

Relationship between rainfall and beach bacterial concentrations on Santa Monica Bay beaches

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ABSTRACT

Rainfall effects on beach water quality in southern California are large enough that county health departments typically issue warnings for the public to avoid recreational water contact for 3 days following a storm. To enhance the scientific foundation for these preemptive public health warnings, we examined the relationship between rainfall and beach indicator bacteria concentrations using 5 years of fecal coliform data taken daily at 20 sites in southern California. There was a countrywide increase in ocean bacterial concentrations associated with almost all storms larger than 6 mm and with every storm larger than 25 mm. Only for storms less than 2.5 mm was there no observable rainfall effect. Bacterial concentrations remained elevated for 5 days following a storm, although they generally returned to levels below state water quality standards within 3 days. The length of the antecedent dry period had a minimal effect on this relationship, probably reflecting a quickly developed equilibrium between the decay of older fecal material and the introduction of new fecal material to the landscape.

Key words | bacteria, beach water quality, rainfall

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INTRODUCTION

Rainfall has been found in several studies to negatively affect beach bacterial water quality (Lipp *et al.* 2001; Boehm *et al.* 2002; Schiff *et al.* in press). This effect is manifested through enhanced stormwater runoff of animal feces and other bacterial sources that are deposited on land between storms. It can also result from human sewage input through infiltration-mediated leaks in the sewage transmission infrastructure.

Rainfall effects on coastal water quality are of particular concern in southern California where the stormwater conveyance systems are independent of the sewage treatment infrastructure and urban runoff flows unimpeded to the ocean. Moreover, southern California has an arid environment with a short rainy season and long dry periods when land-based contaminants accumulate. Rainfall effects are substantial enough that county health departments throughout southern California typically issue warnings for the public to avoid recreational

water contact for 3 days following storms larger than 2.5 mm.

Rain-based public health warnings can be an effective supplement to the direct testing of water samples because laboratory measurement methods to enumerate indicator bacteria require an 18-h to 96-h incubation period. By the time laboratory results are obtained and warnings are issued, exposure has already occurred for a day or more (Leecaster & Weisberg 2001; Boehm *et al.* 2002). However, the underlying relationship between rainfall and beach bacterial concentrations is poorly understood. Current rain-based warnings are issued for a 3-day period independent of factors such as storm size, storm duration, and antecedent rainfall. Here we examine the relationship between rainfall and beach bacterial concentrations, and how it is affected by factors such as storm size, to improve the scientific foundation for rain-based warning systems.

METHODS

Our study evaluated the Los Angeles County warning system, where warnings to avoid recreational contact are typically issued countywide whenever rainfall exceeds 2.5 mm at the Los Angeles International Airport (LAX) gauge. We selected Los Angeles County because beach bacterial measurements are collected daily, allowing us to evaluate the bacterial response to all rain events and to assess trailing conditions.

We used three data sources in our analyses: (1) rain data from the LAX gauge, which measures rain hourly in 0.25 mm increments; (2) flow data from the Los Angeles Department of Public Works Ballona Creek gauge, which measures flow hourly (Ballona Creek drains the largest coastal watershed in the county); and (3) beach bacterial data from the City of Los Angeles, which measures fecal coliforms daily at 20 sites using membrane filtration. Twelve of these sites are located on coastal beaches 50 m from outlets for land-based runoff, five are on coastal beaches at a distance from runoff outlets, and three are on beaches in protected embayments. Our analyses are based on data from 1995 through 2000, although a description of general rainfall patterns for the area is based on 14 years of LAX records.

The relationship between rainfall volume and runoff volume was accomplished by comparing LAX rain data and Ballona Creek flow data. Storm runoff volume was calculated as the increase above base flow from the time of the initial flow increase following a storm event until flow returned to within 20% of the original base flow.

The relationship between rainfall volume and beach bacterial concentrations was evaluated by calculating the percentage of beaches that exceeded State of California water quality standards (400 cfu/100 ml for fecal coliforms) as a function of rainfall amount. Rainfall was quantified as the sum of all rain in the 24 h preceding the time of bacterial sampling, which typically takes place in early morning. We assessed how long a rainfall event affected water quality by grouping rain events into categories (<2.5, 2.5–6, >6–25, and >25 mm) and comparing countywide mean bacterial concentrations as a function of days since the rain event. This analysis was conducted

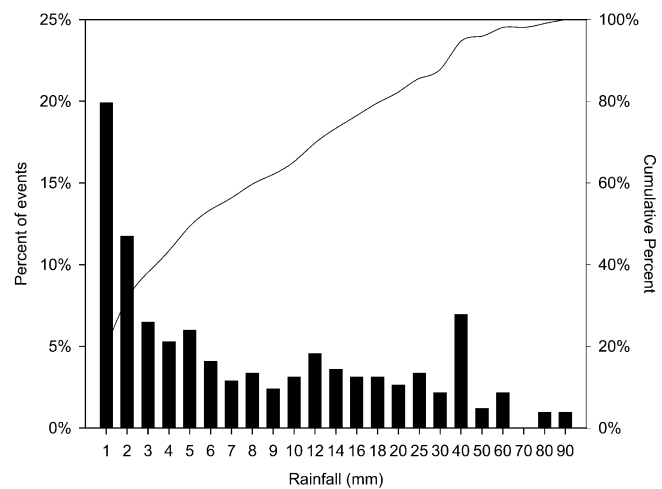


Figure 1 | Frequency distribution of storm size at the LAX rain gauge between 1987 and 2000. Termination of a storm event was defined as six consecutive hours with no measured rainfall.

separately for beach sites located near to, and at a distance from, runoff outlets.

RESULTS

Most rainfall events in southern California were small (Figure 1). Half of the storms were less than 6 mm and only 14% were greater than 25 mm. Most storms were also of short duration. Most storms lasted less than 6 h, with only 6% lasting a day or more (Figure 2).

Ballona Creek flow was linearly related to rainfall (Figure 3). The intercept of the rainfall-runoff relationship was 0.9 mm, indicating the average storm size necessary to yield an increase in river flow.

Every storm larger than 25 mm resulted in an increase in the number of beach sites failing water quality standards compared with that occurring during dry weather background conditions (Figure 4). Ninety-one percent of the rain events between 6 mm and 25 mm produced an increase in the number of sites failing water quality standards. For storms smaller than 2.5 mm, there was almost no increase above background levels in the number of sites failing beach water quality standards.

Mean bacterial concentrations on Los Angeles beaches were also related to storm size. For sites located at

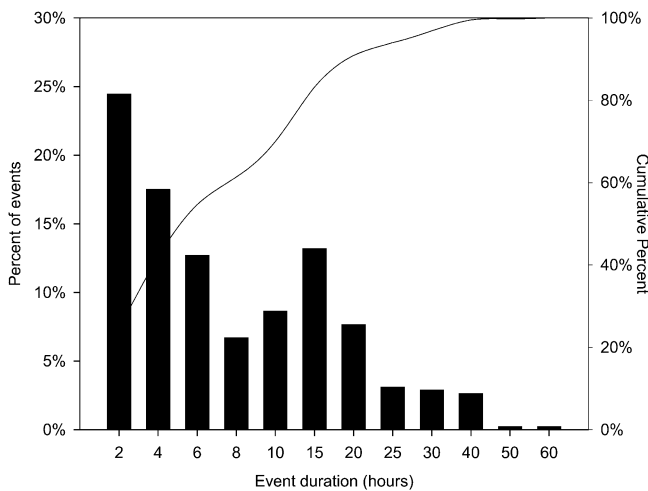


Figure 2 | Frequency distribution of storm duration at the LAX rain gauge between 1987 and 2000.

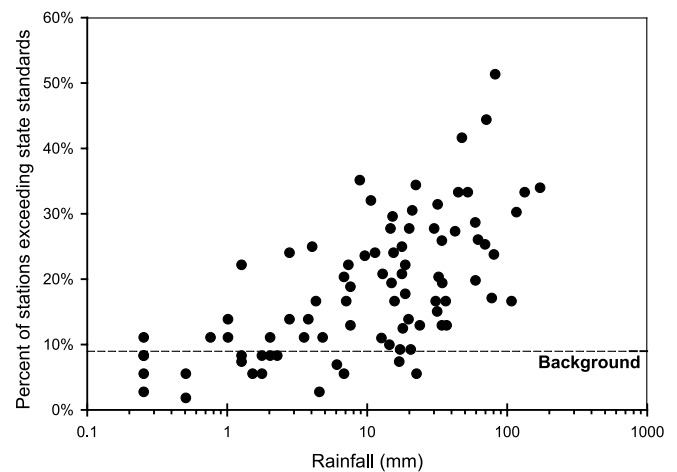


Figure 4 | Percent of Los Angeles County beach bacterial sampling sites exceeding water quality standards as a function of rainfall amount.

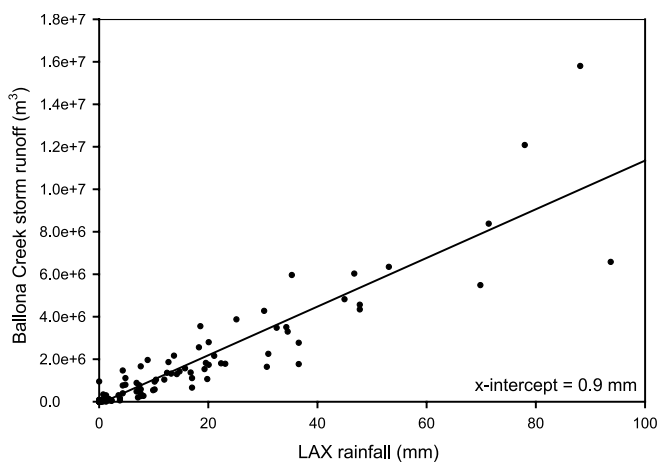


Figure 3 | Relationship between LAX rainfall and Ballona Creek flow between 1995 and 2000.

a distance from a runoff outlet, only the largest storms yielded average concentrations in excess of state standards (Figure 5). For sites near a runoff outlet, mean bacterial concentrations exceeded state standards for storms as small as 6 mm.

For large storms, the highest bacterial concentrations occurred on the first day following the storm (Figure 5). For smaller storms, the highest bacterial concentrations occurred on the second day, probably reflecting the longer transport time under lower flow conditions. The average

bacterial concentrations returned to background levels in 5 days for all size rain events. Average bacterial concentrations returned below state standards within 3 days for sites near runoff outlets, but took 4 days at sites away from outlets for storms larger than 25 mm.

The period between storms appeared to have minimal influence on the relationship between rainfall and fecal coliform concentrations (Figure 6). The median period between storms was 20 days and the longest period was 226 days, reflecting the long dry season in southern California. No correlation was found between antecedent dry period and mean fecal coliform concentration, regardless of storm size.

DISCUSSION

The relationship we observed between rainfall and bacterial concentrations supports the use of a rain-based beach water quality warning system. Storms larger than 6 mm consistently led to beach water quality degradation. However, warnings are typically issued for storms as small as 2.5 mm and the need to issue warnings for storms between 2.5 and 6 mm is less clear. These smaller storms never led to countywide average bacterial concentrations exceeding state standards nor did they lead to more than

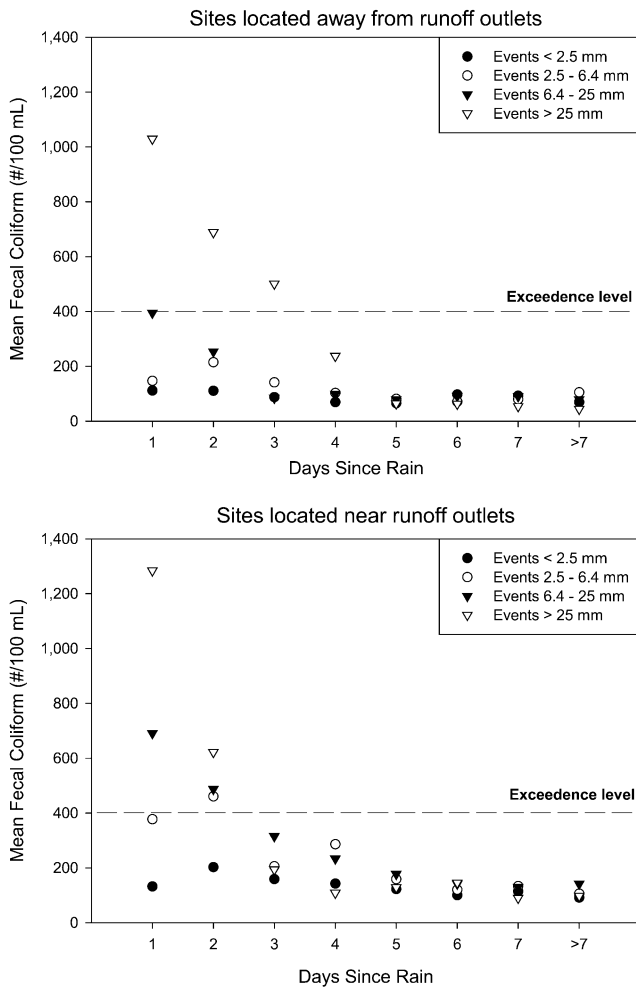


Figure 5 | Mean fecal coliform concentrations in relation to the number of days following rain.

25% of beaches failing water quality standards. Still, there was a predictable increase in the number of beaches affected, and our analysis probably underestimates the extent of the water quality problem because it was based on fecal coliform data. California also has standards for enterococci, which exceed state standards more frequently than fecal coliforms (Noble *et al.* 2003).

Beach water quality effects were not associated with storms smaller than 2.5 mm, which probably results from two factors. First, small storms are more likely to infiltrate into groundwater than to drain into creeks, which is reflected in the intercept term for the rainfall-to-Ballona-Creek-runoff relationship (Figure 3). Second, small storms

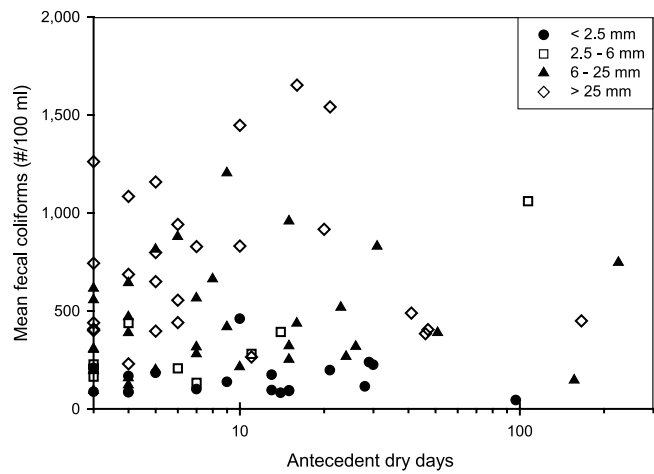


Figure 6 | Mean fecal coliform concentrations at Los Angeles beaches following a storm as a function of antecedent dry days.

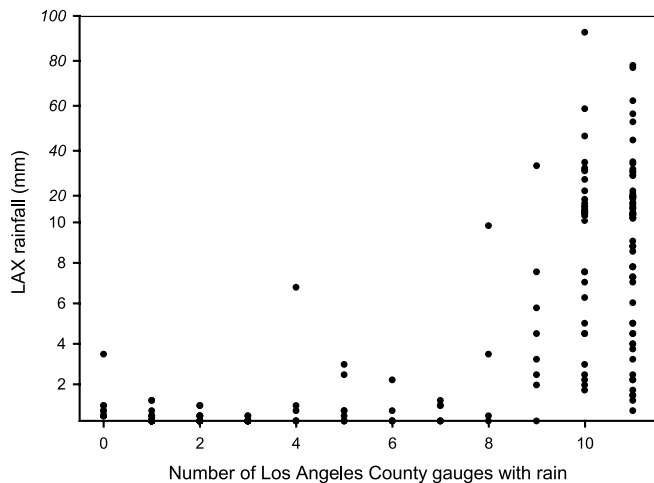


Figure 7 | Relationship between rainfall at the LAX gauge and the number of other rain gauges in Los Angeles County recording rainfall.

are more likely to occur locally rather than regionally, making countywide predictions using the LAX gauge problematic. To assess how often storms occurred regionally, we quantified the percentage of other rain gauges in the county that recorded rainfall when rainfall was recorded at LAX. We found that this percentage was highly variable for storms less than 2.5 mm, but rainfall was recorded at nearly 100% of the gauges for larger storms (Figure 7).

Many constituents are present in runoff at higher concentrations after long periods without rainfall (Bertrand-Krajewski *et al.* 1998). Known as the 'first flush' effect, it reflects the accumulation of materials on land between storms. In contrast, we found that the length of antecedent dry period had little effect on beach bacterial concentrations. The most likely explanation for this difference is that bacterial concentrations are more labile than chemical constituents, as indicator bacteria typically decay within a few days (Rajala & Heinonen-Tanski 1998). The lack of antecedent influence on the rainfall relationship suggests that equilibrium between new fecal material additions to the landscape and decay of older fecal material is reached within a few days following a storm.

Los Angeles beaches have a highly variable amount of development in their watersheds (Dojiri *et al.* in press). The southern beaches adjacent to urban Los Angeles have watersheds that are more than 85% developed. The watersheds of the northern beaches are designated reserves with almost 90% open space. We found that there was little difference in the rainfall:bacterial concentration relationship between these two regions. We found that a more important factor in determining beach bacterial concentration was hydrography of the runoff outlet closest to the sampling station. Some outlets drain right across the beach with a large enough slope to prevent tidal mixing. Others have a shallow slope, allowing mixing to occur before runoff reaches the beach. Beaches near outlets with upstream tidal mixing consistently had lower bacterial concentrations, particularly following small storms.

CONCLUSIONS

There was a clear relationship between the incidence of rainfall and reduction in beach bacterial water quality in Los Angeles County. For storms larger than 6 mm, the pattern of water quality degradation was consistent enough to justify the issuance of predictive public health

warnings in advance of bacterial sample collection. Bacterial concentrations remained elevated for up to 5 days following a storm, though they generally returned to levels below state water quality standards within 3 days.

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