Modeling Arid, Urbanized Watersheds: Part II, Bacterial Runoff

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ABSTRACT

Santa Monica Bay (SMB) has a large extent of bacterial water quality exceedences that disproportionately occur near storm drains and during wet weather. A dynamic water quality model with 15-minute time steps was developed to assist managers in estimating bacterial concentrations and loads from unmonitored watersheds and predict the potential effectiveness of various management actions. A wet weather sampling program was initiated to capture water quality changes at similarly small time steps. The sampling program captured at least 10 grab samples per site-event at 6 small catchments of single land uses for calibration and two larger watersheds uses for model validation.

Nearly 10^{15} enterococci are discharged to SMB during a median rain year. Urbanized areas comprised 42% of the area, but had 84% of the enterococcus load. Urban watersheds have higher rates of water quality exceedences during wet weather; between 11 and >100 days per year in urban watersheds compared to one and six days per year in predominately open watersheds. Sensitivity analysis estimated that minor to modest changes in annual bacterial loading would be expected based upon altering degradation rates (<1% change in load), maximum build-up concentrations (<10%), or wash-off coefficients (<20%). Rainfall during a relatively wet year could result in a doubling of bacterial exceedences.

INTRODUCTION

High bacteria levels that impact water quality is a nationwide problem. Bacterial pollution was the number one leading cause of water quality impairments in ocean and tidal estuaries representing nearly 75% of the impairments in assessed waterbodies around the country (US EPA 2000). The problem of bacterial levels exceeding water quality thresholds for body contact recreation is particularly pronounced in Southern California where our beaches are prized tourist destinations with an estimated 170 million beachgoers annually (Schiff *et al* 2001a). This high level of shoreline recreation generates an estimated $9 billion in ocean-related activities. It is not surprising that southern California expends more than $3 million annually on shoreline bacterial monitoring, more than any other part of the country.

Santa Monica Bay (SMB) beaches (Figure 1), are a good example of the problems faced by shoreline water quality managers in southern California and around the nation. Approximately 1,500 shoreline mile-days exceeded water quality thresholds for enterococcus, fecal coliform, or total coliform over the five-year period from 1995-2000 (Schiff *et al* 2001b). More than half of these exceedences were located $\leq$ 50 m from a storm drain outlet. After more careful examination, nearly two-thirds of the exceedences near storm drains occurred during wet weather events. The problem of wet weather exceedences is not a problem unique to SMB or southern California, but is common around the country (Schiff and Kinney 2001, US EPA 1987).

The water quality problems found in SMB has led the state to add specific SMB beaches to their list of impaired waterbodies, the 303(d) list. This means that SMB managers must identify the sources and loading of bacteria and then implement actions to restore water quality through a total maximum daily load (TMDL) process. The process is hampered, however, by several factors. First, not all watersheds to SMB are monitored, so all of the sources and loadings of bacteria are unknown. Second, once these sources and loadings are identified, SMB managers have no efficient mechanism for evaluating the most effective management strategies for implementing improvements to water quality.

Watershed models provide a tool to estimate the concentrations and loading of bacteria from unmonitored watersheds and to evaluate the effectiveness of different potential management strategies. It would be extremely difficult and costly to continually measure bacteria loadings to the SMB from all of its watersheds. Estimating stormwater pollutant loadings to southern California beaches from unmonitored watersheds has been accomplished using simple static models (Escobar 1999, Ackerman and Schiff 2001, Wong *et al.* 1997). Static models greatly simplify rainfall-runoff dynamics and associated bacteria loadings to the SMB. Static models make many assumptions and apply a simple runoff coefficient and constituent concentration for each land use to determine a net loading in response to a rain event. They are best suited to long-term averages and annual rainfall estimates and, thus, limited in their TMDL application because they cannot resolve the time or spatial scales needed to evaluate the loading or the effectiveness of various management scenarios. For example, simple static models cannot account for build-up and wash-off of bacteria from different land surfaces.

Coupled dynamic hydrologic and water quality models have the capability to dramatically improve bacterial concentration and loading estimates to SMB over static models. Dynamic models incorporate build-up and wash-off from various land surfaces, as well as account for degradation as bacteria travel downstream from its source to receiving waters. In addition, dynamic models enable mangers to understand the mechanisms of bacterial runoff and the potential management actions that SMB managers may want to explore. The dynamic model assessment of inter-storm and intra-storm bacterial concentration variability is particularly important in arid watersheds like SMB. Southern California averages 12-14 storms per year and increasing flows have been measured at less than 5 cfs to more than 10,000 cfs in less than two hours (Tiefenthaler *et al* 2001). Therefore, within-storm scenarios must be evaluated at time scales of minutes. Moreover, storm drain systems are separate from sanitary sewer systems so this alters the cost of implementing diversions of wet weather discharges to sanitary treatment plants.

The goal of this modeling effort was to develop a dynamic water quality loading model for bacteria in SMB watersheds. The model was designed to simulate short temporal variability (e.g. 15 min) of bacterial contamination in stormwater runoff. The model was calibrated at small spatial scales of specific land uses, then validated at watershed scales of mixed land uses. A wet weather sampling program was initiated to generate the water quality measurements necessary for calibration and validation. The model was then evaluated for sensitivity to bacterial degradation, build-up and wash-off rates, as well as changes in rainfall quantity.

METHODS

Approach

We selected the Hydrologic Simulation Program – FORTRAN (HSPF) (Bicknell *et al*. 1997) to estimate volumetric and pollutant loadings to the bay. This model required extensive data including meteorological, hydraulic, land use, topography, and water quality characteristics throughout the study area. The details of the data collection for the calibration and validation of the hydrologic component of the model are presented in Ackerman and Schiff (2001b). However, a great deal of local runoff water quality data was necessary for calibration and validation in the present study. Since the model was designed to estimate changes in concentration over short intervals, water quality measurements were necessary at these same intervals (i.e. approximately every 15 min). The model was calibrated at small spatial scales of homogeneous land uses, then validated at the mouths of larger watersheds of mixed land uses.

Watershed Description

The SMB is composed of 28 watersheds covering an area of 1079 km^2 (Figure 1). The northern part of the watershed is predominately open land use composed of state parks and national forest. In contrast, the southern portion of the watershed is almost completely urban composed of metropolitan Los Angeles. Annual rainfall in the watershed over the last 50 years averaged 11.1 inches, but the range from year to year can be extreme; the 10th and 90th percentiles over the same time period are 5.2 to 20.7 inches. Not only are the year-to-year variations in rainfall extreme, but similar variability can occur within the SMB watershed where the annual average rainfall is nearly double in portions of the North Bay than in the South Bay. Much of this variation is driven by 300m elevation changes of the coastal mountains in the North Bay relative to the flat coastal plains in the south bay.

Water Quality Sampling

We collected bacteria concentration data at eight sites to support model calibration and validation (Figure 1). Six sites were single land uses (0.5 to 2.6 km^2) sampled for model calibration. These sites included high density residential, low density residential, commercial, industrial, agricultural, and open land uses. Two sites were watershed-wide sites of mixed land uses sampled for model validation. These sites included Santa Monica Canyon (41 km^2) and Ballona Creek (339 km^2). These two sites represent the mix of land uses present in SMB; Santa Monica Canyon has a large open space component (79% open space) and Ballona Creek has a large urbanized component (82% developed).

In addition to the short-term monitoring data generated as part of this project, long-term historical monitoring data was also compiled for Ballona Creek and a second SMB watershed, Malibu Creek (Figure 1). The long-term monitoring data at Ballona Creek was generated by the City of Los Angeles who collected single grab samples weekly at Sawtelle Avenue for analysis of total coliform, *E. coli*, and enterococcus between January 1997 and June 1999 (unpublished data). The long-term monitoring data at Malibu Creek was generated by Heal the Bay, a local environmental advocacy group, who collected single grab samples weekly for analysis of total coliform between January 1996 and December 2000 (unpublished data). In both cases, we parsed the data into wet days based on rainfall $\geq$ 0.1 in measured at rain gauges within the respective watersheds.

The sampling methodology was designed to capture the changes in flow and water quality throughout an event at each site. Between 10 and 13 grab samples per storm event were taken and analyzed for total coliforms, *E. coli*, and enterococcus using chromogenic substrate methods (ref.). We used *E. coli* as a surrogate for fecal coliform. Sampling size was based studies from the Santa Ana River, a watershed 20 miles south, that identified the most efficient sampling strategy for characterization of water quality for an entire storm event (Leecaster *et al* 2001). The design staggered effort so that the first part of the event was sampled more densely to ensure that the rising portion of the hydrograph was captured in sufficient detail. The result was the water quality equivalent of a hydrograph, termed a pollutograph.

Assumptions

As with any modeling exercise, assumptions are necessary to represent the natural behavior of a system. We made three assumptions including: (1) the runoff water quality characteristics throughout the area were homogenous so that extrapolation to unmonitored areas was applicable; (2) only wet weather flows associated with rain events were modeled and that nuisance, non-storm dry weather flows were not included; and (3) bacteria loadings were only associated with surface flows and groundwater contributions of bacteria were low.

The water quality model designed in this study was built on previous hydrologic model calibration and validation (Ackerman and Schiff 2001b). The hydrologic model calibrated and validated well in both non-urbanized and urbanized watersheds, which represented the range of land use coverage in the SMB. Like the hydrologic model, we assumed that the calibrated and validated model from monitored areas was applicable throughout the region.

We focused our effort on estimating concentrations and loads from wet weather runoff. Therefore, we assumed that all flows were derived from precipitation. However, watersheds in the South Bay are highly urbanized and small nuisance flows may exist during dry periods that are not derived from rainfall or groundwater. Dry weather flows have been measured in some SMB watersheds (i.e. Ballona or Malibu Creek). In these instances, dry weather flows comprised a small fraction of the annual volume (Tiefenthaler *et al* 2001). Hence, this assumption appears warranted.

The exception to this assumption was in Malibu Creek. Tetra Tech (2001) quantified loads to Malibu Creek by non-point sources including septic systems and agriculture activities. Since non-point source data existed in that watershed for those activities, their loads were included in the model's predicted loads.

Groundwater bacterial contributions were assumed to be negligible. The majority of watersheds run dry within hours to days following most wet weather events. Hence, we only sampled surface water runoff and incorporated bacteria loadings from surface water runoff. The largest exception to this assumption is Malibu Creek. In this case, we were able to incorporate bacterial contributions as described in the previous paragraph.

The model incorporates a build up rate that asymptotically approaches a maxima. This build up rate can be either constant or time-variable. A constant value was assumed because we did not have sufficient information on time variable (i.e. seasonal) build up rates. Likewise, there was insufficient information for establishing bacterial concentration maxima. Therefore, we set the maximum concentration to 1.8 times the build-up rate.

Calibration and Validation

The bacteria wash-off parameters in HSPF were adjusted for each indicator bacteria (*E. coli*, total coliform, and enterococcus) for each land use catchment. The modeled and measured pollutographs were then compared. The flow-weighted mean concentration of each indicator bacteria was calculated at each land use for both modeled and measured estimates and then compared for similarity.

The only exception to this process was the open land use. In this case, our open land use sampling didn't provide enough information for a sufficient modeling calibration. In response to this, we compiled water quality data for open areas throughout southern California (Table 1). The geometric mean and standard deviations of all the empirically monitored data was calculated for southern California. We then simulated an open catchment for a two-year period and the flow-weighted mean concentration and standard deviation during wet weather was calculated. Next, bacterial build-up and concentration maxima, similar to other land use calibrations, were adjusted until the flow-weighted mean from the simulated catchment mirrored the geometric mean of the empirically measured results from open land uses regionally.

We applied the water quality parameters calibrated at each land use to larger, mixed land uses watersheds for model validation by generating pollutographs for each indicator bacteria. We then compared the modeled indicator bacteria pollutographs to the measured pollutographs at those watersheds.

We also assessed the long-term validation of bacterial concentrations by comparing simulated bacterial concentrations in the model to locally generated monitoring results. To accomplish this, we calculated flow-weighted mean concentrations and standard deviations for the wet weather discharges during the same time periods as the empirical monitoring data. Next, we calculated the geometric mean (because no flow data existed) and standard deviations of bacterial concentrations during wet weather events for the empirical data. The simulated and empirical data were then compared.

Application

We applied the calibrated and validated model to the 28 watersheds in the SMB. The model was applied to the median rainfall year (1991) for the time period 1947 to 1998. The model output was evaluated based on a loading for each of the indicator bacteria and for water quality threshold exceedences. The water quality thresholds were those adopted by the State of California (California Assemble Bill 411); (1) total coliforms > 10,000 mpn/100 mL; (2) fecal coliforms > 400 mpn/100 mL; or (3) enterococcus 104 mpn/100 mL. In most cases, we used the daily average bacterial concentration for comparison to thresholds. To provide an assessment of potential peaks in bacterial concentrations, we also compared the water quality thresholds to the 90^{th} percentile of one-hour averages during each day of the one-year simulation.

Sensitivity analyses were performed on five key model parameters. Bacteria may degrade as it is transported to the beach. To explore the model sensitivity to this factor, we altered the decay rate by +/- 25% and quantified the change on total loading by each watershed to SMB. Bacterial concentration and loading predictions may be sensitive to two additional model assumptions; the bacteria maximum concentration and wash-off rate. We assumed a constant build-up rate and maximum bacteria concentration of 1.8 times the build-up rate. The sensitivity analysis investigated the effect of altering the maximum concentration in two fashions; lowering the maximum concentration to 1.5 the build-up rate and setting the maximum concentration with a time variable component that varied by season (1.8 for October - March and 1.5 for April - September). We altered the maximum concentration and generated load estimates under each scenario. Next, we used a bacterial wash-off coefficient of 90% with a rainfall of 0.5 in/hr. The fourth sensitivity analysis used modeled estimates of bacterial loading for each land use by altering the wash-off coefficient from 0.01 to 1.0. Finally, the model sensitivity was tested for differences in rainfall based on the 50-year historical record. Although we used the median rainfall year (1991) for the default model, we also predicted model output for the 10th percentile (1990) and 90th percentile (1993) years based on the number of days with measurable rainfall.

RESULTS

The agricultural land use had the greatest flow-weighted mean concentrations of *E. coli* and enterococcus of the six land uses evaluated (Table 2). High density residential had the greatest flow-weighted concentrations of total coliforms and the second highest flow-weighted concentration of fecal coliforms of the six land uses. Open land use had the lowest flow-weighted concentrations of all three indicator bacteria evaluated. The flow-weighted mean concentrations for all three indicators from all developed land uses (high and low density residential, commercial, industrial, and agriculture) exceeded water quality thresholds established by the State of California for body contact recreation. Open land use only exceeded water quality thresholds for enterococcus.

Calibration

Despite the high degree of variability within a storm event, the majority of the land use models calibrated well to their catchments (Figure 2). One example is the industrial land use where modeled pollutographs for all three indicator bacteria predicted measured flow weighted mean concentrations were less than a factor of two. Depending upon the indicator bacteria, the modeled flow-weighted mean concentrations averaged a factor of two to 10 times higher compared to the measured flow-weighted mean concentrations on a storm-by-storm basis. In almost all storm events, the modeled estimates were within the range of variability of the measured estimates for every indicator.

The build-up rates calibrated for each indicator bacteria varied among land uses (Table 3). For example, the build-up rate for fecal coliform ranged from 8×10^{7} mpn/ acre-day at industrial land uses to 5×10^{10} mpn/ acre-day at agricultural land uses. The build-up rate also varied within a land use category for the different indicator bacteria. The greatest range existed for commercial land uses from 5×10^{8} fecal coliform / acre-day to 3×10^{10} total coliform / acre-day.

Validation

The model validated on both short-term (pollutograph) and long-term (2 to 5 years) time scales (Figure 3 and 4). Modeled pollutographs at both Santa Monica Canyon and Ballona Creeks compared well to the measured data. This is significant because modeled predictions followed empirical measurements at both relatively open and urban watersheds, respectively. Similarly, modeled concentrations were near the average of measured concentrations at Malibu and Ballona Creeks over longer time periods (Figure 5). The difference between the measured and modeled concentrations on wet weather days ranged by less than a factor of two, on average, for any of the indicators measured. In addition, the flow-weighted mean concentration of each of the indicator bacteria was well within the range of variability in measured data.

Application

Bacterial loadings during a median wet year for the SMB amounted to 10^{15} enterococcus, 10^{15} fecal coliform, and 10^{16} total coliform. Using enterococcus as an indicator, the model predicted a disproportionate level of loading to SMB (Figure 6). The more urbanized South Bay watersheds accounted for only 44% of the total area, but contributed 84% of the enterococcus load. Similarly, South Bay watersheds had disproportionately more days of exceedence than the more open land use dominated North Bay watersheds (Table 4). The number of days of exceedence ranged from one to six days per year in the North Bay compared to between 11and >100 days per year in the South Bay watersheds.

Sensitivity

Bacterial degradation played a minor role in controlling the dynamics of water quality in wet weather runoff to SMB (Figure 7). Altering the presumed decay rate of 0.8/day by +/- 25% resulted in a 1% increase/decrease on total loading of bacteria to SMB. This is likely due to the short travel times of SMB watersheds, which are relatively short and steep. The greatest changes in bacterial loading were for Malibu and Ballona Creeks, the two longest watersheds in the SMB

Altering the maximum build-up concentration only marginally affected our modeled estimates of bacterial loading to SMB (Figure 8). Reducing the maximum build-up concentration from 1.8 to 1.5 the build-up rate resulted in a 10% reduction in enterococcus loading from a land uses in the SMB. Using a seasonally time-variable maximum build-up concentration resulted in a 2% decrease in enterococcus loading from land uses in the SMB. This is likely due to the lack of rain during the spring/summer season.

Altering wash-off rates that estimated 90% wash-off in one hour moderately affected enterococcus loading (Figure 9). Increasing and decreasing the wash-off rate of 0.5 by 50% resulted in an 18% and 12% change in enterococcus loading, respectively.

Altering rainfall had a potentially larger effect on estimating the number of water quality threshold exceedences due to wet weather runoff (Table 4). Wetter years (90^{th} percentile) resulted in a 0 to 50% increase in the number of exceedence days, depending upon the watershed. The differences among watersheds were a function of the watershed characteristics and the disparity in rainfall among specific rain gauges during any single specific year.

Altering the method for selecting concentrations to compare against thresholds had the largest effect on estimating the number of water quality threshold exceedences (Table 4). For example, changing from a daily average to using the 90^{th} percentile of one-hour averages increased the number of exceedence days by approximately 50% across all of the watersheds in SMB. The one hour averages tended to accentuate peak concentrations; most storms in southern California rarely last more than several hours and daily averaging tended to decrease overall concentrations.

DISCUSSION

The dynamic water quality model HSPF was able to predict concentrations and loads of bacteria during wet weather events in an arid watershed like SMB with reasonable accuracy. This is encouraging because HSPF was not designed in arid watersheds like those found in southern California and little model validation for arid watersheds can be found in the literature. In addition, HSPF worked well in relatively open as well as urbanized watersheds even though HSPF was not specifically designed for intensely urban watersheds like those found in southern California.

The dynamic model was able to reproduce concentrations and loads of bacteria on long and short time scales. While validation of bacterial concentrations over time scales of years has been shown in other areas such as Muddy Creek, VA (MCTEW 1999) or St Louis Bay, MS (Huddleston *et al* 2001), validating bacterial concentrations at intervals of minutes has rarely been attempted. However, these time scales are imperative in arid urbanized watersheds where storms may last only a few hours and watershed loading responds quickly. Moreover, stormwater managers in urban watersheds need to evaluate within storm options such as retention, detention, or treatment for only portions of storms because flows increase rapidly to extremely high rates and capturing an entire storm volume is often unmanageable.

Now that a wet weather model exists, managers in the SMB can use the model to assist in TMDL development in at least three areas. First, the model can be used for estimating loadings from unmonitored watersheds with relative confidence. This, of course, is a function of the second utility of the model; evaluating critical conditions. For example, managers in SMB need to decide if they are going to assign load and wasteload allocations based upon an average rainfall year or, perhaps, a year with more rainfall as we evaluated herein. Other critical conditions that can be evaluated include data averaging schemes such as monthly, daily, or hourly averages of water quality concentrations. Third, different management endpoints can be considered using the model. For example, modeled estimates of water quality exceedences could be compared to a management endpoint that expects every wet day meet water quality thresholds. In contrast, the model could be compared to a predetermined percentage of wet days that exceed water quality thresholds based upon 303(d) listing criterion. Regardless of the management endpoint, the model is flexible enough to allow interpretation across a range of potential strategies.

The weakest predictions in the model presented in this paper are for the open land use category. We used a regional open land use approach to offset our lack of local land use data. While we were able to calibrate our model using this approach, and it led reasonable validations in our open land use watershed (Santa Monica Canyon), it represented a lack of certainty that we feel is necessary. A second contributing factor to the weakness of modeling open land use is the tremendous variability among open land use sites. The regional data compilation aptly demonstrated that bacteria concentrations can vary by orders of magnitude among sites, likely due to sources within each catchment.

The model was relatively insensitive to many of the model assumptions leading to an improved confidence in the modeling results. Changes in bacterial degradation, maximum build-up concentrations, and wash-off rates only changed indicator bacterial loading to SMB by a maximum of 20% during a typical rain year. However, variations in rainfall can alter assessments of potential water quality exceedences by as much as 50%. This is due to the hydrologic component of the model, which is also relatively sensitive to rainfall (particularly in urban impervious watersheds). Hence, increased runoff volumes increased bacterial loading to SMB (Ackerman and Schiff 2001b).

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Table 1. Geometric mean densities of indicator bacteria in wet weather runoff from open land uses throughout the southern California region.

Site Location	County	Fecal Coliform (mpn or cfu /100 mL)	Enterococcus (mpn or cfu /100 mL)	Total Coliform (mpn or cfu /100 mL)
Pacific Beach[1]	San Diego	10,300	4,080	63,100
Rose Creek[1]	San Diego	1,990	7,310	69,800
Rose Creek[1]	San Diego	15,300	12,500	92,100
Rose Creek[1]	San Diego	2,400	2,460	34,900
Trancas Canyon[2]	Los Angeles	4,980	15,300	22,800
Brown’s Creek	Los Angeles	10,000	10,600	70,000
Alamo St.[2]	Ventura	12,100	-	206,500
Regional Value		6,700	7,000	62,900

[1] Schiff and Kinney 2001
[2] Los Angeles County Department of Public Works unpublished data
[3] Ventura County Flood Control District unpublished data

Table 2. Flow-weighted mean concentrations (in mpn/100 mL) of indicator bacteria during wet weather at a variety of land use and mass emission sites in the Los Angeles region.

Site	Number of Storms	Number of Samples	Enterococcus	Fecal Coliform	Total Coliform
MASS EMISSION					
Ballona Creek	2	21	40,290	11,480	288,290
Santa Monica Canyon	2	21	28,160	10,810	352,610
LAND USE					
Agriculture	2	25	26,190	22,900	202,080
Commercial	2	22	20,020	3,200	284,560
High density residential	2	22	8,260	14,620	755,560
Industrial	2	18	2,450	1,070	31,630
Low density residential	2	23	8,710	4,900	52,640
Open	1	10	382	59	6,450

Table 3. Model build-up rates for fecal indicator bacteria calibrated by land use in Santa Monica Bay.

Land Use	Fecal Coliform (mpn/ ac*d)	Total Coliform (mpn/ ac*d)	Enterococcus (mpn/ ac*d)
Agriculture	5×10^{10}	3×10^{11}	2×10^{10}
Commercial	5×10^{8}	3×10^{10}	3.5×10^{9}
High Density Residential	3×10^{9}	6×10^{10}	2.5×10^{9}
Industrial	8×10^{7}	3×10^{9}	1.5×10^{8}
Low Density Residential	6×10^{8}	1.5×10^{10}	2×10^{9}
Open	9×10^{9}	8.2×10^{10}	9.5×10^{9}
Transportation	1×10^{8}	3.5×10^{9}	3.5×10^{9}
Mixed Urban	6.6×10^{8}	1.2×10^{10}	2.1×10^{9}

Table 4. Predicted number of days with water quality threshold exceedences for each of the 28 Santa Monica Bay watersheds. Estimates are daily averages or the 90th percentile of one-hour averages each day. Exceedences based on daily averages or 90th percentile of one hour averages are modeled during a median rainfall year or a relative wet (90th percentile rainfall) year.

Watershed	Daily Average		90th Percentile of Hourly Averages	
	Median rainfall	90th Percentile rainfall	Median rainfall	90th Percentile rainfall
Arroyo Sequit	6	10	17	28
Nicholas Canyon	3	5	17	26
Los Alisos Canyon	6	5	17	26
Encinal Canyon	5	5	17	26
Trancas Canyon	8	12	17	29
Zuma Canyon	9	12	17	31
Ramera Canyon	7	10	17	27
Escondido Canyon	7	12	17	29
Latigo Canyon	6	8	17	28
Solstice Canyon	7	12	17	28
Corral Canyon	7	12	17	28
Malibu	23	52	30	62
Carbon Canyon	6	3	17	26
Las Flores Canyon	1	2	17	24
Piedra Gorda Canyon	2	2	17	25
Pena Canyon	2	8	17	28
Tuna Canyon	6	5	17	27
Topanga Canyon	4	9	18	29
Castle Rock	3	9	17	29
Santa Ynez	4	3	17	27
Pulga Canyon	8	13	17	33
Santa Monica Canyon	16	10	44	64
Santa Monica	36	41	58	75
Ballona	343	343	346	346
Dockweiler	12	13	25	33
Hermosa	10	13	23	31
Redondo	15	20	26	35
Palos Verde	11	13	25	32

Figure 1. Map of the Santa Monica Bay watersheds including Malibu Creek, Santa Monica Canyon, and Ballona Creek. Circles indicate land use sampling locations.

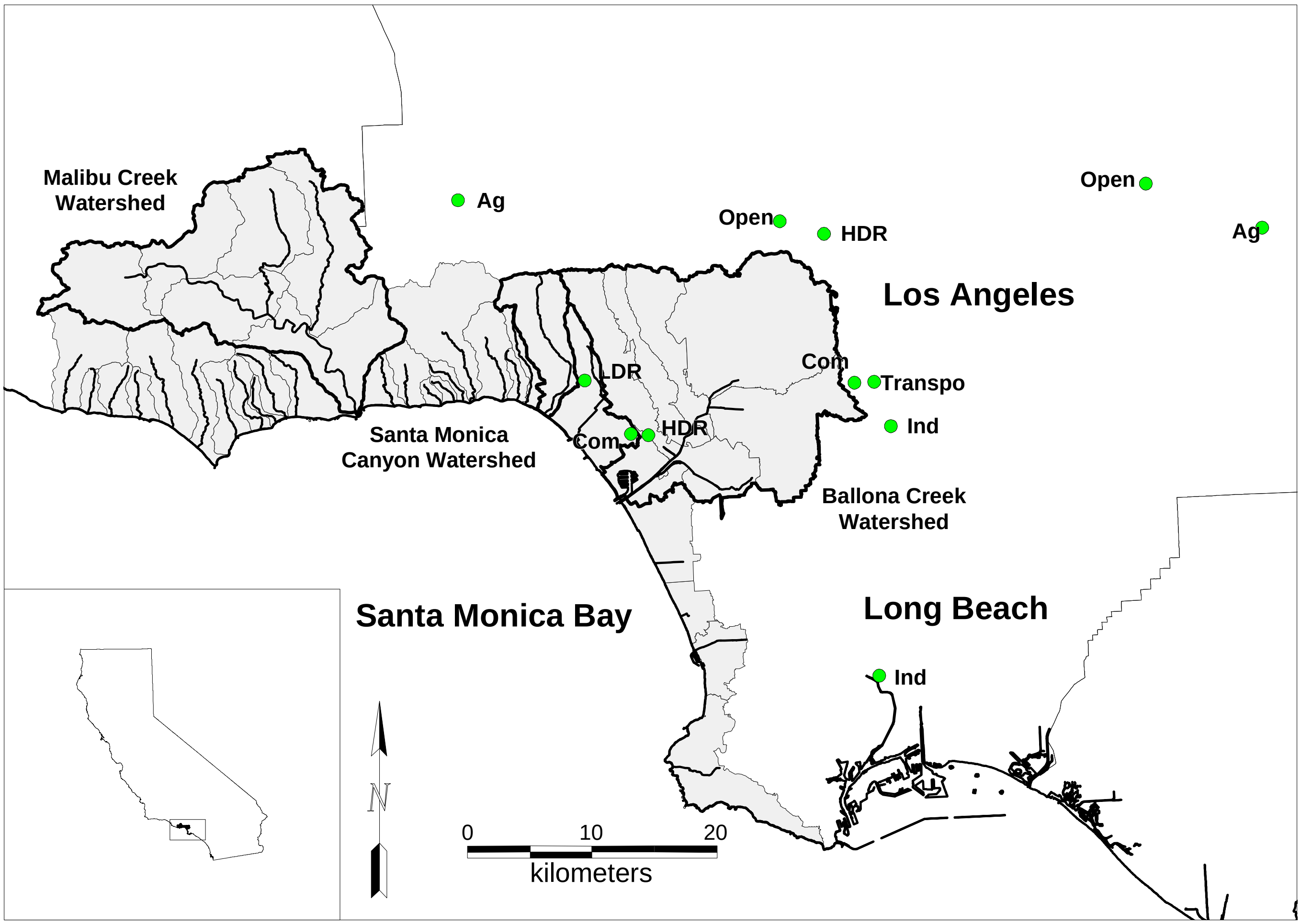

Figure 2. Comparison of flow-weighted mean concentrations (and standard deviation) from modeled versus empirical measurements at five different calibration land use sites.

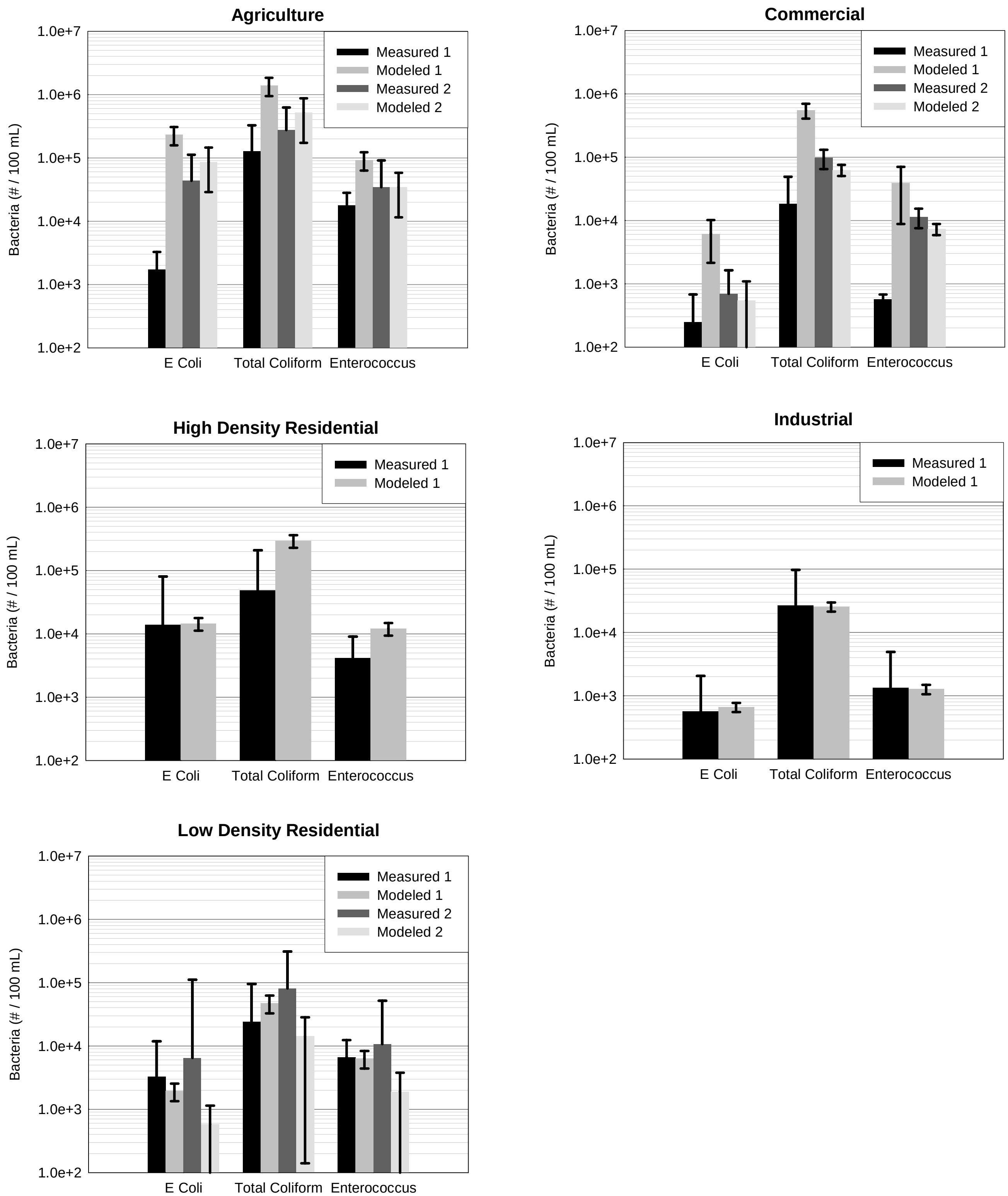

Figure 3. Comparison of modeled and measured pollutographs for indicator bacteria at the Santa Monica Canyon validation watershed (April 7, 2000).

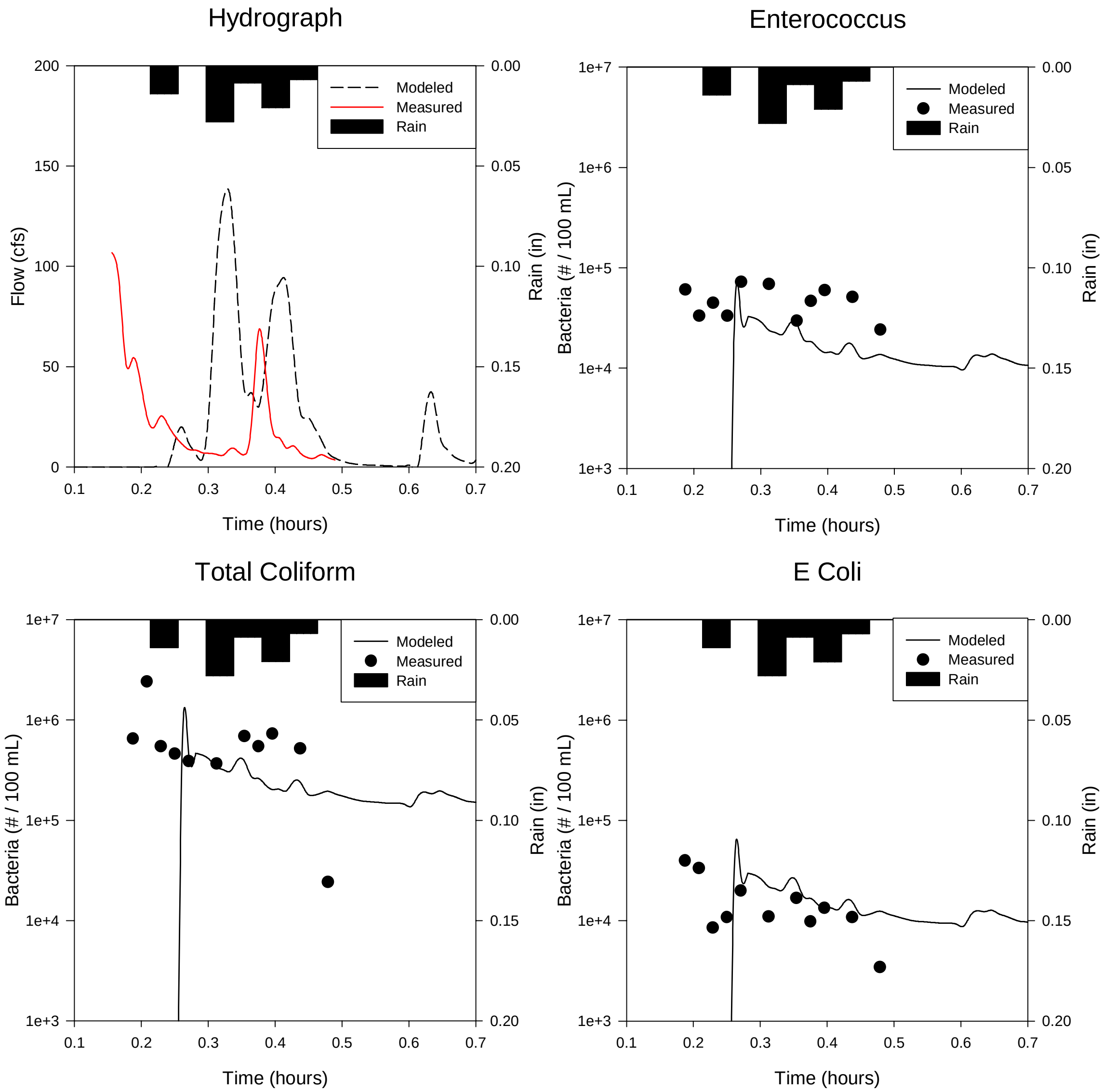

Figure 4. Comparison of flow-weighted mean concentrations (and standard deviation) of indicator bacteria at Santa Monica Canyon and Ballona Creek during validation storm events.

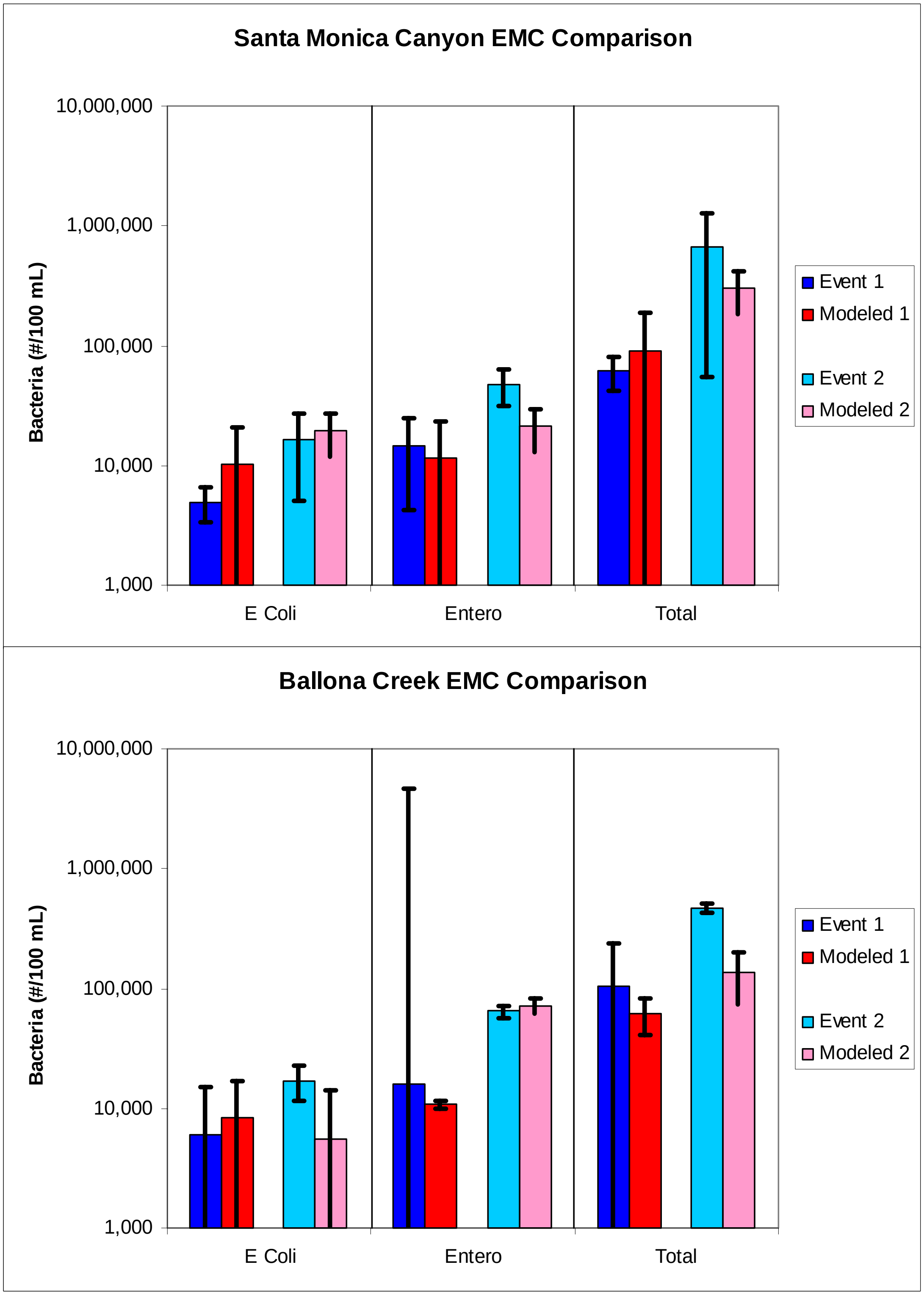

Figure 5. Geometric mean (and standard deviation) of measured and modeled bacteria concentrations during wet weather in Ballona Creek (1997-1999) and Malibu Creeks (1995-1999).

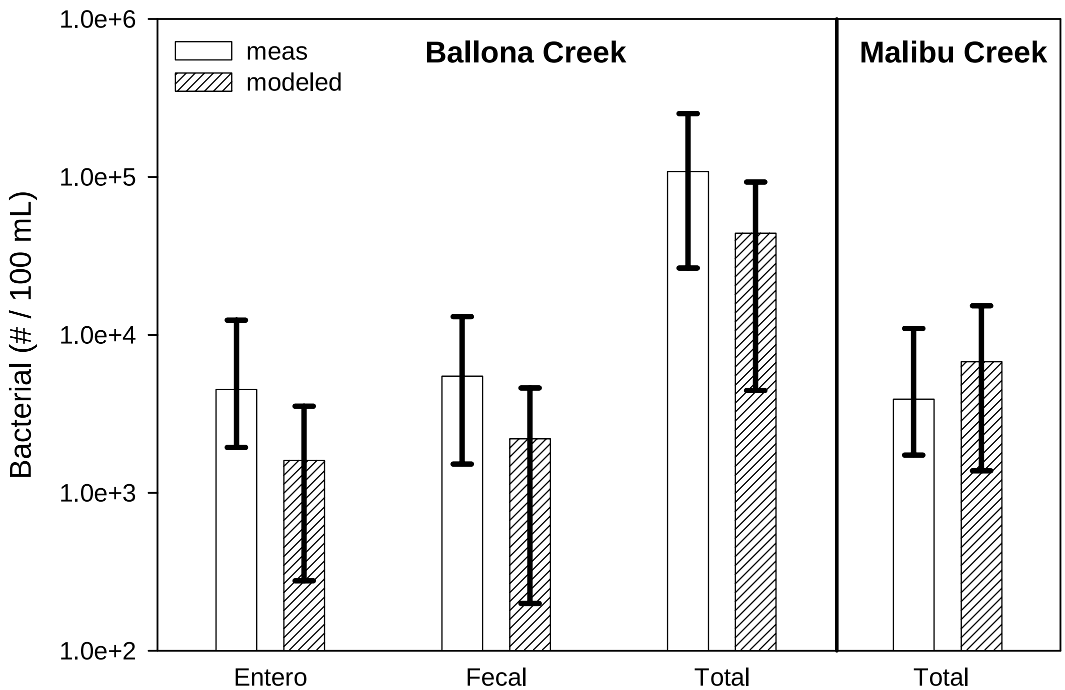

Figure 6. Estimated wet weather loading of enterococcus to Santa Monica Bay during a median rainfall year (1991) from 28 watersheds that contribute bacteria.

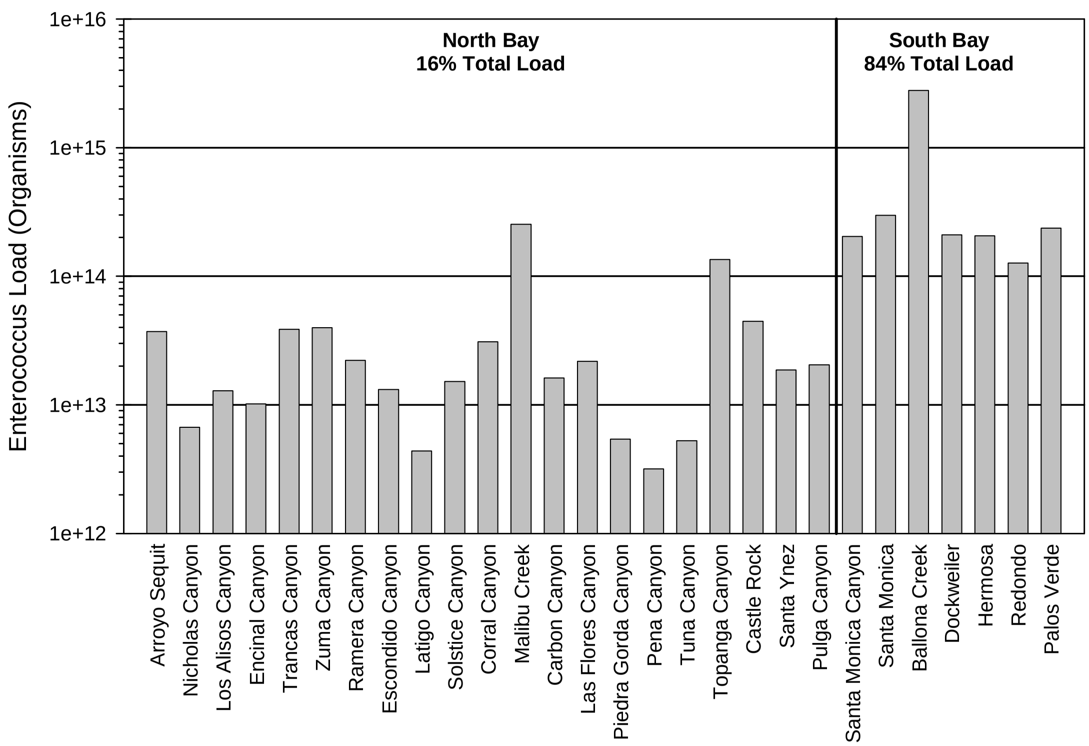

Figure 7. Sensitivity of wet weather enterococcus loads to Santa Monica Bay as a function of increasing or decreasing the bacterial decay rate by 25%.

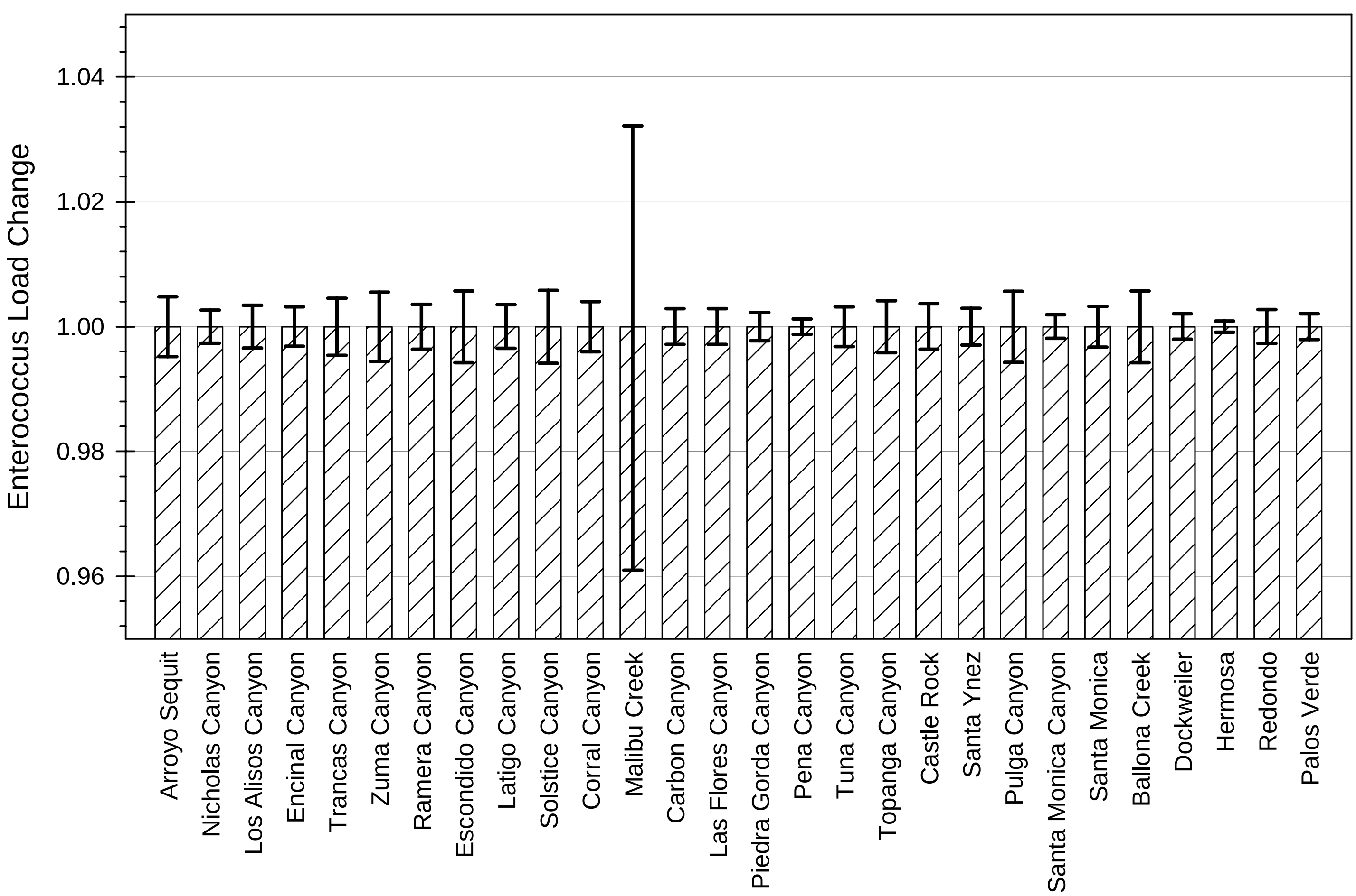

Figure 8. Sensitivity of modeling wet weather enterococcus loads to Santa Monica Bay as a function of decreasing the build-up maximum concentration from 1.8 to 1.5 times the build-up rate. A second analysis used a seasonally time-variable rate of 1.8 from October to March and 1.5 from April to September.

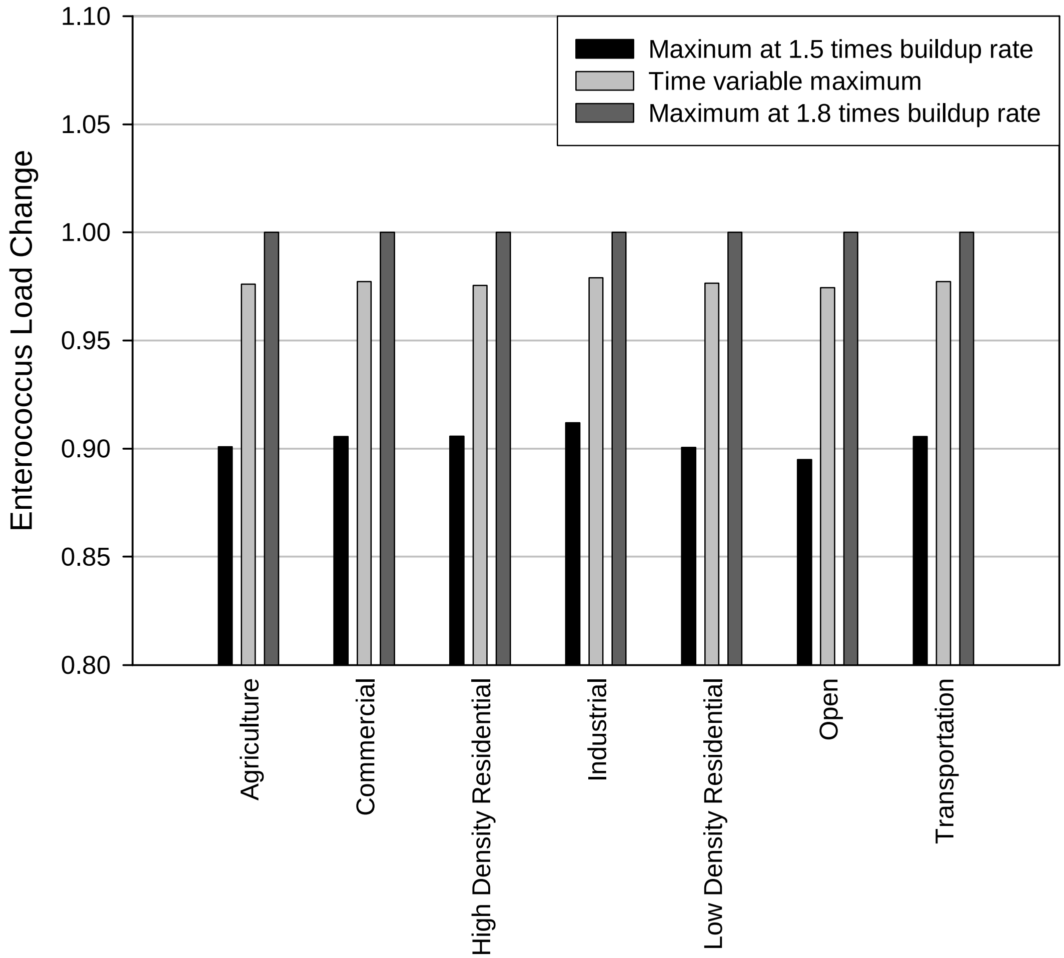

Figure 9. Sensitivity of wet weather enterococcus loads as a function of increasing or decreasing the modeled washoff rate of 90 percent loss in one hour. Wash-off rates of 0.5 are the default model value.