613***
San Juan	0.619***	0.519***	0.496***
San Mateo	0.502***	0.415**	0.407***
San Onofre	0.583***	0.517**	0.328*
Santa Margarita	0.491***	0.636**	0.367**
San Luis Rey	0.458***	0.556**	0.387***
San Diego	0.727***	0.775***	0.598***
Tijuana	0.773***	0.548**	0.727***

Discharge and Bacteria Concentrations

Rivers / Creeks	Total	High	Low
Los Angeles	0.247**	0.195	0.056
San Gabriel	0.322***	0.012	0.131
Santa Ana	0.433***	0.725***	0.168
San Juan	0.257**	−0.239	0.202
San Mateo	0.513***	0.623***	0.248*
San Onofre	0.546***	0.505**	0.264*
Santa Margarita	0.478***	0.545*	0.342**
San Luis Rey	0.453***	0.608***	0.290**
San Diego	0.529***	0.676***	0.320**
Tijuana	0.539***	0.568**	0.323**

Precipitation and Bacteria Concentrations

Rivers / Creeks	Total	High	Low
Los Angeles	0.346***	0.255	0.200
San Gabriel	0.419***	0.036	0.251*
Santa Ana	0.432***	0.464**	0.175
San Juan	0.411***	−0.004	0.319**
San Mateo	0.489***	0.454**	0.158
San Onofre	0.451***	0.468**	0.135
Santa Margarita	0.501***	0.647***	0.325**
San Luis Rey	0.544***	0.686***	0.376***
San Diego	0.507***	0.554**	0.299**
Tijuana	0.495***	0.421*	0.293**

River and creeks listed north to south.
Total = six years of data; High = months with $> =$ 25 mm of precipitation; Low = months with $<$ 25 mm of precipitation.
Levels of statistical significance: * = $p < 0.05$ ** = $p < 0.01$ *** = $p < 0.001$.
Precipitation data reported at less than 1/100 of a inch.
Discharge data reported as cubic feet per second.
Bacteria Concentration data reported as *Enterococcus* colony forming units per 100 ml seawater.

differed between the urban and undeveloped watersheds. Median beach bacteria concentrations tended to be higher at the developed watersheds compared to the undeveloped watersheds (Table 1). Of the five rivers that drain urbanized watersheds (*Los Angeles, San Gabriel, Santa Ana, San Diego*, and *Tijuana*), median bacteria concentrations ranged from high and medium levels, and one had low levels. In contrast, one undeveloped watershed (*San Luis Rey*) had medium levels of beach water quality, and the three other undeveloped watersheds (*San Mateo, Santa Margarita,* and *San Onofre*) had low to median bacteria levels. Again, the relatively undeveloped *San Juan Creek* was unique because the median bacteria levels at the beach nearest it's outlet (Doheny) were the highest of the ten in the region.

The physical size of a watershed can influence its water quality; therefore, area should be controlled for when evaluating the influence of watershed development on water quality. The watersheds of southern California vary in size and level of development, making comparisons difficult (Table 1). However, one pair of watersheds is of similar size but differing in land-use: the *San Gabriel* watershed (640 m^2) is highly developed, and the larger *Santa Margarita* watershed (750 m^2) is relatively undeveloped. The *Santa Margarita* watershed is influenced by human impacts, but it contains a negligible amount of urban land cover (Table 1).

The *San Gabriel* and *Santa Margarita* watersheds received similar amounts of precipitation over the six year study period (Figure 2-A). Median precipitation was slightly higher in *San Gabriel* watershed (0.29 in) than in *Santa Margarita* watershed (0.26 in); Mann-Whitney U = 449; $p < 0.003$. Although these watersheds were of comparable size, *San Gabriel River's* median monthly total discharge (2,605 cfs) was more than six times

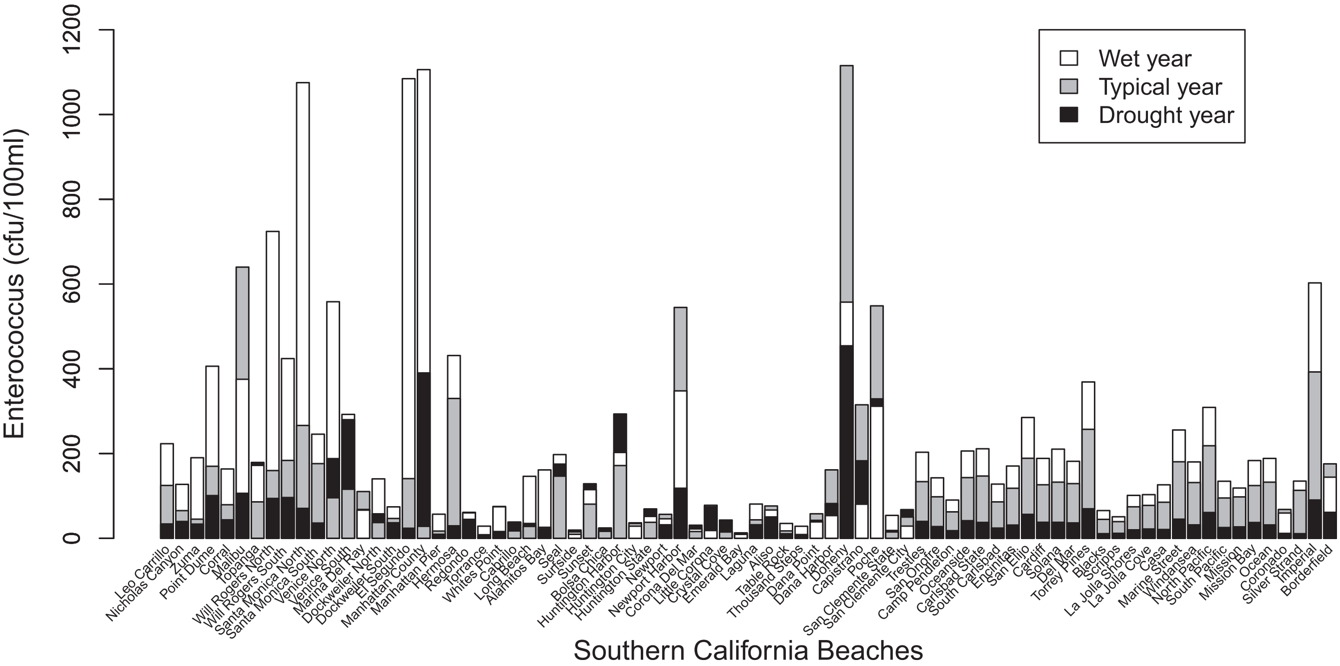

Figure 3—Annual Mean *Enterococcus* Concentrations for 78 Southern California Beaches in Three Years of Variable Precipitation: Drought Year (2002); Typical Year (2001); Wet Year (2005).
Bars overlap with lowest value in foreground and highest value in back
Black Bars = Mean annual bacteria concentration in 2002 drought year with 23 cm of precipitation
Grey Bars = Mean annual bacteria concentration in 2001 typical year with 41 cm of precipitation
White Bars = Mean annual bacteria concentration in 2005 wet year with 79 cm of precipitation
Beaches are listed north to south
Los Angeles County beaches: Leo Carrillo to Long Beach (left)
Orange County beaches: Seal to San Onofre (center)
San Diego County beaches: Camp Pendleton to Boarder Field (right)

greater than the *Santa Margarita River* (405 cfs); Mann-Whitney U = 3; $p < 0.001$, (Table 1; Figure 2-B). The developed watershed generated higher discharge rates in part due to the consistent source of base-flow generated by permitted discharges (135 million gallons per day of treated wastewater), and in part due to the higher level of development, which generates larger peaks of storm water runoff.

The *San Gabriel* and *Santa Margarita* watersheds also produced significantly different bacteria concentrations at beaches near their respective outlets (Table 1; Figure 2-C). The monthly median bacterial concentrations were significantly higher for the developed *San Gabriel* watershed (186 cfu) compared to the undeveloped *Santa Margarita* watershed (10 cfu); Mann-Whitney U = 94; $p < 0.001$. By holding constant watershed size and precipitation, the influence of watershed development on coastal water quality becomes pronounced.

Variable Precipitation, Level of Development and Coastal Water Quality. Variable precipitation generated a differential response in coastal water quality for developed watersheds compared to undeveloped watersheds (Figures 2 and 3). Both watersheds received comparable precipitation levels, yet the developed *San Gabriel* watershed generated greater flow rates and higher bacteria concentrations in the coastal waters compared to the undeveloped *Santa Margarita* watershed (Figure 2). During dry years both watersheds had relatively lower runoff rates and lower bacteria concentrations, and both runoff and bacteria concentrations increased with increasing precipitation levels. However, the developed watershed experienced increased flow and bacteria levels at a far greater rate compared to the undeveloped watershed, which expressed a muted response to the changing precipitation levels over time.

Annual mean bacteria concentrations varied across most beaches in the years with high, typical and low precipitation (Figure 3). However, the intensity of change in water quality among years differed at beaches near outlets based on the level of development in the watershed. For all the study beaches, the variables watershed size, level of development, and population density, were stable during the three years presented; precipitation was the changing variable in that time. The less developed contiguous areas in south Orange County and north San Diego County (middle right, Figure 3), had relatively low levels of water contamination across all three representative years (excepting the three large peaks around Doheny). The consistently clean beaches contrast with the highly developed watersheds that drain to the beaches of Santa Monica Bay and north Orange County (left side, Figure 3), which experienced greater changes in mean annual bacteria concentrations over the same three years. Given that rainfall amounts were similar across all watersheds in each year, the range of coastal water contamination resulted from the different levels of development in their watersheds.

Discussion

Longitudinal data covering 2000–2005 document the strong association between precipitation, runoff waters, and coastal water quality for the southern California coastline. The analysis conducted expands beyond previous studies by investigating the geo-temporal associations by region, by individual watershed, and by specific beach. Six years of data also allowed for comparative analysis between years with different levels of precipitation.

Precipitation, Runoff and Coastal Water Quality. Southern California typically receives little rainfall annually, yet precipitation has a powerful influence on coastal water quality in the region. This conclusion is based on the strong correlations between the variables expressed across all watersheds and most beaches in the region (Table 2), and is supported by the data plotted in Figures 2 and 3. The two watersheds in Figure 2 demonstrate how rain, discharge and water quality data exhibit simultaneous peaks over time. Figure 3 shows the variability of mean water quality for all beaches with years of dramatically different levels of precipitation. For most of the southern California coastline the levels of contamination in recreational waters varied with changing precipitation levels: the worst water quality occurred when precipitation levels were highest. This finding is consistent with previous studies that have also reported levels of rainfall directly impacting the level of pollution found in southern California coastal waters (Ackerman, 2003; Digiacomo, 2004; Dwight, 2002; He, 2008; Noble, 2003; Schiff, 2003; Washburn, 2003).

Level of Development and Coastal Water Quality. Level of development within southern California watersheds directly influenced the quality and volume of water discharged into the recreational coastal waters. Higher bacteria concentrations were consistently found at beaches near highly developed areas, and the difference in water quality between developed and undeveloped watersheds was significant (Table 1, Figure 2). Less developed watersheds had little impact on coastal water quality in dry seasons, and only moderate impact during precipitation events. In contrast, rivers draining highly developed watersheds were associated with significant impacts on coastal water quality year round. In general, pollution levels were highest where population densities were greatest. This finding is consistent with previous studies that reported level of development within watersheds having a direct impact on water quality (Arnold, 1996; Kay, 2008; Klein, 1979, Mallin, 2000; Selvakumar, 2006; Young, 1999).

Interestingly, the association between precipitation and water quality was weaker for the developed compared to the undeveloped watersheds (Table 2). For example, the two most developed watersheds (*Los Angeles* and *San Gabriel*) had the weakest correlations between precipitation and water quality. These large river systems also had some of the most contaminated beach water of the coastline. The median monthly discharge from these two rivers is seven times greater than all the other rivers and creeks combined (Table 1). The primary source of dry weather flow for these two rivers is treated wastewater, providing a consistently high base-flow and contaminant load. Precipitation contributes only a small portion of the total volume of river flow, thus decoupling precipitation and coastal water quality. The result is weaker correlations as compared to the undeveloped watersheds, where flow and water quality are more tightly coupled to rainfall events.

Other variables can influence water quality in some regions, such as the timing of snow melt, or irrigation and agricultural practices. Snow-melt from the southern California mountains is captured in reservoirs and recharge basins, and has no influence on coastal water quality. Runoff waters from agricultural irrigation cannot increase in the region because the tightly controlled water delivery system is already maximized, and imported water allotments are federally mandated to decrease in the future. The expected trend is for decreased releases of dry weather runoff water from agriculture and urban areas due to enhanced water conservation efforts and increased regulation of polluted discharges. The capture and retention of dry weather runoff and storm water runoff would improve coastal water quality.

Variable Precipitation, Level of Development and Coastal Water Quality. Changes in precipitation levels had a stronger effect on water quality for the developed areas compared to undeveloped areas. This conclusion is based on results showing that an urbanized watershed had higher response to variable precipitation over multiple years compared to an undeveloped watershed. In support of this finding, the annual-scale response of water quality at all beaches to changing precipitation was greater at the developed watersheds compared to the undeveloped watersheds, regardless of how wet or dry the year was.

Climate Variability, Coastal Water Quality, and Public Health. Most climate change models predict the southern California region will experience decreased precipitation in the future. This study and others demonstrate how coastal water bacteria concentrations can change depending on the amount of rainfall delivered to the region. If precipitation levels decrease by a significant amount in the future, then the contaminate load delivered to recreational beaches would decrease, thus reducing risk to the beach swimming public.

The potential public health benefit of reduced risk from recreational waters would not be equally distributed along the coast. The influence of precipitation on water quality varies by level of development in the watershed upstream of each beach. Beaches near the more developed watersheds would see the greatest decrease in mean bacteria concentrations as a result of decreased precipitation. These are also the most highly-attended beaches and thus would provide the greatest potential overall health benefit from the improved water quality. If climate change causes decreased rain levels comparable to those experienced in the drought year of this investigation, then most beaches would have the potential for cleaner recreational waters similar to those reported during 2002 (black bars in Figure 3).

The strong relationship between precipitation and coastal water quality works both ways. If precipitation rates increase in the future, out of accordance with most model projections, the region would benefit in many ways from the increased availability of water. However, coastal water quality at most beaches would be negatively affected by greater bacterial loads delivered with the higher volumes of storm water runoff (white bars in Figure 3).

More than half of all recreational beach water exposures in southern California occur during the summer months when the water is warmer and people have available vacation time (Dwight, 2007). The enormous number of beach visitors in the summer results in the majority of recreational water associated illnesses to occur in the three summer months, and not in the winter when water bacteria concentrations are much greater (Brinks, 2008). Increases and decreases in precipitation during the winter months would not likely impact beach water quality during the summer. If average temperatures increase in the region as projected by climate models, recreational water associated illnesses could increase in the summer months due to higher visitation rates. This scenario may result in reduced risk from cleaner coastal waters in the winter, yet an increasing overall public health burden due to greater numbers of beach visitors responding to higher air temperatures.

There were a small percentage of beaches that maintained very low bacteria concentrations regardless of precipitation level (Figure 3). Future variability in precipitation is expected to have little impact on water quality at those beaches, as they would remain clean regardless. There were also a few beaches that were consistently polluted regardless of changes in precipitation levels, such as Doheny beach. Future variability in precipitation would have little impact on coastal water quality at these beaches because their current pollution sources already overwhelm any effect of variable rainfall. Beaches with high bacteria concentrations during dry weather are typically located near sewage outfalls (e.g., Doheny beach, south Huntington Beach), or other constant sources of contamination such as treated sewage flowing from the Los Angeles and San Gabriel Rivers.

The effect of precipitation on southern California's coastal water quality occurs in the winter months during the rainy season. In the winter, beaches have the lowest attendance levels of the year, and the ocean water is sufficiently cold to require a wetsuit for prolonged exposure. The primary beneficiaries from decreased winter rain related pollution would be the large surfing community who use the recreational waters despite the cold conditions of the winter.

Aside from the potential public health benefit from cleaner coastal waters explored here, the arid desert region of coastal southern California would face many challenges from decreased rainfall. This highly populated area may experience increased heat waves, decreased availability of potable water, increased wildfires, and more. Droughts have historically caused significant economic and environmental problems in the region. The prospect of prolonged drought would have tremendous negative effects on one of the United State's most productive and populated regions.

This study investigated the influence of precipitation on coastal water quality across space, but at finite points in time (annually) and across time at individual locations spanning the entire southern California coastline. Analysis of individual years found precipitation was similar across ten watersheds, yet variability in water quality was observed between watersheds with different levels of development. The urbanized areas had higher coastal water bacteria concentrations compared to the undeveloped areas. Analysis between years of high, moderate, and low precipitation (and urban development was relatively constant over the study time), variable precipitation had a significant influence on coastal water quality and stream flow across most sites, but the magnitude of influence precipitation had on coastal water quality varied by the level of development within the contributing watershed. The undeveloped watersheds express a small but measurable response in coastal water bacteria concentrations for different levels of rainfall, remaining low regardless of rainfall and stream flow. However, water quality near the urbanized watersheds responded to variable precipitation strongly, with more rainfall delivering greater pollution loads to the recreational coastal waters. Using the drought year as a surrogate for a drier future climate, we conclude that decreased rainfall would result in smaller pollution loads being delivered to the coastal waters.

Conclusion

Precipitation and ensuing runoff strongly control the rate of polluted water delivered to most beaches in southern California. Variable precipitation generates a greater response in coastal water bacteria concentrations in developed watersheds compared to undeveloped areas. Projected regional declines in precipitation as a consequence of climate change may result in less contaminated water delivered to coastal waters, thus decreasing risk of water associated illnesses during winter months.

Revision submitted December 12, 2010.

References

Ackerman D.; Weisberg S. B. (2003) Relationship between Rainfall and Beach Bacterial Concentrations on Santa Monica Bay Beaches. *J Water Health*, **1** (2), 85–89.

Anderson, J. R.; Hardy, E. E.; Roach, J. T.; Witmer, R. E. (1976). A Land Use and Land Cover Classification System for Use with Remote Sensor Data. U.S. Geological Survey Circular 671, U.S. Department of the Interior.

Arnold, C.; Gibbons, J. (1996) Impervious Surface Coverage: The Emergence of a Key Environmental Indicator. *J. Am. Plann. Assoc*, **62**, 243.

Bay, S. M.; Greenstein, D. J. (1996) Toxicity of Dry Weather Flow from the Santa Monica Bay Watershed. *Southern California Academy of Sciences*, **95** (1), 33–45.

Brinks, M. V.; Dwight, R. H.; Osgood, N. D.; Sharavanakumar, G.; Turbow, D. J.; El-Gaouhry, M.; Caplan, J. S.; Semenza, J. C. (2008) Health Risk of Bathing in Southern California Coastal Waters. *Archives of Environmental and Occupational Health*, **63** (3), 123–325.

Brownell, M. J.; Harwood, V. J.; Kurz, R. C.; McQuaig, S. M.; Lukasik, J.; Scott, T. M. (2007) Confirmation of Putative Stormwater Impact on Water Quality at a Florida Beach by Microbial Source Tracking Methods and Structure of Indicator Organism Populations. *Water Research*, **41** (16), 3747–3757.

Colford, J. M. (2009) Screening Candidate Water Quality Indicators for Associations with Swimming-related Illness. *Proceedings of U.S. EPA National Beach Conference*, April 20–22, Huntington Beach, CA.

Crowther J.; Kay, D.; Wyer, M. D. (2001) Relationships between Microbial Water Quality and Environmental Conditions in Coastal Recreational Waters: The Fylde Coast, UK. *Water Research*, **35** (17), 4029–38

Curriero, F. C.; Patz, J. A.; Rose, J. B.; Lele, S. (2001) The Association between Extreme Precipitation and Waterborne Disease Outbreaks in the United States, 1948–1994. *American Journal of Public Health*, **91** (8), 1172–1174.

Digiacomo, P. M.; Washburn, L.; Holt, B.; Jones, B. H. (2004) Coastal Pollution Hazards in Southern California bserved by SAR Imagery: Stormwater Plumes, Wastewater Plumes, and Natural Hydrocarbon Seeps. *Marine Pollution Bulletin*, **49**, 1013–1024.

Dwight, R. H.; Semenza, J. C.; Baker, D. B.; Olson, B. H. (2002) Association of Urban Runoff with Coastal Water Quality in Orange County, California. *Water Environment Research*, **74** (1), 82–90.

Dwight, R. H.; Baker, D. B.; Semenza, J. C.; Olson, B. H. (2004) Health Effects associated with Recreational Water Use in Urban vs. Rural California, *American Journal of Public Health*, **94** (4), 565–567.

Dwight, R. H.; Brinks, M. V.; Sharavanakumar, G.; Semenza, J. C. (2007) Beach Attendance and Bathing Rates for Southern California Beaches, *Ocean and Coastal Management*, **50**, 847–858.

Epstein, P. R. (2005) Climate Change and Human Health, *New England Journal of Medicine*, **353** (14), 1433–1436.

Field, R.; O'Shea, M.; Brown, M. P. (1993) The Detection and Disinfection of Pathogens in Storm-generated Flows. *Water Science Technology*, **28** (3–5), 311–315.

Gaffield, S. J.; Goo, R. L.; Richards, L. A; Jackson, R. J. (2003) Public Health Effects of Inadequately Managed Stormwater Runoff, *American Journal of Public Health*, **93** (9), 1527–1533.

Gold, M.; Bartlett, M.; Dorsey, J.; McGee, C. (1991) Storm Drains as a Source of Surf Zone Bacterial Indicators and Human Enteric Viruses to Santa Monica Bay, Santa Monica Bay Restoration Project, August.

Greenough, G.; McGeehin, M.; Bernard, S. M. (2001) The Potential Impacts of Climate Variability and Change on Health Impacts of Extreme Weather Events in the United States, *Environmental Health Perspectives*, **109** (2), 191–198.

Grum M.; Jørgensen, A. T.; Johansen, R. M.; Linde, J. J. (2006) The Effect of Climate Change on Urban Drainage: An Evaluation based on Regional Climate Model Simulation. *Water Science Technology*, **54** (6–7), 9–15.

Haile, R. W., et al. (1999). (1999) The Health Effects of Swimming in Ocean Water Contaminated by Storm Drain Runoff, *Epidemiology*, **10** (4), 355–363.

Haramoto, E.; Katayama, H.; Oguma, K.; Koibuchi, Y.; Furumai, H.; Ohgaki, S. (2006) Effects of Rainfall on the Occurrence of Human Adenoviruses, Total Coliforms and Escherichia coli in Seawater, *Water Science Technology*, **54** (3), 225–30.

He, L. M.; He, Z. L. (2008) Water Quality Prediction of marine recreational beaches receiving watershed baseflow and stormwater runoff in southern California, USA, *Water Research*, **42** (10–11), 2563–2573.

Heijs, J.; Wilkinson, D.; Couriel, E. (2002) Project CARE: Reducing Wet Weather Overflows to Improve Beach Water Quality, *Water Science Technology*, **46** (6–7), 35–46.

Hsu, B. M.; Huang, Y. L. (2008) Intensive Water Quality Monitoring in a Taiwan Bathing Beach, *Environmental Monitoring Assessment*, **144** (1–3), 463–468.

Hunter, P. R. (2003) Climate Change and Waterborne and Vector-borne Disease, *Journal of Applied Microbiology*, **94**, 37S–46S.

Kay, D.; Crowther, J.; Stapleton, C. M. et al. (2008). (2008) Faecal Indicator Organism Concentrations and Catchment Export Coefficients in the U.K., *Water Research*, **42** (10–11), 2649–2661.

Klein, R. D. (1979) Urbanization and Stream Quality Impairment, *Water Resources Bulletin*, **15** (4), 953.

Mallin, M. A.; Williams, K. E.; Esham, E. C.; Lowe, R. P. (2000) Effect of Human Development on Bacteriological Water Quality in Coastal Watersheds, *Ecological Applications*, **10**, 1047.

McCarthy, D. T.; Mitchell, V. G.; Deletic, A.; Diaper, C. (2007) Escherichia coli in Urban Stormwater: Explaining their Variability, *Water Science Technology*, **56** (11), 27–34.

Neumann, C. M.; Harding, A. K.; Sherman, J. M. (2006) Oregon Beach Monitoring Program: Bacterial Exceedances in Marine and Freshwater Creeks/outfall samples, October 2002–April 2005, *Marine Pollution Bulletin*, **52** (10), 1270–1277.

Noble, R. T. (2000) A Regional Survey of the Microbiological Water Quality along the Shoreline of the Southern California Bight. *Environmental Monitoring and Assessment*, **64**, 435–447.

Noble, R. T. (2003) Storm Effect on Regional Beach Water Quality along the Southern California Shoreline, *Journal of Water and Health*, **1** (1), 23–31.

Patz, J. A.; McGeehih, M. A.; Bernard, S. M. (2000) The Potential Health Impacts of Climate Variability and Change for the United States: Executive Summary of the Report of the Health Sector of the U.S. National Assessment, *Environmental Health Perspectives*, **108** (4), 367–376.

Patz, J. A.; Vavrus, S. J.; Uejio, C. K.; McLellan, S. L. (2008) Climate Change and Waterborne Disease Risk in the Great Lakes region of the U.S., *American Journal of Preventative Medicine*, **35** (5), 451–458.

Prüss, A. (1998) Review of Epidemiological Studies on Health Effects from Exposure to Recreational Water, *International Journal of Epidemiology*. **27**, 1–9.

Reeves, R. L.; Grant, S. B.; Mrse, R. D.; Copil Oancea, C. M.; Sanders, B. F.; Boehm A. B. (2004) Scaling and Management of Fecal Indicator Bacteria in Runoff from a Coastal Urban Watershed in Southern California. *Environmental Science and Technology*, **38** (9), 2637–2648.

Rose, J. B.; Epstein, P. R.; Lipp, E. K.; Sherman, B. H.; Bernard, S. M.; Patz, J. A. (2001) Climate Variability and Change in the United States: Potential Impacts on Water- and Foodborne Diseases caused by Microbiologic Agents. *Environmental Health Perspectives*, **109** (Suppl 2), 211–221.

Saliba, L. J.; Helmer, R. (1990) Health Risks associated with Pollution of Coastal Bathing Waters. *World Health Statistics Quarterly*, **43**, 177–184.

Southern California Coastal Water Research Project. (2004) Dry Weather Water Quality in the San Gabriel River. www.sccwrp.org/view.php?id=260.

Schiff, K. C.; Morton, J.; Weisberg, S. B. (2003) Retrospective Evaluation of Shoreline Water Quality along Santa Monica Bay Beaches. *Marine Environmental Research*, **56** (1–2), 245–253.

Schijven JF, de Roda Husman AM, 2005, Effect of climate changes on waterborne disease in The Netherlands, *Water Science Technology*, **51**(5):79–87

Selvakumar, A.; Borst, M. (2006) Variation of Microorganism Concentrations in Urban Stormwater Runoff with Land Use and Seasons. *Journal of Water Health*, **4** (1), 109–124.

Shuval, H. (2003) Estimating the Global Burden of Thalassogenic Diseases: Human Infectious Diseases Caused by Wastewater Pollution of the Marine Environment. *Journal of Water Health*, **1** (2), 53–64.

Soyeux, E.; Blanchet, F.; Tisserand, B. (2007) Stormwater Overflow Impacts on the Sanitary Quality of Bathing Waters. *Water Science Technology*, **56** (11), 43–50.

Turbow, D. (2009) Addressing Disease Surveillance Needs for Marine Recreational Bathers. *Journal of Water and Health*, **7** (1), 45–54.

United States Geological Survey. (2001) National Land Cover Data. http://seamless.usgs.gov.

Wade, T. J.; Nitika, P.; Eisenberg, J. N.; Colford, J. M. (2003) Do US EPA Water Quality Guidelines for Recreational Waters Prevent Gastrointestinal Illness? A Systematic Review and Meta-analysis. *Environmental Health Perspectives*, **111**, 1102–1109.

Washburn, L.; McClure, K. A.; Jones, B. H.; Bay, S. M. (2003) Spatial Scales and Evolution of Storm Water Plumes in Santa Monica Bay. *Marine Environmental Research*, **56**, 103–125.

Young, K. D.; Thackston, E. L. (1999) Housing Density and Bacterial Loading in Urban Streams. *Journal of Environmental Engineering*, **125**, 1177.

Zmirou, D.; Pena, L.; Ledrans, M.; Letertre, A. (2003) Risks Associated with the Microbiological Quality of Bodies of Fresh and Marine Water used for Recreational Purposes: Summary Estimates based on Published Epidemiological Studies. *Archives of Environmental Heath*, **58**, 703–711.