DRY-WEATHER METALS AND BACTERIA LOADING IN AN ARID, URBAN WATERSHED: BALLONA CREEK, CALIFORNIA

ERIC D. STEIN* and LIESL L. TIEFENTHALER
Southern California Coastal Water Research Project, 7171 Fenwick Lane, Westminster, CA 92683-5218, USA
*(*author for correspondence, e-mail: erics@sccwrp.org; Tel: +714-372-9233, Fax: +714-894-9699)*

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Abstract. Dry-season urban runoff from watersheds in arid regions can contribute substantial concentrations and loads of bacteria and metals to downstream receiving waters. However, there are few studies that have evaluated the relative contributions of different sources of these constituents along a specific creek or channel. This study involved analysis of the relative contribution of various storm drain sources to the total dry-season loading of metals and bacteria in the Ballona Creek (California) watershed. Approximately 40 actively flowing storm drains and 12 in-river sites were sampled three times during the spring and summer of 2003 for flow, total and dissolved metals, and bacteria. These data were analyzed in terms of mean concentration and load, temporal variability, and spatial distribution of substantial inputs to the creek. In general, Ballona Creek exhibited a bimodal distribution of elevated metals and bacteria, corresponding to locations where storm drains with consistently high concentrations and loads discharge to the creek. Of the 40 drains sampled, 4 accounted for 85% of the daily storm drain volume. Between 91% and 93% of the total daily load for metals was contributed by eight drains, while nine drains consistently had the highest concentrations of metals and bacteria. Metals concentrations were observed to vary by up to five-fold and bacterial counts by up to five orders of magnitude on an intra- and inter-annual basis. However, despite this variability, a relatively small number of storm drain inputs can be expected to account for the majority of loading.

Keywords: arid watersheds, bacteria, dry season, metals, water quality

1. Introduction

Increased urbanization has been shown to result in increased runoff and pollutant loading to receiving waters (Schueler, 1994; U.S. EPA, 1995; Davis *et al.*, 2001). The high amounts of impervious surfaces associated with urban landscapes result in increased magnitude and frequency of surface runoff during wet-season and dry-weather conditions (Roesner and Bledsoe, 2003). The accumulation of toxic compounds, such as heavy and trace metals, from urban runoff can result in downstream bioaccumulation and toxicity (Schueler, 1994). Similarly, bacterial loading to streams in urban areas has been well documented as one of the most common pollutants affecting aquatic systems (Porcella and Sorenson, 1980; Simpson *et al.*, 2002).

Over the past 10 years, management of urban runoff has focused primarily on the evaluation and control of storm water. However, recent studies have shown that dry-season runoff can be a significant contributor to total annual load (Piechota and Bowland, 2001; McPherson *et al.*, 2002; Ackerman *et al.*, 2003; Stein *et al.*, 2003), particularly in arid environments where dry season stream flow is comprised mainly of urban runoff and other effluent. The distinction between wet- and dry-season pollutant loading characteristics is important because management strategies differ for these two sources. For example, storm water management typically focuses on retention or detention, whereas dry-season runoff control focuses on treatment, diversion, infiltration, and source control.

Management strategies for dry-weather pollutant loading such as diversion, treatment, and source control rely on an understanding of the specific sources or locations in the watershed that contribute the greatest proportional loading. Source identification can be particularly problematic in urban watersheds that are dominated by non-point source runoff. In contrast to watersheds where wastewater or industrial effluent comprises a significant source that can be managed, watersheds dominated by urban runoff have many sources of different sizes distributed throughout the watershed. Understanding the relative contribution of these sources to receiving water loading is critical to efficient allocation of source control strategies.

The Ballona Creek watershed in the greater Los Angeles, California, area provides an optimum environment for conducting a source identification study. The watershed is approximately 80% urbanized, and there are no permitted wastewater or consistent industrial discharges to Ballona Creek (with the exception of discharges associated with construction, cleanup, and dewatering activities). Consequently, almost all the dry-season flow in Ballona Creek results from nuisance runoff from urban surfaces. Routine monitoring of dry-weather flow by the City of Los Angeles in 2001 and 2002 showed detectable levels of arsenic, cadmium, chromium, copper, nickel, zinc, and lead with concentrations of cadmium, copper, nickel, zinc, and lead exceeding State water quality criteria on at least an occasional basis. McPherson *et al.* (2002) characterized long-term wet and dry-weather flow and loading from the Ballona Creek Watershed and determined that between 10% and 30% of annual runoff volume and between 8% and 42% of the total annual load of trace metals occur during the dry season. This translates to between 100 and 500 kg/yr of dry-season loading for most metals. Suffet and Stenstrom (1999) also found elevated concentrations of certain volatile organic carbon (VOC) in dry-season runoff from Centinela Creek (a tributary to Ballona Creek). Although previous studies have documented dry-weather concentrations and loads within Ballona Creek, none have investigated contributions from storm drains draining various portions of the watershed.

The goal of this study was to investigate spatial patterns of dry-season metals concentrations and mass emissions and bacterial counts in Ballona Creek and to link these patterns with storm drain inputs that contribute to in-river mass emissions. The second goal of this project was to characterize the temporal variability in sources and in receiving water quality. The results of this investigation may be used by watershed managers to determine appropriate strategies to control dry season water quality, such as clean up or diversion of specific storm drains, identification of constituents of concern, and identification of key watershed sources of the constituents of concern.

2. Methods

2.1. Study area

The 329 square kilometers (km^2) Ballona Creek watershed (Figure 1) is located at the north end of Los Angeles, California. The watershed drains through Marina del Rey to the Pacific Ocean and includes portions of the Santa Monica Mountains on the north and the cities of Baldwin Hills and Inglewood on the south. Major tributaries to Ballona Creek include Centinela Creek, Sepulveda Canyon Channel, and Benedict Canyon Channel. Land use within the watershed consists primarily of residential, commercial, industrial, public, and other urban usages.

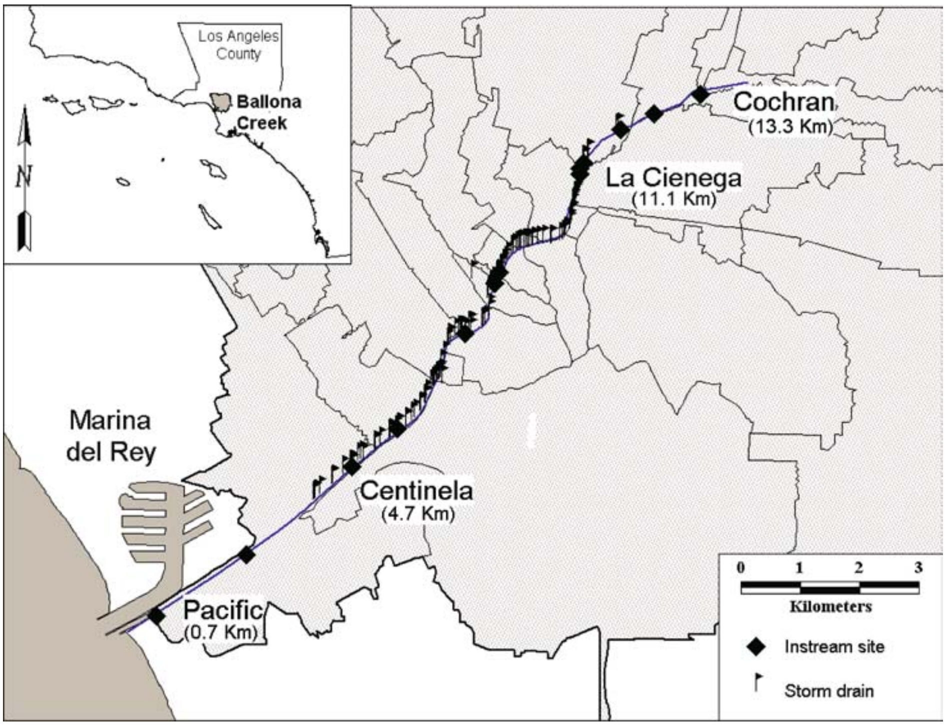

Figure 1. Map of the Ballona Creek watershed. Map showing storm drain and in-river sampling locations.

2.2. Sampling

Storm drain inputs and in-river waters were sampled along the entire 12.7 km of Ballona Creek. Sampling was conducted on May 17, July 16, and September 24, 2003. The last rain prior to the May 17 sampling occurred on May 3 (3.3 cm), and no measurable rain fell between the May and September sampling events. Each event sampled the same location and sampling was conducted in the morning to minimize the effects of diurnal variability.

Approximately 90 storm drains and 12 in-river sites were identified and located for potential sampling using a Garmin® handheld global positioning system (GPS). Of these, all 12 in-river sites and between 35 and 40 storm drains were sampled during each sampling event. The remaining drains lacked sufficient flow to sample or were inaccessible. The 35 to 40 drains sampled spanned the entire above-ground portion of Ballona Creek. At each storm drain sampled, flow was measured using a timed-volumetric or depth-velocity method (whichever was more appropriate for the conditions at a given location). In-river flow was measured at each site using a Marsh-McBirney Model 2000® flow meter. Flow was measured at three points across the channel cross-section and integrated to estimate overall flow at each site.

Water quality samples were collected from storm drains and in-river sites, and immediately placed on ice for subsequent analysis. Storm drains samples were collected by directly filling a single bottle from each drain. At the in-river locations, three composite samples were collected at 20-min intervals. Each composite consisted of three grab samples collected at approximately equal intervals across the channel cross-section. Water samples were analyzed for metals (total and dissolved) and bacteria following protocols approved by the U.S. EPA (1983) and Standard Methods (APHA, 2000). Metals were analyzed using inductively coupled plasma (ICP) methods and bacteria were analyzed using the Idexx QuantiTray® method using the detection limits shown in Table I. Sampling locations are referenced by their distance in kilometers upstream of the mouth of Ballona Creek.

2.3. Data analysis

Results of the flow and water quality sampling were analyzed for spatial and temporal patterns. Means and ranges of flow and concentration for storm drains and in-river sites were analyzed by individual sampling date and by combining the results of all three sampling dates. Constituent mass emissions (i.e. the mass load discharged) for storm drain and in-river sites were calculated by multiplying flow times concentration for each sample:

$$\text{Load} = \sum F_i C_i$$

where F_i was the flow at sampling location i and C_i was the constituent concentration at location i. When multiple samples were averaged, results are presented as

TABLE I
Constituents analyzed

Constituent	Min. Detection Limit (MDLs)	Units	Analytical method
Metals (total and dissolved)			
Arsenic	0.4	ug/L	USEPA 200.7
Calcium	0.03	mg/L	
Magnesium	0.004	mg/L	
Cadmium	0.08	ug/L	USEPA 200.7
Chromium	0.7	ug/L	USEPA 200.7
Copper	1.5	ug/L	USEPA 200.7
Iron	24	ug/L	USEPA 200.7
Lead	3.0	ug/L	USEPA 200.7
Nickel	0.24	ug/L	USEPA 200.7
Selenium	1.4	ug/L	USEPA 200.7
Silver	0.26	ug/L	USEPA 200.7
Zinc	2.0	ug/L	USEPA 200.7
Mercury	0.022	ug/L	USEPA 200.7
Hardness	–	mg/L	SM 2340-B
Bacteria			
Total coliforms	100	MPN/100 mL	Idexx QuantiTray
E. coli	100	MPN/100 mL	Idexx QuantiTray
Enterococcus	10	MPN/100 mL	Idexx QuantiTray

means ±1 standard deviation. Differences between sampling events were investigated using a one-way analysis of variance (ANOVA), with $p < 0.05$ significance level (Sokal and Rohlf, 1969). In all cases, non-detectable results were assigned a value of zero. For bacteria, results that were greater than the maximum quantifiable levels were assigned the maximum value for that test.

3. Results

3.1. Flow

Average in-stream flow in Ballona Creek was 0.34 ± 0.17 cm during the May and September sampling event and 0.73 ± 0.17 cm during the July sampling event. The reason for higher observed flow in July is not known, but could have been due to either a temporary permitted or illicit discharge to the creek. Flow generally increased from upstream to downstream until the point where tidal influence begins (approximately 5 km upstream from the mouth of the creek). Substantial inflows occur near the upper portion of the watershed (7.7 km) where a series of underground storm drains discharge to Ballona Creek and near the lower portion of the watershed (5.8 km) where a large tributary watershed (Sepulveda Channel) confluences with Ballona Creek.

Preliminary surveys identified approximately 90 storm drains that potentially discharge into Ballona Creek. Of these, between 25 and 40 were actively flowing, and were sampled during each sampling event. Of the storm drains sampled, only 21% (9 drains) were flowing above 0.01 cm. Approximately 85% of the 54,000 m^3/day discharged from flowing storm drains was attributable to four storm drains. Variability in storm drain flow, ponding effects, and drain obstructions precluded obtaining flow measurements in every drain during each sampling period.

3.2. METALS

3.2.1. *Metals Concentrations*

Consistent detectable in-river concentrations of copper, iron, lead, nickel, and zinc were observed in Ballona Creek and in the storm drains during all three sampling events (Table II). With the exception of iron (which is primarily a natural earth element), subsequent results and discussion will focus on copper, lead, nickel, and zinc.

In-river metals concentrations varied spatially and temporally. Results of the ANOVA between sampling times indicate that for copper, iron, lead, and zinc, in-river concentrations were significantly higher in July than during the other two sampling events. Results of the May sampling event were generally lower, but the differences between the May and September sampling events were only significant at approximately 30% of the sampling locations. Cadmium and chromium

TABLE II

Mean total metals concentrations, plus standard deviations for all storm drain samples for all sampling events

	Minimum	Mean	SD	Maximum	% Non Detects
Arsenic	ND	3.72	2.81	13.8	16%
Cadmium	ND	0.13	0.33	2.4	75%
Chromium	ND	1.72	1.92	11	28%
Copper	ND	19.85	28.98	232	3%
Iron	ND	524.67	1129.41	7680	1%
Lead	ND	4.41	12.66	102	60%
Nickel	ND	7.32	22.72	25	3%
Selenium	ND	7.19	12.72	100	53%
Zinc	ND	83.25	241.18	2190	2%

Units are in ug/L. In all cases $n = 103$. ND = not detected.

concentrations did not vary between the three sampling events. Temporal variability in the storm drain samples was less pronounced than in the in-river samples. Although storm drain metals concentrations in July and May were consistently the highest and lowest, respectively, differences between sampling periods were less than significant.

Spatial patterns in metals concentrations were relatively similar between metals. The highest mean in-river concentrations of copper, zinc, and nickel were observed immediately downstream of Sepulveda Channel, which drains a 42 km^2 portion of the watershed. Smaller peaks in in-river concentrations for copper, lead, nickel, and zinc were observed downstream of a large storm drain that drains the eastern 60 km^2 of the watershed. These second peaks were most pronounced for copper and zinc.

Of the 35 to 40 storm drains sampled, a relatively small number of drains had high metals concentrations; the locations of these drains roughly correspond to locations of high in-river concentrations. Five storm drains had mean concentrations that were significantly higher ($p < 0.05$) than the other drains. Concentrations in all these drains exceeded twice the mean for all storm drains combined for at least one of the four metals of interest. The locations of these drains roughly correspond to the two locations where in-river peaks in metals concentration were observed.

Comparison of total and dissolved metals concentrations for both storm drains and in-river sites showed that dry-season metals occur predominantly in the dissolved phase, which is generally more bioavailable than the particulate phase (Figure 2).

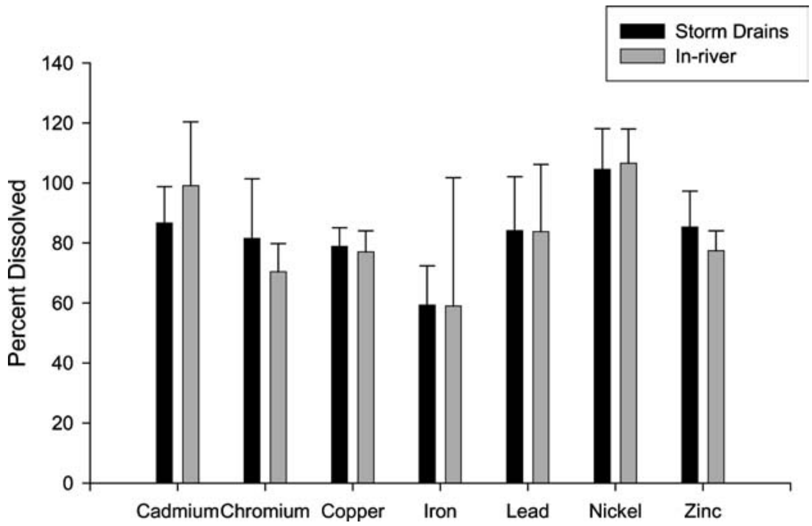

Figure 2. Comparison of percent dissolved metals. Percent of total metals as dissolved fraction in samples collected from storm drains and in-river sites.

3.2.2. *Metals Loadings*

Spatial patterns of in-river metals mass emissions were similar to those observed in the concentration data (Table III). Relatively high in-river metals mass emissions were observed at two locations in the watershed that exhibited the highest storm drain mass loading (Figure 3). Between 91% and 93% of the total daily storm drain mass loading for each metal was accounted for by between 5 and 7 drains (Table IV). Overall, eight storm drains were responsible for the majority of daily mass load for all metals analyzed, and two drains accounted for between 48% and 77% of the total daily storm drain mass load.

3.3. Bacteria

Relatively high bacterial counts were observed throughout Ballona Creek and in all storm drains (Table V). Bacterial counts exhibited a wide range of variability, as indicated by the large standard deviations on all sample means. Although bacterial counts appeared to be slightly higher in July than during the other two sampling events, there were no statistically significant differences between sampling periods for bacteria.

Spatial patterns in bacterial counts were similar to those observed for the metals. In-river *E. coli* and *Enterococcus* concentrations were highest between 4 km and 5 km and between 9 km and 11 km (Figure 4). The spatial pattern of total coliforms concentrations was somewhat random; however, this is likely confounded by the high proportion of samples that exceeded the maximum detection limit, along with the ubiquitous nature of total coliforms.

Of the 35 to 40 storm drains sampled, nine had consistently high concentrations for *E. coli* or *Enterococcus* and three had high concentrations for both bacterial indicators. There was generally only a weak relationship between high in-river bacteria levels and the location of storm drains with high bacterial counts (Figure 4).

4. Discussion

Results of the dry-season sampling conducted in Ballona Creek during the spring and summer of 2003 illustrated clear spatial patterns of mass emission and concentration, and identified some of the primary dry-weather sources of bacteria and metals. Ballona Creek appears to have a bimodal distribution of elevated loads and concentrations, with the highest levels of metals and bacteria occurring between 3 km and 6 km, immediately upstream of the tidal portion of the creek and between 9 km and 12 km, below the portion of the watershed where Ballona Creek daylights from an underground storm drain to an exposed channel.

Metals loading in Ballona Creek appears to be influenced mainly by less than 10 storm drains. The spatial pattern of metals load in Ballona Creek corresponds to the locations of eight storm drains that account for more than 90% of the metals

TABLE III

Mean in-river mass emissions of total metals during the entire sampling period

			Mass Emissions (g/day)							
			Total Copper		Total Lead		Total Nickel		Total Zinc	
Station ID	River Distance from Mouth (Km)	*N*	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Pacific	0.72	NF	NF	NF	NF	NF	NF	NF	NF	NF
Lincoln	2.53	NF	NF	NF	NF	NF	NF	NF	NF	NF
Centinela	4.67	6	27.0	31.7	16.1	7.0	13.7	12.2	63.9	54.6
Sepulveda Channel	5.82	6	477.8	86.7	251.8	108.3	183.6	79.6	1821.8	324.8
Overland	7.7	9	354.5	158.1	194.6	108.0	127.0	65.5	1506.9	432.1
Duquesne	8.62	9	386.4	258.8	184.9	57.7	111.3	74.6	1045.6	719.6
Higuera	8.8	NF	NF	NF	NF	NF	NF	NF	NF	NF
National	10.92	9	762.2	944.7	357.4	288.6	156.2	123.7	1921.0	2165.9
La Cienega	11.09	6	1144.2	970.6	529.0	278.9	196.4	152.6	2436.8	2135.1
Fairfax	11.94	8	494.5	698.3	250.8	410.3	84.6	93.9	902.5	1314.8
Thurman Overpass	12.5	2	0.5	0.6	0.0		0.1	0.1	0.6	0.7
Cochran	13.28	9	197.5	134.0	70.3	38.1	60.3	37.9	461.0	352.2

Units are in g/day.
NF = No flow data.

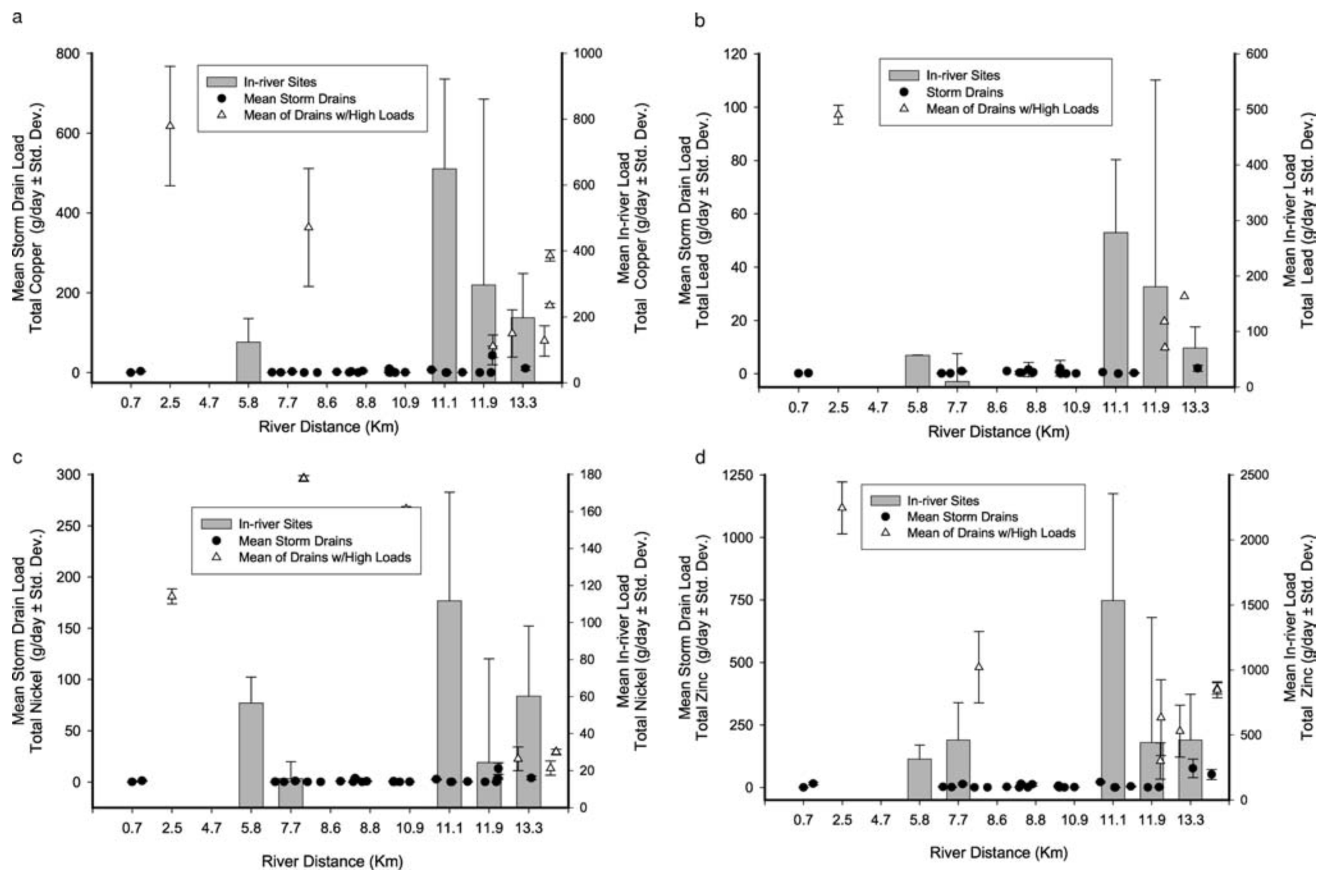

Figure 3. Change in mean in-river metals mass emissions. Graph shows the locations and magnitudes of increases in mean in-river mass emissions (± standard deviation) for all three sampling events combined for (a) total copper, (b) total lead, (c) total nickel (right *y*-axis) (d) total zinc. Left *y*-axis shows mean storm drain mass emissions (± standard deviation) by position along Ballona Creek. Triangles indicate storm drains that collectively contributed 90% or more of the mass emissions to the creek.

TABLE IV
Storm drains contributing the greatest proportion of daily mass load

	Copper	Lead	Zinc	Nickel
BC17	33.5%	62.1%	32.9%	29.4%
BC60	19.8%		14.8%	47.9%
BC199		5.2%	3.3%	
BC200	3.6%	2.6%	8.6%	
BC210	5.3%	18.6%	7.0%	3.7%
BC299	4.3%			2.2%
BC300	9.1%		12.2%	4.8%
BC310	15.9%	3.6%	12.0%	4.8%
Mean Daily Load ± SD (g/day)	1841 ± 126	156 ± 17	3244 ± 210	616 ± 57
Percent of Total Daily Load Due to Listed Drains	91.5%	92.1%	90.8%	92.8%

Note. The percent of total mean daily mass load contributed by each of the listed drains. Drains listed account for a combined total of greater than 90% of the total daily storm drain mass load to the creek.

TABLE V
Geometric mean storm drain bacteria counts and standard deviations for all locations over all three sampling events combined

Constituent	Minimum	Geo Mean	SD	Maximum	Percent Exceeding Maximum Detection Limit
E. coli	<100	4.7E+03	1.5E+04	140,000	4.5%
Enterococcus	<10	5.9E+03	8.8E+03	>240,000	12.0%
Total coliforms	<100	1.0E+05	9.6E+04	>240,000	21.8%

Units are MPN/100 mL. *E. coli* and Total coliforms $n = 110$. *Enterococcus* $n = 108$.

loading to the creek. Two of these drains contribute 50% of the daily storm drain volume and between 48% and 77% of the daily storm drain metals load. However, these drains discharge to the lower portion of Ballona Creek and are associated with only moderate increases to in-river mass emissions. Five drains that discharge to the upper portion of Ballona Creek (in the area where it transitions from an underground storm drain to an above-ground channel) appear to have the greatest effect on in-river metals mass emissions. These five drains account for between 16% and 40% of the total daily metals load; however, because they discharge to the upper portion of Ballona Creek, they have a proportionately larger effect on in-river mass emissions. Other factors undoubtedly contribute to increases in in-river concentrations and mass emissions, such as the potential for tidal recirculation in the

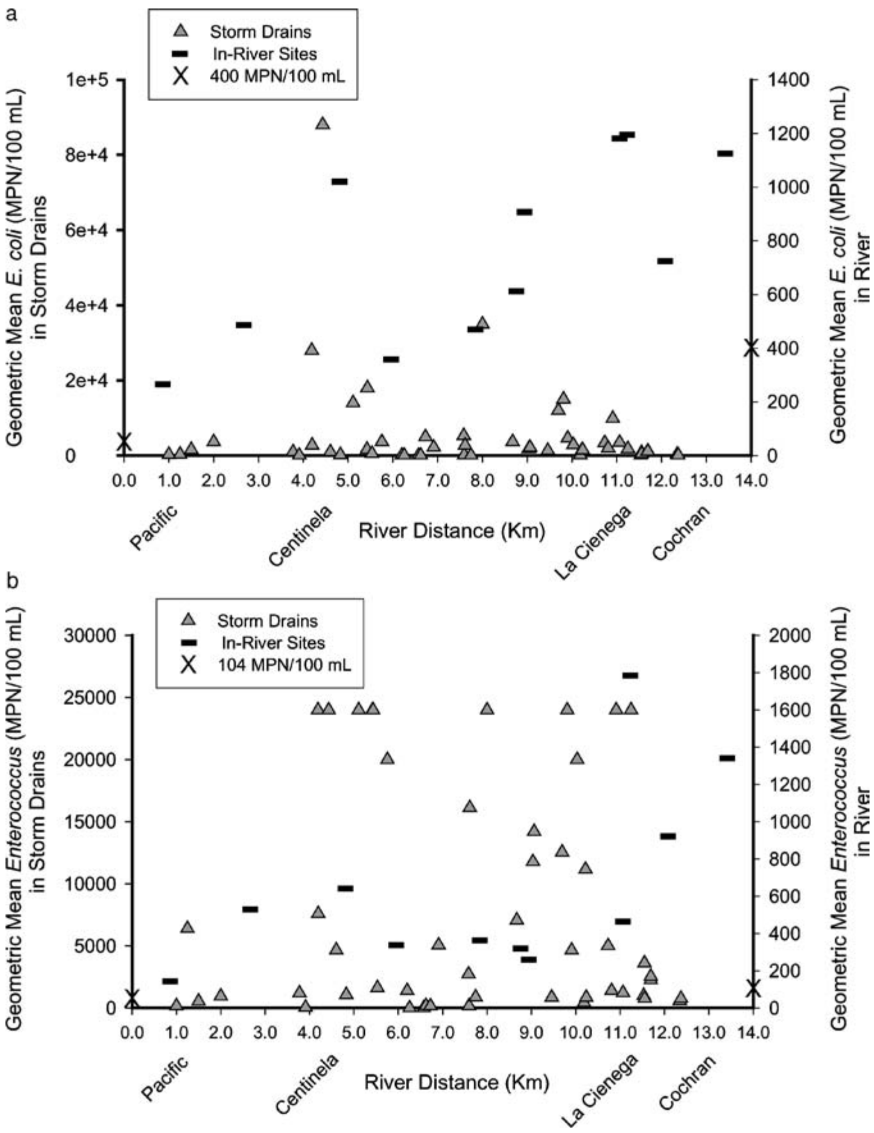

Figure 4. Mean in-river and storm drain bacterial counts. Concentrations of (a) *E. coli* and (b) *Enterococcus* in storm drain and in-river sites in Ballona Creek. Storm drain concentrations are shown on the left axis, in-river concentrations on the right axis. "X" on y-axis = maximum allowable level under State water quality standard.

lower reaches transporting constituents discharged from Centinela Channel back up into the lower reaches of Ballona Creek. Nevertheless, a relatively small number of storm drains contribute a disproportionate load of metals to Ballona Creek.

Although consistent spatial patterns of bacteria and metals were observed between individual sampling events, the magnitude of concentration and mass emissions varied by more than five-fold over the course of a year, as well as between years. Some of the scatter in the storm drain and in-river metals concentrations is likely due to intra-annual variability in the system. Several potential sources of variability may result in a non-steady state condition, such as illicit discharges, permitted periodic discharges of industrial or construction-related effluent, and inherent variability in storm drain discharges. Given this variability, the choice of a single sampling period for this study could have resulted in different conclusions. For example, if samples were collected only in July, conclusions regarding average concentrations would have been higher than if samples were collected solely in May. Conversely, if data from the July sampling event were omitted, the mean in-river concentration would have been 8 ug/L instead of 11 ug/L. In addition to intra-annual variability, metals concentrations may also vary up to five-fold from year to year. For example, measured copper concentrations at 2.5 km (Lincoln Boulevard) were 29 ug/L in 1999 (McPherson *et al.*, 2002), "not-detected" in 2002 (City of Los Angeles 2002), and 6 ug/L in 2003 (this study). Therefore, it is important to account for this variability when assessing the condition of the creek and its compliance with water quality standards; and management decisions should not rely on measurements taken at a single point in time.

Bacterial counts typically vary by up to five orders of magnitude on daily, seasonal, and inter-annual scales. The greater variability observed in bacteria vs. metals data (i.e., several orders of magnitude vs. several fold) is expected. As living organisms, bacterial counts may be affected by many processes that do not influence metals, such as growth, die-off, and random fluctuations in population size. Furthermore, the analytic method used to quantify bacteria is based on colorimetric estimation of bacterial density, which is inherently less precise than the approach used to quantify metals (mass spectroscopy). The extreme variability in the bacteria indicators necessitates more frequent monitoring over longer time periods than for metals in order to make assessments of "typical" bacterial counts. Furthermore, between 5% and 22% of storm drain samples exceed the maximum detectable bacterial counts (depending on the specific indicator). Therefore, mean concentrations reported from storm drains underestimate the actual bacteria levels being discharged to the creek. Regardless, bacterial counts from in-river and storm drain samples consistently and uniformly exceed water quality standards in almost all locations.

The manner in which samples with non-detectable levels of a particular metal are treated may also affect overall estimates of load. Non-detectable values may be assigned a value of zero, half the detection limit, or assumed to equal the detection limit. The degree to which this choice influences general conclusions about loading depends on the frequency of non-detectable values. For the four metals focused on in this study, only storm drain lead samples had a substantial fraction of non-detectable values (60%). In contrast, almost all the in-river samples contained detectable lead levels. If we had assumed that non-detectable values were equal to half the detection limit (instead of zero), our estimate of storm drain load would have increased by

43%; but our estimate of in-river mass emissions would have only increased by 16%. If we had assumed that non-detectable values were equal to the detection limit, our estimate of storm drain load would have increased by 100%, but our estimate of in-river mass emissions would have only increased by 29%. Therefore, for lead, the choice of values to assign to non-detectable results may affect conclusions regarding the spatial distribution of sources and compliance with water quality standards.

The concentrations and loads of metals and bacteria observed in Ballona Creek are comparable to those observed in the dry-weather flow of other urban watersheds, such as the Los Angeles River (Ackerman *et al.*, 2003). For example, daily zinc load in the Los Angeles River (exclusive of publicly owned treatment work (POTW) discharges) was 2,300 g/day, compared to a mean zinc load of 1,442 g/day in Ballona Creek, upstream of the tidal area. Similarly, the daily copper load in the Los Angeles River was 1,036 g/day compared to 545 g/day in Ballona Creek. If the Los Angeles River loads are adjusted for differences in watershed size (834 km^2 vs. 329 km^2), the loads are even more similar: 920 g/day vs. 1,442 g/day for zinc and 414 g/day vs. 545 g/day for copper. Two possible interpretations may account for this similarity. Similar dry-weather metals concentrations could reflect natural background loadings from the two watersheds. Alternatively, similar sources (e.g., residential and commercial runoff, aerial deposition) could be contributing to watersheds. The lack of an undeveloped upper watershed in Ballona Creek, as exists in the Los Angeles River, favors the second explanation. However, further investigation of natural background loadings and aerial deposition will be necessary to answer this question.

Storm drain bacterial counts in Ballona Creek were 20% higher on average than those observed in the Los Angeles River. The mean *E. coli* concentration was 47,000 MPN/100 mL vs. 21,000 MPN/100 mL; and the mean total coliform concentration was 100,000 MPN/100 mL vs. 80,000 MPN/100 mL in Ballona Creek and the Los Angeles River, respectively. These differences are consistent with the uniformly high bacterial counts found in the highly urbanized Ballona Creek watershed.

Finally, as reported in previous studies (McPherson *et al.*, 2002; Stein *et al.*, 2003), dry-season metals load may constitute from a minor to an appreciable portion of total annual load in arid urban watersheds, depending on the amount of annual rainfall. Watersheds such as Ballona Creek experience storm flows approximately 15% of the time (based on 10 years of flow data). During the remainder of the year, dry-weather urban runoff is the predominant source of in-river flow. Comparing empirical data from this and other studies (McPherson *et al.*, 2002; Stein *et al.*, 2003; City of Los Angeles unpublished data) to estimates of storm water loading (Ackerman *et al.*, in preparation) shows that in years with low rainfall, such as 2001–2002, dry-season metals loading may comprise 10% to 25% of the total annual load. Similarly, modeling results show that the relative contribution of dry-season loading to total annual load varies from just over 10% during dry years to less than 1% during wet years, although up to 30% of the total annual volume discharged may occur during the dry season (Ackerman *et al.*, in preparation). Consequently, dry weather mass emissions may substantially affect annual water quality in arid, urban watersheds.

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