# Association of Urban Runoff with Coastal Water Quality in Orange County, California

Ryan H. Dwight, Jan C. Semenza, Dean B. Baker, Betty H. Olson

**ABSTRACT:** The associations between storm events, urban runoff, and coastal water quality have not been well investigated. A temporal and spatial analysis of 2 years of data was conducted to determine associations between urban river discharge and indicator bacteria levels for Southern California beaches and evaluate the contribution of anomalous precipitation to the association. Data show beaches next to rivers had the highest bacterial levels in both wet and dry seasons. Bacterial levels rose substantially across all sites during wet months, and river discharge and bacterial levels were all highest during the winter with the most rainfall. Precipitation was significantly associated (Spearman rank bivariate correlation, $P < 0.01$) with water discharged from the rivers. River discharge was significantly associated with bacterial levels at 20 out of 22 beaches, with the strongest associations at sites next to rivers. The results indicate that urban river discharge is a primary source of Southern California's coastal water pollution and, as a result, swimming at beaches near rivers may pose a significant public health risk. The strong association found between precipitation and water pollution may be relevant to studies of potential health effects associated with climate change. *Water Environ. Res.,* **74,** 82 (2002).

**KEYWORDS:** urban stormwater runoff, coastal waters, indicator bacteria, El Niño, water quality, ocean, storm drains, climate change.

## Introduction

Polluted runoff from urban landscapes is an issue of increasing national concern for a range of interests including public health officials, policymakers, economists, engineers, urban planners, environmental scientists, and the general public. Polluted runoff is of particular concern when it is discharged into public recreational waters, such as coastal beaches, resulting in beach closures and public health risks. Because rainfall can affect the amount of runoff water in a region, it is relevant to determine whether there is an association between precipitation events and water quality over time in urban areas.

Coastal areas in the United States have been rapidly developed over the past century and coastal growth continues at a tremendous pace. A consequence of increasing development and population will be greater amounts of both point and nonpoint source pollution being released into local waterways. River and creek water quality is greatly influenced by land use in the surrounding watershed, and waterways can transport a wide range of pollutants for hundreds of kilometers. Watersheds covered by native vegetation can filter and degrade pollutants, while highly urbanized areas can contribute infectious and toxic chemical pollutants to the aquatic environment through nonpoint source urban runoff (Bay and Greenstein, 1996, and Gold et al., 1991).

Watershed-level research shows a direct association between increasing urban land use and increasing bacterial loading of runoff waters (Young and Thackston, 1999). For example, a study of five coastal estuarine watersheds found enteric bacteria levels decreased away from upstream areas, and bacterial levels in the water were strongly correlated with both population and the percent of land developed in the watershed (Mallin et al., 2000). However, the most important factor associated with levels of fecal coliforms was the amount of impervious surface area. Other researchers also support the use of impervious surface coverage as an important environmental indicator (Arnold and Gibbons, 1996, and Schueler, 1994).

The complex issues surrounding polluted urban runoff are being addressed at several levels in both the government and public sector. The U.S. Environmental Protection Agency (U.S. EPA) has established the Beaches Environmental Assessment, Closure and Health (BEACH) Program to facilitate consistency in beach health protection programs by providing public access to current reports, studies, and testing methods (U.S. EPA, 1997). In addition, the Natural Resources Defense Council (New York), an environmental organization, generates an annual report for the public that compiles national beach water quality data and provides the number and cause of beach closures that occurred in each state for that year (NRDC, 2001). California's state government has taken a leading role in dealing with the problems of urban runoff and coastal water quality by enacting legislation that standardizes not only testing methods and limits applied to measure coastal water quality, but also legislation for a uniform method of public notification of potential health risks. The U.S. Congress unanimously passed the Beaches Environmental Assessment and Coastal Health Act of 2000; however, necessary federal funding has not been appropriated to initiate the program. These activities have heightened questions regarding urban runoff and its potential health effects for humans using impacted recreational beaches.

California's greatest urban runoff problems are in the southern part of the state, where urban sprawl, ongoing development, and millions of residents generate pollution that is discharged to world renowned beaches, thereby exposing millions of people to the pollution. The northern beaches of Orange County, in particular, receive an enormous amount of urban runoff. Indeed, in a relatively small, 24-km (15-mile) area, Southern California's three largest rivers, the Los Angeles, San Gabriel, and Santa Ana Rivers, discharge to recreational waters (Figure 1). The combined watershed for these three rivers drains the majority of the Los Angeles basin, one of the world's most densely populated areas with more than 12 million residents (U.S. DOC, 1999) that encompasses a wide variety of land uses. Many of the watersheds within the basin feeding into North Orange County's coastal waters are covered by impervious surfaces, including storm drains and river beds, allowing for almost no remediation of pollutants. The result is a concentration of large quantities of untreated urban runoff that is directly discharged to coastal waters (Arnold and Gibbons,

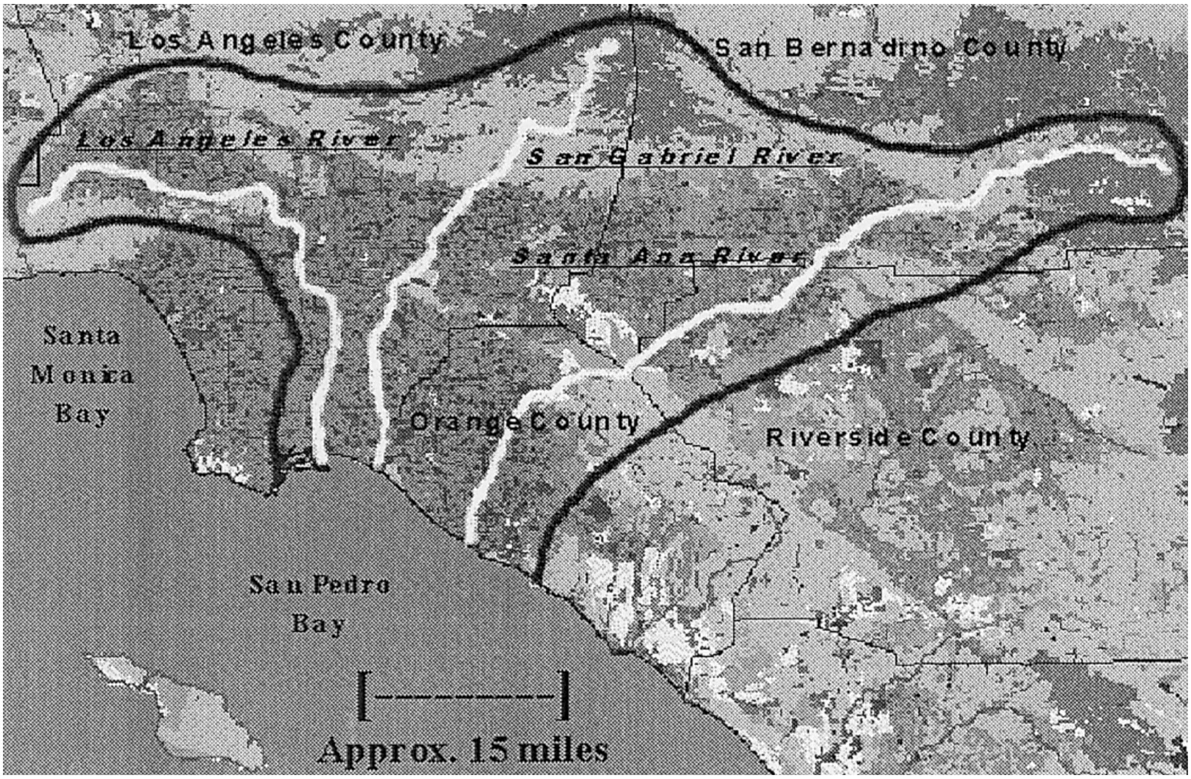


**Figure 1—Combined watershed areas for the Los Angeles, San Gabriel, and Santa Ana Rivers and North Orange County's coastline (mile × 1.609 = km). Source: *University of California, Davis.***

1996, and Schafer and Gossett, 1986 and 1988). The California Resource Agency (CRA, 1997) and the Southern California Coastal Water Research Project (Cross et al., 1991) have reported urban runoff as the most significant source of water pollution impacting coastal waters, estuaries, and bays in Southern California.

Researchers from several disciplines have investigated potential toxic and biological threats from urban runoff pollution in Southern California. A toxicological investigation of Southern California's largest rivers found river discharge volume to be significantly associated with concentration levels of all constituents measured (i.e., total suspended solids, cadmium, chromium, copper, nickel, lead, zinc, 1,1,1-trichloro-2,2-bis(*p*-chlorophenyl)ethane (DDT), and polychlorinated biphenyls [Cross et al., 1991]). The results indicate that the greater the volume of river flow, the higher the pollutant load that is transferred to the coastal zone. A 1993 microbiological study demonstrated the presence of pathogenic human enteric viruses in Los Angeles storm drains where there should be none (Field et al., 1993). An epidemiological investigation conducted in Santa Monica Bay found that people who swam directly in front of urban runoff storm drains were 50% more likely to report an illness than subjects who swam 370 m (400 yd) away (Haile et al., 1999).

Water quality is determined, and health risk predicted, by measuring levels of indicator bacteria. However, several researchers have questioned the validity of indicator bacteria as a measurement of potential health risk associated with recreational waters (Fleisher 1990 and 1991, and Nuzzi and Burhans, 1997). Although indicator bacteria are weak measures of potential health risk, most epidemiological studies have found a correlation between levels of indicator bacteria and rates of illnesses in the exposed population. Regardless, all epidemiological studies to date have been conducted in the dryer months and not during wet months when runoff flow, bacterial levels, and the number of beach closures are the highest (NRDC, 2001).

Although studies of river and coastal water quality have been conducted, the association between the volume of urban runoff and changes in coastal water quality over time has not been documented. The objective of this investigation was to determine if water quality indicators at different beaches along the North Orange County coastline changed in relation to discharge from the Los Angeles, San Gabriel, and Santa Ana Rivers, and how river discharge changed as a function of precipitation. Furthermore, any effects of extreme weather events on coastal water quality were also investigated because such effects, if found, might be relevant to future studies on the potential public health effects associated with climate change.

## Methods

**Data.** The study period encompassed 31 months from January 1997 through July 1999, which covered both the 1998 El Niño and 1999 La Niña Southern Oscillation, two meteorological phenomena that delivered extreme high and low precipitation levels to Southern California. Data from the El Niño year offer an example of what could occur if precipitation levels were to increase because of climate change, and data from the La Niña year offer a comparison dry season.

Mean monthly precipitation data for this period were obtained from the Western Regional Climate Center, Reno, Nevada. Two geographically representative sampling stations were chosen

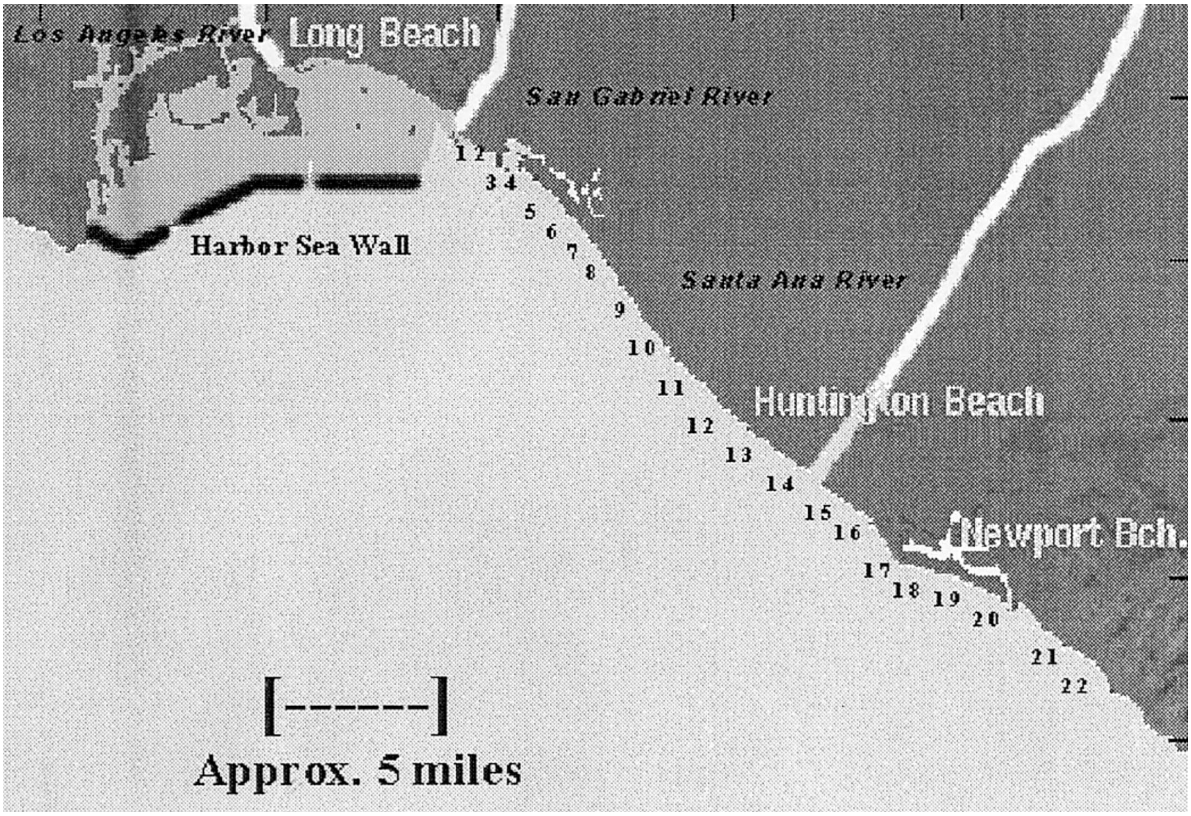


**Figure 2—Twenty-two monitoring stations along North Orange County's coastline (mile × 1.609 = km). Source: *University of California, San Diego.***

within each watershed to calculate the mean monthly rainfall per river watershed. The two stations representing the Los Angeles River were the Los Angeles Civic Center and the Burbank Valley Pump Plant. The San Gabriel River stations were the San Gabriel Fire Department and Montebello. The two stations for the Santa Ana River were the Newport Beach Harbor and the Santa Ana Fire Station.

River discharge data for the three rivers were collected by two different agencies and were provided as mean discharge per month. Discharge data for the Santa Ana River were collected by the U.S. Geological Survey in Santa Ana (station 11078000). Discharge data for the Los Angeles and San Gabriel Rivers were obtained from the Los Angeles County Department of Public Works. Los Angeles River data were collected at Firestone Boulevard (station F34D-R) and San Gabriel River data were collected at Spring Street (station F42B-R).

North Orange County's microbiological coastal water quality data were obtained from the Orange County Health Care Agency, Santa Ana, California. Total coliform was the indicator bacteria used to measure water quality because it was the only measure for which data existed for the entire study period. Five sites were sampled by the Orange County Health Care Agency and the rest were sampled by the County Sanitation District of Orange County, Fountain Valley, California.

A mean value per month was calculated from the values of the individual days sampled in that month. These calculations were conducted for each of the different North Orange County beach sites along the coast. Monthly means rather than daily values were used in the analysis because the number of samples collected per month ranged between 4 and 20, depending on the month, with summer months sampled more often than winter months. In addition, the two agencies had different sampling regimes in terms of the number of days they sampled per month and the days on which they sampled and, as a result, it was more reliable to use monthly means than daily data.

County officials collected water samples at 22 beaches along North Orange County's coastline approximately 1.6 km (1 mile) apart (Figure 2). Beginning north in Seal Beach, sampling site 1 was 1st Street, the first public beach south of the Los Angeles and San Gabriel river mouths. Sampling site 22 was Crystal Cove, which was approximately 13 km (8 mile) south of the Santa Ana River. Exact locations of the intermediate sites are given in Table 1.

**Statistical Analysis.** A spatial analysis was conducted of mean bacterial levels for the 22 beach sites over the entire 31-month study period. Because the seasonal weather pattern in Southern California typically consists of three winter months with moderate precipitation and 9 months of little to no precipitation, the data were stratified into dry months ($n = 20$) and wet months ($n = 11$), with a "wet month" defined as any month that received more than 25 mm (1 in.) of precipitation.

Temporal associations were also explored between precipitation levels and river discharge, and between river discharge and the bacterial levels found at different beaches. For the temporal analysis of water quality, discharge data for the Los Angeles and San Gabriel Rivers were combined because the Los Angeles River ends in the Long Beach Harbor and the harbor's main outlet is a 1.6-km (1-mile) opening that is next to the mouth of the San Gabriel River. Water from the two rivers and the Los Angeles and

**Table 1—Spearman's correlation coefficients (*r*) for mean monthly river discharge by mean monthly total coliform counts at 22 Orange County beach sites: calculated for total, wet, and dry months.**

| | | Spearman's correlation coefficient (*r*) | | |
|---|---|---|---|---|
| Sampling station | Location | Total ($n$ = 31) | Wet[a] ($n$ = 11) | Dry ($n$ = 20) |
| Sites near Los Angeles and San Gabriel Rivers | | | | |
| 1 | Seal Beach: 1st Street | 0.64[b] | 0.65[c] | −0.18 |
| 2 | Seal Beach: 8th Street | 0.66[b] | 0.43 | 0.15 |
| 3 | Seal Beach: 14th Street | 0.45[c] | 0.48 | −0.25 |
| 4 | Seal Beach: Sea Way | 0.30 | 0.01 | 0.06 |
| 5 | Sunset Beach: Broadway | 0.43[c] | 0.10 | −0.07 |
| 6 | Bolsa Chica Beach | 0.54[b] | 0.40 | 0.28 |
| 7 | Bolsa Chica Reserve | 0.64[b] | 0.30 | 0.24 |
| 8 | Huntington: Bluffs | 0.55[b] | 0.50 | 0.05 |
| Sites Near Santa Ana River | | | | |
| 9 | Huntington: 17th Street | 0.60[b] | 0.63[c] | 0.22 |
| 10 | Huntington: Jacks Shop | 0.60[b] | 0.50 | 0.35 |
| 11 | Huntington: Edison Plant | 0.25 | 0.39 | 0.03 |
| 12 | Huntington: Magnolia Street | 0.43[c] | 0.41 | −0.12 |
| 13 | Huntington: Brookhurst Street | 0.54[b] | 0.61[c] | 0.29 |
| 14 | Huntington: Santa Ana River | 0.73[b] | 0.74[b] | 0.32 |
| 15 | Newport: Orange Street | 0.67[b] | 0.73[b] | 0.01 |
| 16 | Newport: 52nd Street | 0.65[b] | 0.78[b] | −0.13 |
| 17 | Newport: 38th Street | 0.62[b] | 0.47 | 0.03 |
| 18 | Newport: 15th Street | 0.57[b] | 0.44 | −0.13 |
| 19 | Newport: Balboa Pier | 0.58[b] | 0.43 | 0.04 |
| 20 | Newport: The Wedge | 0.68[b] | 0.55 | 0.40 |
| 21 | Newport: Corona Del Mar | 0.43[c] | 0.26 | 0.14 |
| 22 | Crystal Cove | 0.55[b] | 0.36 | 0.20 |

[a] Months with more than 25 mm (1 in.) of rain.
[b] Correlation is significant with $P \ll 0.01$ (2-tailed).
[c] Correlation is significant with $0.01 \leq P < 0.05$ (2-tailed).

Long Beach harbors merges and flows south with prevailing currents onto the first of the beach sampling sites.

The three datasets were analyzed using Spearman rank bivariate correlations ($P < 0.01$) run with SPSS Science (Chicago, Illinois) statistical software. Spearman rank bivariate correlations were used because the data were not normally distributed.

## Results

**Spatial Pattern.** Beaches close to the river discharge points had the highest levels of total coliform indicator bacteria in both wet and dry months (Figure 3). During wet months, the highest total coliform bacteria levels were found at the two beaches closest to the rivers, sampling station 1 (1st Street) in Seal Beach and station 15 (Orange Street) in Newport Beach. The mean level of total coliform bacteria for the wet month was 150 times greater than the total coliform levels found at station 22 (Crystal Cove), the site farthest from the rivers. Beach sites within approximately 8 km (3 mile) of river discharge points all had mean total coliform bacteria levels greater than 1000 colony forming units (cfu)/100 mL, while concentrations at most of the sites farther away were well below that level. During dry months, mean bacterial levels dropped substantially across all sites; only station 3 (14th Street) in Seal Beach recorded a mean greater than 500 cfu/100 mL (Figure 3). Regardless, the same distribution pattern was evident during dry months with beaches near river discharge points having the highest total coliform bacteria levels (i.e., more than 10 times the levels at the farthest site). Station 21 (Corona Del Mar) and station 22 (Crystal Cove), the two sites furthest from the rivers, consistently registered the best water quality during both wet and dry months.

**Temporal Pattern.** Total coliform bacteria levels were much higher during wet months than dry months. This pattern was evident across all the beach sites, as shown in Figure 3. It is important to note that the wet month scale is 4.5 times greater than the dry month scale. In 1998, El Niño resulted in extreme precipitation for the Southern California region (expressed as the pronounced spike seen in Figure 4). Figures 4 through 6 show 2.5 years of data for mean precipitation, mean river discharge, and mean bacterial levels at beach sites next to the discharge points, stations 1 (1st Street) and 15 (Orange Street). Figure 4 shows the large changes that occurred over time in the amount of precipitation delivered to the Southern California region, which corresponded with large changes in the amount of river discharge and the levels of total coliform bacteria found in the coastal waters.

**Correlational Analysis.** Spearman rank bivariate correlations between mean precipitation per month and mean river discharge per month were analyzed during the entire study period and stratified by wet and dry months. During all months, precipitation and river discharge for each of the three rivers were significantly correlated as follows: Los Angeles and San Gabriel Rivers ($r$ = 0.89, $P < 0.01$) and Santa Ana River ($r$ = 0.80, $P < 0.01$). During wet months, in particular, precipitation and river discharge were correlated as follows: Los Angeles and San Gabriel Rivers ($r$ = 0.71, $P < 0.01$) and Santa Ana River ($r$ = 0.63, $P < 0.05$).

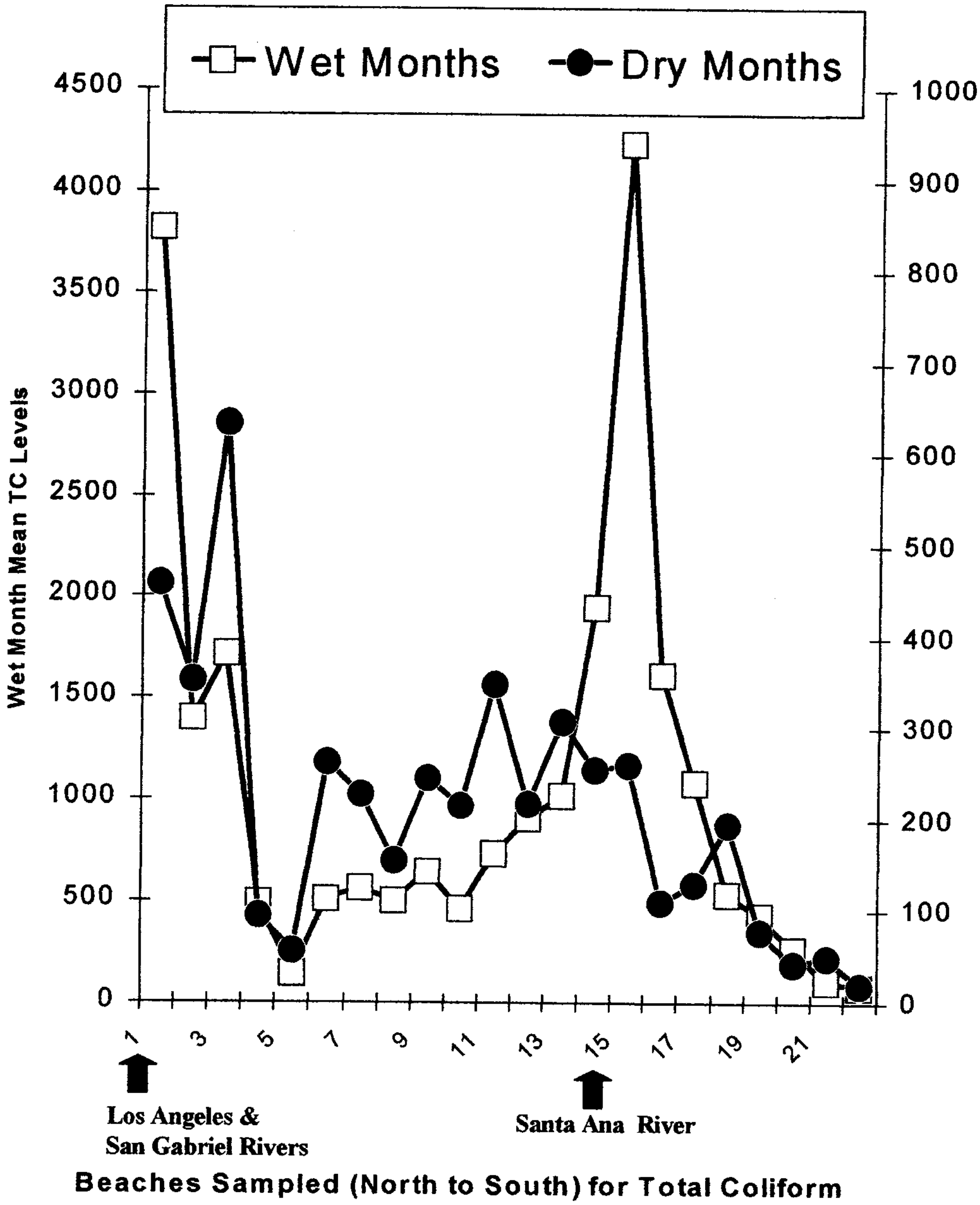


**Figure 3—Mean total coliform levels (cfu) for 22 sampling stations by wet and dry months for January 1997 to July 1999. Wet month scale is 4.5 times the dry month scale. Source: *Orange County Health Care Agency*.**

However, the correlations were not statistically significant during the dry months with the exception of the Los Angeles River, where river discharge remained correlated with precipitation ($r = 0.57$, $P < 0.01$). The decreased association between precipitation and river discharge during dry months is expected because there was little to no rain at the time to generate much runoff.

Table 1 presents Spearman ranked bivariate correlations between mean river discharge per month and mean total coliform bacteria levels per month for all 22 beach sites. River discharge was significantly associated with bacterial levels for almost all the beaches when analyzed over the entire time period, with the strongest associations found at the sites closest to the river discharge points, as follows: $r = 0.64$ for the combined San Gabriel and Los Angeles Rivers with total coliform levels at sampling station 1 (1st Street), and $r = 0.67$ for the Santa Ana River with total coliform levels at sampling station 15 (Orange Street) (both significant at the $P < 0.01$ level). When stratified by wet months, only beach sites near the rivers (and station 9) had significant correlations between total coliform bacteria levels and river discharge. There were no significant associations at any beach site during dry months.

The microbiological water quality data were also analyzed at the daily level (data not shown) to explore the effect of individual rain events on coastal water quality. This was an exploratory analysis because, as previously mentioned, daily water quality data were not systematically collected during the entire study period. Nevertheless, it was found that, following precipitation events, a plume of pollution registered as a pulse of indicator bacteria at beaches next to rivers. Over the course of time and distance the levels of bacteria decreased by means of dilution and degradation while

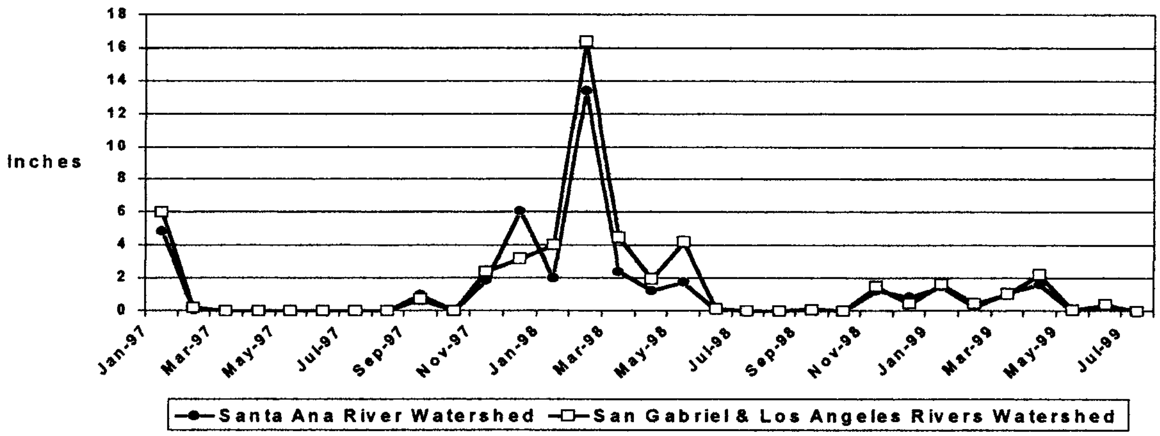


**Figure 4—Mean precipitation per month for Santa Ana River watershed and combined San Gabriel and Los Angeles Rivers watersheds (in. × 25.4 = mm). Source: *Western Regional Climate Center.***

being transported by prevailing currents to other area beaches. The total coliform bacteria levels and longevity of the plumes corresponded to the amount of precipitation in the area.

## Discussion and Conclusions

Results from this study demonstrate that a primary source of North Orange County's coastal water pollution is urban runoff discharged by the Los Angeles, San Gabriel, and Santa Ana Rivers. Each river contributes urban runoff pollution to North Orange County's beaches and the confluence of the three rivers greatly influences the levels of bacteria found in coastal waters. The significant association between precipitation and river discharge suggests the majority of river water is generated by precipitation events in the Los Angeles basin. The significant association between river discharge and coastal total coliform bacteria levels suggests the rivers are a primary, although not the only, source of total coliform bacteria in North Orange County's coastal waters.

In the summer of 1999, Huntington Beach suffered from extended beach closures, which the media reported as having a profound impact on coastal tourism, local revenues, and the area's reputation. After an exhaustive search for the source of the fecal-based pollution, Orange County officials suspected it was urban runoff. Results from this study support their suspicions that urban runoff from the Santa Ana River resulted in elevated indicator bacteria levels.

Furthermore, results from this study show that water at the beaches near these river mouths had much higher total coliform bacteria levels compared with the sites farther away. The beaches near the rivers also happen to be popular recreational locations in Seal Beach, Huntington Beach, and Newport Beach. Use of these beaches, with their consistently higher total coliform levels, may pose an appreciable public health risk. The site located farthest from the rivers was station 22 (Crystal Cove), which had the best water quality of all the sites throughout the year.

The public health threat from urban runoff represents a relatively new area of investigation. Previously, most epidemiological studies focused on recreational waters contaminated with treated and untreated domestic wastewater (Pruss, 1998, and Saliba, 1990). All but a few of those studies found significant associations between water pollution indicators and the incidence of infections within exposed subjects. The general consensus is that recreational contact with wastewater-contaminated waters is a public health

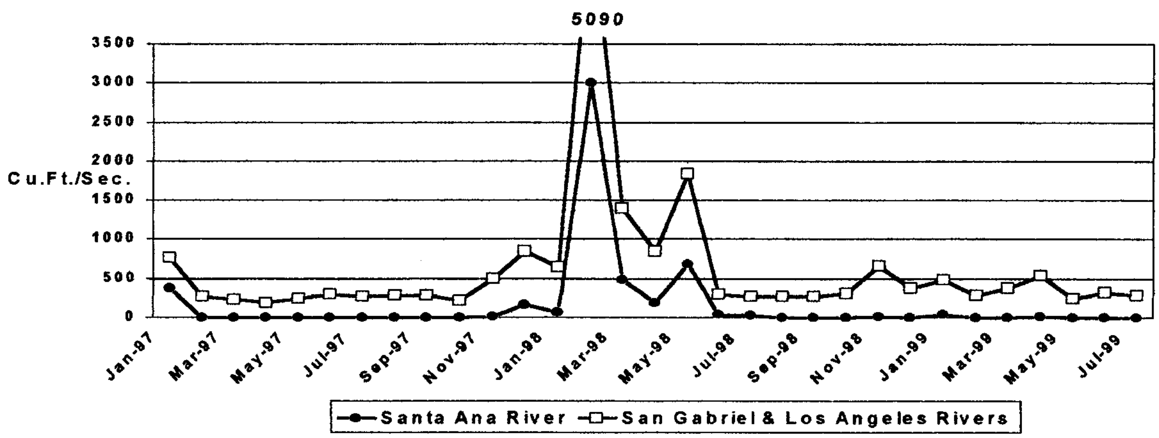


**Figure 5—Mean discharge per month for Santa Ana and Combined San Gabriel and Los Angeles Rivers (cfs × 0.028 32 = m$^3$/s. Source: *U.S. Geological Service.***

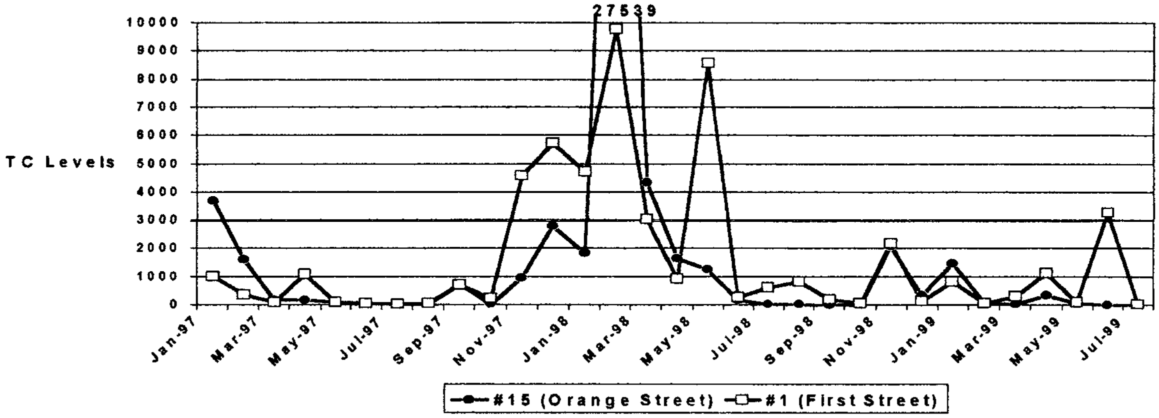


**Figure 6—Mean total coliform levels per month at Rivermouth Beaches: station 15 (Orange Street) and station 1 (1st Street). Source: *Orange County Health Care Agency.***

hazard that can result in several types of infections (Pruss, 1998, and Saliba, 1990). Some illnesses that have been reported from recreational contact with waterborne pathogens include gastrointestinal, sinus, respiratory, eye, ear, throat, and skin infections, as well as some severe, but rare, illnesses such as hepatitis, cholera, and typhoid (Fleisher et al., 1996, and Saliba and Helmer, 1990).

One of the first studies to investigate health threats from urban runoff was conducted in neighboring Santa Monica Bay in 1996. The study was conducted during dry summer months at three storm drains, each of which received runoff from relatively small watersheds. As previously noted, the study found that swimmers near storm drains were significantly more likely to become ill than those who swam farther away (Haile et al., 1999). These findings suggest that, even without rain, Southern California's urban runoff from a relatively small watershed can pose a direct threat to the health of swimmers.

If a public health risk exists in Santa Monica during the dry summer months, then, correspondingly, the threat to North Orange County could be worse because of the much higher volume of runoff delivered to the latter entity's coastal beaches year-round. The increased risk should be especially high during the winter months, when precipitation and coastal bacterial levels are higher than in summer months (assuming the results of previous epidemiology studies conducted during dry seasons are applicable to times of high discharge and high bacterial levels). The direct linear association between microbial indicator levels and increasing illness rates devised by Cabelli et al. (1982) supports this assumption.

Millions of people swim at North Orange County beaches every year and, therefore, any increase in risk will be expressed by large numbers of sick individuals. Of additional concern is that 48% of summer beach bathers are children 12 and under (Haile et al., 1999), an age group shown to be more likely than adults to report illnesses from recreational contact with polluted water (Cabelli et al., 1979, and Haile et al., 1999). The severity of illnesses associated with polluted recreational waters varies, although most of the illnesses are subclinical and remain unreported. However, a respiratory infection or a case of gastroenteritis does cause problems for an individual and society as a whole in terms of lost work hours, medical costs, and quality of life (Fleisher et al., 1998).

Results from this study show that precipitation and water quality are closely associated and, as such, changes in precipitation levels will directly influence both water quality and public health. There is consensus in the scientific community that global temperatures are increasing as a result of the greenhouse effect. The resulting warming is predicted to have powerful influences on climate and weather patterns, including increases in precipitation and extreme weather events for certain areas (IPCG, 2001). Correspondingly, increased rainfall from climate changes is predicted to increase river flow in all nine of the world's major high-latitude rivers (Karl et al., 1997, and Van Blarcum et al., 1995).

The strong associations between precipitation, river discharge, and levels of total coliform bacteria in coastal waters found in this study suggests increasing precipitation from climate change will lead to greater amounts of polluted runoff in urban areas, which, in turn, could lead to higher levels of waterborne pathogens. Results also show that coastal bacterial levels are highest during extreme weather events, such as the El Niño in the winter of 1998. With the direct correlation between illness rates and waterborne pathogens found by epidemiologists (Pruss, 1998, and Saliba, 1990), it is reasonable to suspect that increased precipitation may well result in higher rates of waterborne infections. In fact, this association was recently shown in a study that found that more than one-half of all waterborne disease outbreaks during the past 50 years in the United States followed a period of heavy rainfall and subsequent runoff (Curriero et al., 2001).

The magnitude of effect from climate change and increased precipitation varies regionally because the vulnerability of each watershed is unique. Runoff water quality is influenced by many factors, including the amount of precipitation delivered to the area, land uses and population within the watershed, the dynamics of the watershed and receiving water body, and the financial ability of residents to mitigate pollution and risk.

Current research on public health related to climate change primarily focuses on vector-borne infections such as malaria, dengue fever, yellow fever, or Hanta virus. Attention should be paid to more common pathogens such as enteric bacteria (*Escherichia coli, Salmonella, Staphylococci, Campylobacter*, and *Aeromonas*), viruses (hepatitis, rotaviruses, *Vibrio cholera*, Norwalk, and adenoviruses), and parasitic protozoa (*Giardia, Cryptosporidium, Toxoplama gondii*, and *Cyclospora*), all of which can be transmitted via water. Climate also has a tremendous influence on microecology, and increased prevalence of any of these pathogens can result in significant public health consequences.

Results from this study and that of Cross et al. (1991) suggest that increased precipitation for the Southern California region would result in greater levels of pathogens and toxins being discharged into the coastal waters. However, public health problems associated with polluted runoff may be most significant in less developed nations where waterborne gastroenteritis has been, and continues to be, the leading cause of childhood mortality. Any increase in health risk from polluted waters would result in thousands, if not millions, of avoidable infant deaths. Negative public health effects from increased rainfall will only be exacerbated by continued growth in both population and development.

One public health approach for addressing pollution in recreational waters is to increase the effectiveness of risk communication to the beach-swimming public. For example, the relationship found in the study's exploratory analysis between single rain events and the intensity of individual pollution plumes suggests larger storms should trigger closures at urban river-mouth beaches and extended advisories for nearby beaches. While small rain events having little to no impact on coastal waters may not merit a public health warning, models should be developed for different watershed areas using existing water quality and precipitation data to aid health officials in issuing measured public health advisories. An important factor to consider in predicting coastal water pollution levels is the volume and quality of runoff being discharged into the coastal zone. A river traversing through a highly urbanized area, such as Los Angeles, will transport far more polluted runoff than a small coastal creek. Existing data for indicator organisms (*Enterococci* and fecal coliforms) can also be used to estimate the effect of temperature, currents, and tides on the longevity and distribution of pathogens in coastal waters.

One of the strengths of this study is its use of three independently collected datasets from different government organizations to link coastal water quality with precipitation and urban river flow. There are two primary weaknesses in this study. The first is the use of monthly averages as opposed to daily values. More in-depth analysis can be conducted at the daily level if a single event or an individual site is being investigated. However, because the objective was to investigate patterns at several beaches over an extended period of time, the broader, but less refined, monthly means were investigated. The second weakness of this study is its use of bacteriological data. As indicator organisms, total coliforms do not accurately measure public health risk and, as such, their use has been rejected by the U.S. EPA (Cabelli et al., 1983). However, total coliforms were the only indicator organisms for which data exist covering the study period. Furthermore, multiple tube fermentation, the technique used for enumerating total coliform concentrations in water samples, generates a most probable number index. Most probable number values have relatively large confidence intervals (data not provided), thus further reducing the reliability of total coliform as a measure of water quality.

Orange County has been testing its coastal waters for indicator organisms, fecal coliforms, and *Enterococci* since the summer of 1999. It is recommended that this analysis be conducted again when a sufficient amount of data for the other indicators is acquired during extreme weather events.

Southern California is focused on the problems of nonpoint source urban runoff pollution. Although the issue is large and amorphous, addressing the issue should be feasible because polluted runoff water from the Los Angeles basin primarily flows into three main rivers. Surprisingly, this concentration of pollutants may be beneficial because it allows for focused mitigation. For example, during the summers of 2000 and 2001, officials in Orange County began diverting more than 8000 $m^3$/d (2 mgd) of urban runoff from the Santa Ana River and other storm channels. The urban runoff was pumped to the municipal wastewater system where it was treated and safely discharged offshore. Diversions are able to collect polluted water from a large urbanized watershed area and completely remove it from public recreational beaches. This strategy is impossible during large storm events because of treatment plant capacity. Thus, the largest pollution discharges will still reach the coastal beaches. Regardless, diversions are a viable pollution abatement tool that should be used in conjunction with other interventions such as source reduction through public education, creation of wetlands and natural areas to facilitate bioretention and bioremediation of pollutants (Davis et al., 2001), and formation of policies that better define and achieve public health objectives.

Orange County has a problem with urban runoff pollution that is generated by millions of people in four different counties. The problem this community faces today will be faced by coastal areas around the world as population and coastal development continue to grow. Solutions to urban runoff pioneered by various local groups will offer valuable guidance for developing areas worldwide.

## Acknowledgments

**Credits.** The authors are grateful to Harvey Molotch, director of the Ocean and Coastal Policy Center of the University of California, Santa Barbara, as well as the University of California Toxic Substances Research and Teaching Program for financial support. The authors also thank JoAnne Prause, Dele Ogunseitan, and Jason Wilkinson for their assistance.

**Authors.** At the time of this study, Ryan H. Dwight was a graduate student in the Environmental Health Science and Policy Program, Department of Environmental Analysis and Design, of the School of Social Ecology at the University of California, Irvine. Betty H. Olson is a professor in and interim director of the program. Jan C. Semenza is a professor at the School of Community Health, Portland State University, Oregon. Dean B. Baker is director of and a professor in the Center for Occupational and Environmental Health of the University of California, Irvine. Correspondence should be addressed to Betty H. Olson, Environmental Health Science and Policy Program, School of Social Ecology, University of California, Irvine, CA 92697; e-mail: bholson@uci.edu.

*Submitted for publication January 26, 2001; revised manuscript submitted November 16, 2001; accepted for publication December 4, 2001.*

*The deadline to submit Discussions of this paper is May 15, 2002.*

## References

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

Bay, S.M., and Greenstein, D.J. (1996) Toxicity of Dry Weather Flow from the Santa Monica Bay Watershed. *South. Calif. Acad. Sci.*, **95**, 33.

Cabelli, V.J.; Dufour, A.P.; Levin, M.A.; McCabe, L.J.; and Haberman, P.W. (1979) Relationship of Microbial Indicators to Health Effects at Marine Bathing Beaches. *Am. J. Public Health*, **69**, 7, 690.

Cabelli, V.J.; Dufour, A.P.; McCabe, L.J.; and Levin, M.A. (1982) Swimming-Associated Gastroenteritis and Water Quality. *Am. J. Epidemiol.*, **115**, 606.

Cabelli, V.J.; Dufour, A.P.; McCabe, L.J.; and Levin, M.A. (1983) A Marine Recreational Water Quality Criterion Consistent with Indicator Concepts and Risk Analysis. *J. Water Pollut. Control Fed*., **55**, 1306.

California Resource Agency (1997) California's Ocean Resources Management Program, California's Ocean Resources: An Agenda for the Future. *Water Qual.*, March.

Cross, J.; Schiff, K.; and Schafer, H. (1991) Surface Runoff to the Southern California Bight. In Annu. Rep. South. Calif. Coastal Water Res. Project, El Segundo, Calif., 19.

Curriero, F.C.; Patz, J.A.; Rose, J.B.; and Lele, S. (2001) The Association Between Extreme Precipitation and Waterborne Disease Outbreaks in the United States, 1948–1994. *Am. J. Public Health*, **91**, 1194.

Davis, A.P.; Shokouhian, M.; Sharma, H.; and Minami, C. (2001) Laboratory Study of Biological Retention for Urban Stormwater Management. *Water Environ. Res.*, **73**, 5.

Field, R.; O'Shea, M.; and Brown, M.P. (1993) The Detection and Disinfection of Pathogens in Storm-Generated Flows. *Water Sci. Technol*., **28**, 311.

Fleisher, J.M. (1990) Conducting Recreational Water Quality Surveys: Some Problems and Suggested Remedies. *Mar. Pollut. Bull.,* **21**, 562.

Fleisher, J.M. (1991) A Reanalysis of Data Supporting U.S. Federal Bacteriological Water Quality Criteria Governing Marine Recreational Waters. *Res. J. Water Pollut. Control Fed.,* **63**, 259.

Fleisher, J.M.; Kay, D.; Salmon, R.L.; Jones, F.; Wyer, M.D.; and Godfree, A.F. (1996) Marine Waters Contaminated with Domestic Sewage: Nonenteric Illnesses Associated with Bather Exposure in the United Kingdom. *Am. J. Public Health*, **86**, 1228.

Fleisher, J.M.; Kay, D.; Wyer, M.D.; and Godfree, A.F. (1998) Estimates of the Severity of Illnesses Associated with Bathing in Marine Recreational Waters Contaminated with Domestic Sewage. *Int. J. Epidemiol*., **27**, 722.

Gold, M.; Bartlett, M.; Dorsey, J.; and 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, Calif., August.

Haile, R.W.; Witte, J.S.; Gold, M.; Cressey, R.; McGee, C.; Millikan, R.C.; Glasser, A.; Harawa, N.; Ervin, C.; Harmon, P.; Harper, J.; Dermand, J.; Alamillo, J.; Barrett, K.; Nides, M.; and Wang, G. (1999) The Health Effects of Swimming in Ocean Water Contaminated by Storm Drain Runoff. *Epidemiol.*, **10**, 355.

Intergovernmental Panel on Climate Change (2001) *Climate Change 2001: Impacts, Adaptation and Vulnerability.* Geneva.

Karl, T.R.; Nicholls, N.; and Gregory, J. (1997) The Coming Climate. *Sci. Am*., **276**, 7883.

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

Natural Resources Defense Council (2001) Testing the Waters: A Guide to Water Quality at Vacation Beaches. Annual report, New York.

Nuzzi, R., and Burhans, R. (1997) The Use of Enterococcus and Coliform in Characterizing Bathing-Beach Waters. *Environ. Health*, **July/Aug.**, 16.

Pruss, A. (1998) Review of Epidemiological Studies on Health Effects from Exposure to Recreational Water. *Int. J. Epidemiol*., **27**, 1.

Saliba, L.J., and Helmer, R. (1990) Health Risks Associated with Pollution of Coastal Bathing Waters. *World Health Stat. Q.*, **43**, 177.

Schafer, H., and Gossett, R. (1986) Municipal Wastewater and Runoff Inputs to the Southern California Bight. *Proc. Managing Inflows Calif. Bays Estuar*., Bay Institute, Sausalito, Calif., 57.

Schafer, H., and Gossett, R. (1988) Storm Runoff in Los Angeles and Ventura Counties. Final Report to California Regional Water Quality Control Board, Southern California Coastal Water Research Project, Long Beach, Calif., June.

Schueler, T. (1994) The Importance of Imperviousness. *Watershed Prot. Tech.*, **1**, 100.

U.S. Department of Commerce (1999) Population Estimates for Los Angeles and Orange Counties Combined. U.S. Census Bureau, Suitland, Md.

U.S. Environmental Protection Agency (1997) *The BEACH Program*. EPA-820/F-97-002, Office of Water, Washington, D.C.

Van Blarcum, S.C.; Miller, J.R.; and Russel, G.L. (1995) High Latitude River Runoff in a Doubled $CO_2$ Climate. *Climatic Change*, **30**, 1, 7.

Young, K.D., and Thackston, E.L. (1999) Housing Density and Bacterial Loading in Urban Streams. *J. Environ. Eng*., **125**, 1177.