Levels and patterns of fecal indicator bacteria in stormwater runoff from homogenous land use sites and urban watersheds

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ABSTRACT

Routine stormwater monitoring programs focus on quantification of average fecal indicator bacteria (FIB) concentration at the terminal watershed discharge point. While important for permit compliance, such monitoring provides little insight into relative bacteria levels from different land use types or the mechanisms that influence FIB concentrations. The goal of this study was to quantify the relative levels and flux patterns of *Escherichia coli*, enterococci, and total coliforms from representative land use (LU) types. Bacteria concentrations were measured over the entire storm duration from 8 different LU types over 13 storm events in 5 southern California watersheds during the 2000–2005 storm seasons. In addition, runoff samples were collected from 8 bottom of the watershed mass emission (ME) sites. Intra-storm and intra-season patterns were investigated in order to identify mechanisms that influence patterns of FIB concentrations. Mean FIB event mean concentrations (EMCs) at LU sites ranged from 10^3 to 10^5 MPN/100 ml. Recreational (horse stables) LU sites contributed significantly higher storm EMCs than other LU types. Early season storms repeatedly produced higher EMCs than comparably sized late season storms. For most storms sampled, the highest bacterial concentrations occurred during the early phases of stormwater runoff with peak concentrations usually preceding peak flow.

Key words | bacteria, event mean concentration, land use sources, mass emissions, southern California, stormwater

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INTRODUCTION

Fecal indicator bacteria (FIB) in urban stormwater is known to occur from many sources, including runoff from fertilized cropland, animal wastes associated with residential development, failing septic or sewer systems, and urban storm drains (Cook & Baker 2001; Moog & Whiting 2002; Jamieson *et al.* 2003).

Bacteria in stormwater runoff from developed and undeveloped land uses often result in high levels in downstream receiving waters (Edwards *et al.* 1997; Crowther *et al.* 2002; Sigua *et al.* 2010). Increased bacteria levels can cause management concerns in terms of public and ecological health and can affect the ability of areas to achieve intended recreational uses (Jones 1997). As a result, there is increasing regulatory and economic pressure to reduce FIB levels. Reduction is most effectively done via Best Management Practices (BMPs) designed to control sources and improve water quality of downstream systems (Inamdar *et al.* 2002; Makarewicz 2009). For example, Lewis *et al.* (2010) reported that for every 10 m of buffer length, there was a 24% reduction in fecal coliform in runoff from pastures fertilized with manure. Similarly, Miller *et al.* (2008) showed that vegetated buffer strips and straw mulch BMPs significantly reduced *Cryptosporidium* and fecal coliform concentrations in storm water runoff.

Although effective, installation and maintenance of BMPs can be costly. Knowledge of relative FIB levels from different types of land use can help managers make informed decisions

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regarding priority areas for BMP implementation. Such knowledge can also be used in concert with studies of bacterial sources, such as those by Dombek *et al.* (2000) and Griffith *et al.* (2003) and to begin reducing the most prevalent sources of bacteria. BMP implementation can also be informed by knowledge of inter and intra storm patterns in bacteria concentrations, which can allow targeting of certain storms or periods within a storm for runoff control.

Previous studies conducted by Tiefenthaler *et al.* 2008 and Stein *et al.* 2006, to understand the complex spatial and temporal patterns that affect trace metals and polyaromatic hyrdorcarbons (PAHs) in storm water runoff from a variety of land uses in the greater Los Angeles region, showed that peak concentrations were observed during the early part of the storm and that the highest constituent loading was observed early in the storm season. The present research adds to the previous studies by characterizing patterns of FIB in stormwater runoff from developed land surfaces.

The goal of this study is to improve understanding of the sources and spatial and temporal patterns of bacteria in urban runoff. We accomplish this goal by quantifying bacteria event mean concentration (EMC) and flux associated with storm water runoff from representative land uses; compare EMC and flux between urban (developed) and non urban (undeveloped) watersheds; and investigate within-storm and within-season factors that affect bacteria concentration and flux.

METHODS

Study areas

Stormwater bacteria data were collected from 10 urban and 2 non-urban watersheds in the greater Los Angeles metropolitan area in southern California. Urban watersheds were densely populated (approximately 90 residents/km^2; US Census Bureau 2000) ranging from 49 to 94% developed. In contrast, the two non-urban watersheds each had less than 5% urban area.

Within the urban and non-urban watersheds, stormwater runoff was sampled from a range of homogenous land use (LU) sites as well as mass emission (ME) sites that integrate runoff from all the LU types in contributing watersheds (Table 1; Figure 1). The ME sites consist of natural streams in the two undeveloped watersheds and engineered flood control channels (highly modified rivers) in the developed watersheds, all of which ultimately discharge to recreational beaches and harbors along the Pacific Ocean. The 8 ME sites ranged in size from 31 to 2,161 km^2 and were sampled during the 2000–2001 through 2004–2005 storm seasons (Table 1). The 19 homogeneous LU sites were sampled over the same time period and represent 8 LU types. LU categories included

Table 1 | Sampling sites with corresponding watershed size and number of storms sampled. NA = size not available

	Watershed size (km^2)	No. of storms sampled
Mass Emission Sites		
LA River above Arroyo Seco	1460	3
LA River at Wardlow	2161	4
Verdugo Wash	65	4
Arroyo Seco	130	2
Ballona Creek	338	7
Dominguez Channel	187	2
Santa Monica Canyon	41	2
Open Space Arroyo Sequit	31	4
Land Use Sites		
High Density Residential (#1)	0.017	3
High Density Residential (#2)	0.518	2
High Density Residential (#3)	1.000	2
Low Density Residential (#1)	0.977	3
Low Density Residential (#2)	0.177	1
Commercial (#1)	NA	1
Commercial (#2)	2.453	1
Commercial (#3)	0.059	3
Industrial (#1)	0.004	3
Industrial (#2)	0.001	1
Industrial (#3)	2.771	1
Industrial (#4)	0.008	1
Agricultural (#1)	0.985	4
Agricultural (#2)	0.800	1
Recreational (#1)	0.026	2
Transportation (#1)	0.010	1
Transportation (#2)	0.002	1
Open Space (#1)	9.49	1
Open Space (#2)	2.89	1

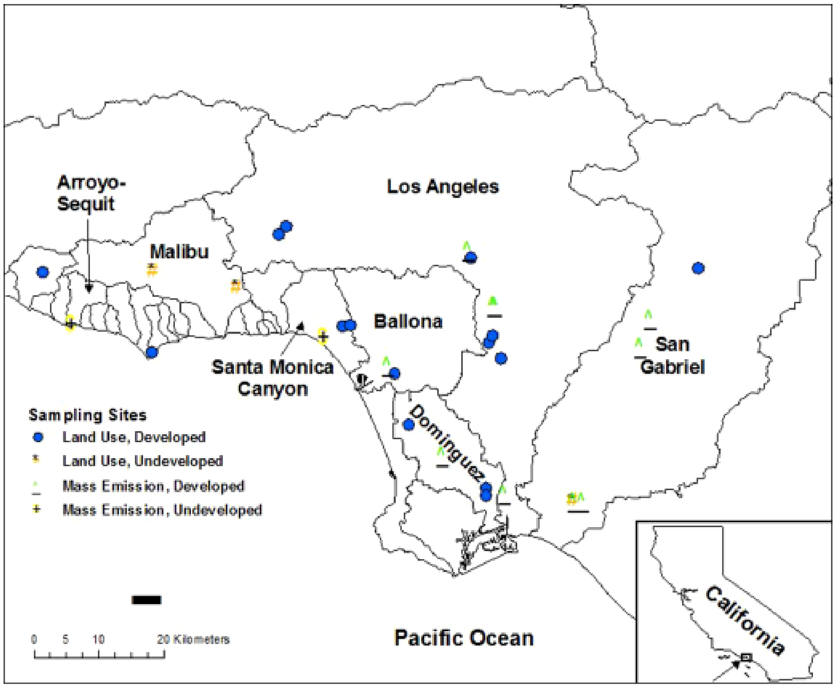

Figure 1 | In-river mass emission and land use sampling sites and watersheds within the greater Los Angeles region, California. Watersheds indicated with dots contained land use (LU) sites that drain catchments that are >90% undeveloped.

high density residential, low density residential, commercial, industrial, agricultural, recreational (horse stable), transportation, and open space, and ranged in size from 0.001 to 9.49 km^2. The recreational LU area researched in this paper is unique compared to other more commonly studied recreational areas (i.e. golf courses and public parks) in that it focused on equestrian land uses.

Sampling and analysis

A total of 20 discrete storms (a measurable precipitation event at least 72 h from the previous measurable precipitation event which results in a total precipitation accumulation equal to or greater than 0.10 inch of rainfall) were sampled, with each site being sampled between 1 and 7 individual storms. Rainfall ranged from 0.12 to 9.68 cm per storm and antecedent conditions varied from 0 to 142 days without measurable rain. Rainfall was measured using a standard tipping bucket at each site that recorded at 0.025-cm increments. Water quality sampling was initiated when flows were greater than base flows by 20%, continued through peak flows, and ended when flows subsided to less than 20% of base flow. Flow at ME sites was estimated at 15-minute intervals using existing, county maintained flow gauges or stage recorders in conjunction with historically derived and calibrated stage-discharge relationships. At ungauged ME sites and previously unmonitored LU sites, stream discharge was measured as the product of the channel cross-sectional area and the flow velocity. Velocity was measured using an acoustic Doppler velocity (AV) meter. The AV meter was mounted to the invert of the stream channel, and velocity, stage, and instantaneous flow data were transmitted to a data logger/controller on query commands found in the data logger software.

Between 10 and 15 discrete grab samples were collected per storm at approximately 30- to 60-minute intervals for each site-event based on optimal sampling frequencies in southern California described by Leecaster *et al.* (2001). Samples were collected more frequently when flow rates were high or rapidly changing and less frequently during lower flow periods. All water samples were collected by one of three methods: 1) peristaltic pumps with Teflon tubing and stainless-steel intakes that were fixed at the bottom of the channel or pipe pointed in the upstream direction in an area of undisturbed flow, 2) direct filling of the sample bottle either by hand or affixed to a pole, or 3) indirect filling using an intermediate bottle for securing large volumes. After collection, the samples were stored in pre-cleaned polyethylene plastic bottles on ice with Teflon-lined caps until they were shipped to the laboratory for analysis. All samples were analyzed within six hours of collection.

Laboratory analysis

FIB analysis

Concentrations of *E. coli* and enterococci were measured by chromogenic substrate technology using kits supplied by IDEXX Laboratories, Inc. (Westbrook, ME). *E. coli* was measured using Colilert-18 media, while enterococci were measured using Enterolert media. Ten-fold and 100-fold dilutions of water samples were made with deionized water containing the appropriate media and sodium thiosulfate, mixed to dissolve, dispensed into trays (Quanti-Tray/2000), and heat-sealed. Samples were incubated overnight according to the manufacturer's instructions and inspected for positive wells. Conversion of positive wells from these tests to a most probable number (MPN) was done following (Hurley & Roscoe 1983).

Total suspended solids

TSS were analyzed by filtering a 10- to 100-ml aliquot of stormwater through a tared 1.2-mm Whatman GF/C glass fiber filter (GFF). The filters plus solids were dried at 60°C for 24 hours, cooled, and weighed (40 CFR Part 136, July 1, 1996 (APHA 1992).

Data analysis

Four basic analyses were used to characterize temporal patterns and determine sources of FIB in stormwater. Prior to analysis bacterial concentrations were log-transformed to improve normality. Non-detectable results were assigned a value of one-half the minimum detection limit, based on the inability to log transform a value of zero.

For the first analysis, event flow-weighted mean concentrations (EMC) and flux rates among undeveloped and developed ME sites were compared to determine if significant differences existed among watershed types. The EMCs from the homogeneous LU sites were also compared. Using only those samples for a single storm, the EMC was calculated according to Equation (1):

$$\mathrm{EMC} = \frac{\sum_{i=1}^{n} C_i^{*} F_i}{\sum_{i=1}^{n} F_i} \tag{1}$$

Where: EMC = event flow-weighted mean concentration for a particular storm, C_i = individual runoff sample concentration of *i*th sample, F_i = instantaneous flow at the time of *i*th sample, and n = number of samples per event.

Flux estimates facilitated loading comparisons among watersheds of varying sizes. Flux was calculated as the ratio of the mass loading per storm and watershed area. Differences in concentration between ME or LU sites were investigated using a one-way ANOVA, with a $p < 0.05$ significance level followed by Tukey-Kramer post-hoc test for multiple comparisons (Sokal & Rohlf 1995).

The second data analysis used Spearman Rank correlation coefficients (p; a nonparametric measure of correlation) to explore the relationships between FIB concentrations, stormwater runoff volume, and TSS (Townsend 2002). Significant relationships were determined based on a $p < 0.05$.

The third and fourth analyses investigated temporal patterns in FIB concentrations at two scales. Variability in flow and FIB concentration within storm events were investigated for the presence of a concentration-based first flush by examining the time-concentration series relative to the hydrograph using a plot we term a pollutograph. Seasonal patterns in FIB concentration were investigated by plotting EMCs as a function of cumulative annual rainfall prior to the date of the storm being sampled. For this analysis, all ME and LU sites were analyzed as a group to look for differences between early- (October–December) and late season (April–May) storms across the sampling region.

RESULTS

Rainfall

The study period encompassed a representative range of rainfall conditions. On an annual basis, there are two distinct climatic periods in southern California: a dry (semi-arid) period from late May to mid-October, and a wet period from mid-October through late May. Winter storms typically provide 85 to 90% of the annual average rainfall (38.4 cm), with about 30 cm of total precipitation being distributed over 3 to 5 large and 8 to 10 small storms (Ackerman & Weisberg 2003). Annual rainfall quantities in Los Angeles can be highly variable. The 2004–2005 rainfall season brought 94.6 cm of rain to downtown Los Angeles, making it the second wettest season in Los Angeles since records began in 1877 (National Weather Service 2005). In contrast, during the 2001–2002 season rainfall totaled a mere 11.2 cm, 27 cm below the seasonal average.

FIB concentration and flux from specific land uses

Mean *E. coli*, enterococci, and total coliform EMCs were significantly greater at ME sites from developed compared to undeveloped watersheds (ANOVA, $p = 0.006$). For example the mean EMC at the developed Ballona Creek watershed was two orders of magnitude higher than at the undeveloped open space Arroyo Sequit watershed (10^4 MPN/100 ml vs. 10^2 MPN/100 ml; Figure 2). Furthermore, the higher concentrations from developed watersheds were generated by substantially less rainfall than necessary to generate concentrations from open space watersheds (2.07 ± 1.22 cm for storms in developed watersheds vs 6.49 ± 3.79 cm for storms in undeveloped watersheds).

Mean *E. coli* concentrations and EMCs were significantly higher from the recreational (REC) LU site compared to the commercial (COM), high density residential (HDR), industrial (IND), and transportation (TRANS) LU sites (i.e., $5.3 \pm 1.7 \times 10^5$ MPN/100 ml (REC) vs. $8.2 \pm 7.7 \times 10^3$ MPN/100 ml (COM), $p = 0.004$; Figure 2). Agricultural (AG) LU sites contributed the second greatest mean indicator bacteria EMCs, but were not statistically different from all

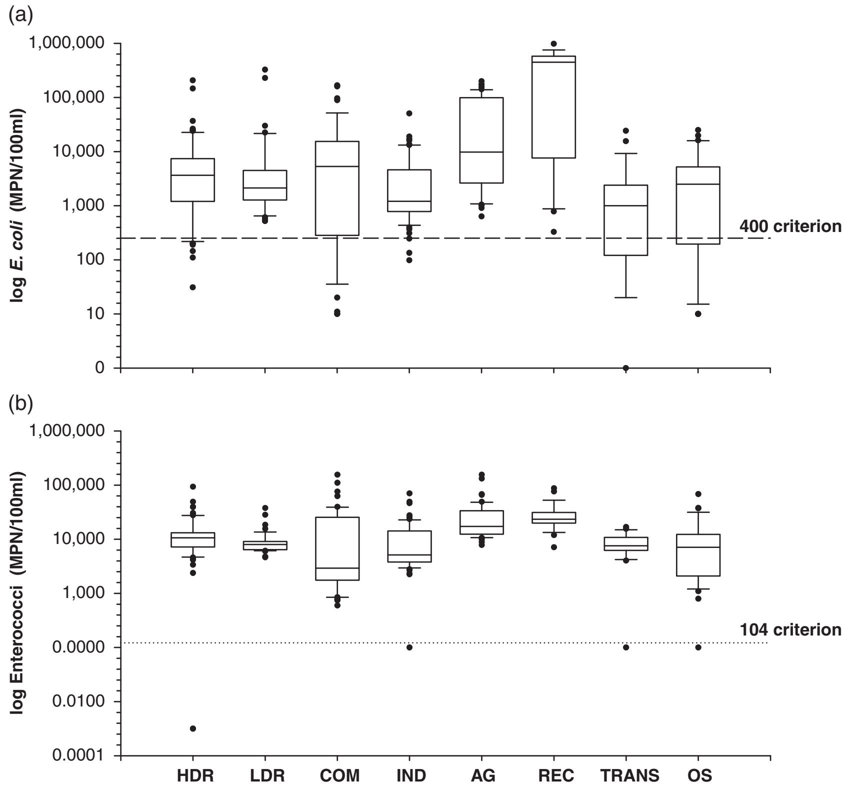

Figure 2 | Distribution of *Escherichia coli* (*E. coli*) (a) and enterococci (b) concentrations during the 2000–2001 through 2004–2005 wet seasons from land use (LU) sites. HDR = high density residential, LDR = low density residential, COM = commercial, IND = industrial, AG = agricultural, REC = recreation with horses, TRANS = transportation and OS = undeveloped open space.

other LU sites (i.e., $4.0 \pm 1.4 \times 10^4$ MPN/100 ml (AG) vs. $3.8 \pm 2.3 \times 10^3$ MPN/100 ml (IND) *E. coli*). Flux patterns between LU sites were similar, with agricultural and recreational sites producing the greatest flux, typically in the range of 10^{14} colonies/km^2.

A Spearman's correlation matrix (Table 2) of TSS, stream flow and FIB indicates that *E. coli* was significantly positively correlated ($p < 0.0001$) with TSS from agricultural, recreational and open LU sites. *E. coli* concentrations from low-density residential and industrial LU sites were weakly correlated with TSS. Enterococci was significantly correlated ($p < 0.0001$) with total suspended solids from low density residential, agricultural, recreational and transportation LU sites and all correlations with the exception of the low density residential site were positive. Enterococci counts from commercial and open LU sites were weakly and positively correlated with TSS. All three FIB concentrations were significantly correlated ($p < 0.0001$) with stream flow at the commercial, high density residential and agricultural LU sites, but not at other sites. Stream flow and TSS were not significantly correlated with each other. There was also no correlation when looking at the overall data set.

Temporal patterns in FIB concentrations

Within-storm variability

E. coli and Enterococci concentrations varied with time as a function of flow over the course of storm events for both the LU and ME sites (Figures 3 and 4). In all cases, bacterial concentrations increased markedly preceding peak flow. For example, Enterococci concentrations stayed high for a relatively short period at the developed Ballona Creek site (ca. 1.5 h) and then decreased back to base levels within two hours (Figure 3(a)). In contrast, *E. coli* concentrations were an order of magnitude lower than those of Enterococci and were more variable, exhibiting two separate peaks around 2.6×10^4 MPN/100 ml and an order of magnitude lower than Enterococci concentrations (Figure 3(b)). Although the pattern of an early peak in concentration was comparable in

Table 2 | Correlations between TSS, stream flow and FIB during storm condition; Spearman's correlation coefficient (ρ), and the number of samples (n). Bold numbers indicate significant correlations ($p < 0.05$); Bold numbers with asterisk (*) indicate significant correlations ($p < 0.01$)

	Total suspended solids			Stream flow		
Land-use site	***E. coli***	**Enterococci**	**Total coliforms**	***E. coli***	**Enterococci**	**Total coliforms**
High Density Residential	−0.0815	0.0226	−0.0196	***0.611**	−0.0564	0.0656
	42	42	42	42	42	42
Low Density Residential	**−0.3640**	***−0.603**	−0.1800	0.2390	0.0400	−0.2690
	37	37	37	37	37	37
Commercial	0.2460	**0.3540**	***0.416**	***0.772**	***0.819**	***0.796**
	47	47	47	47	47	47
Industrial	***−0.389**	**−0.3040**	−0.1300	**−0.2510**	**−0.2480**	−0.1330
	55	55	55	55	55	55
Agricultural	***0.553**	***0.616**	**0.3560**	**0.2810**	***0.436**	***0.688**
	44	44	44	44	44	44
Recreational	***0.694**	***0.767**	***0.732**	−0.0162	***0.587**	−0.0921
	20	20	20	20	20	20
Transportation	**0.5190**	***0.741**	***0.672**	***−0.712**	0.3920	−0.3470
	20	20	20	20	20	20
Open	***0.67**	***0.461**	0.1740	0.2550	0.2230	−0.1990
	30	30	30	30	30	30

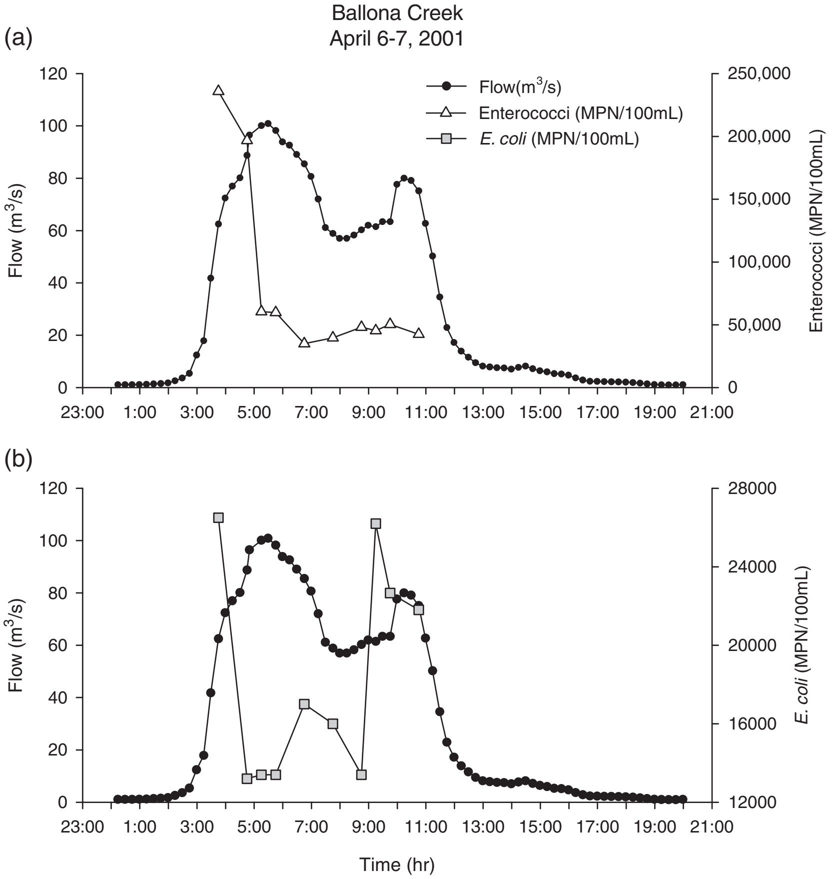

Figure 3 | Enterococci (a) and *Escherichia coli* (*E. coli*) (b) concentrations with time for a storm event from the developed Ballona Creek watershed. Total coliforms concentrations showed a similar pattern.

both urban and non-urban watersheds, in the undeveloped watersheds the peak concentration tended to occur later in the storm and persist for a longer duration (i.e., three to four hours; Figure 4). Furthermore, flow continued above base flow conditions for a longer duration in the non-urban watersheds. However, FIB concentrations steadily decreased following the early peak in storm.

Within-season variability

Antecedent dry period (expressed as cumulative annual rainfall) was strongly correlated with FIB concentrations from ME sites in an exponential manner ($r^2 = 0.67–0.92$; Figure 5). Early season storms generally had higher Enterococci and total coliforms EMCs than late season storms both within and between watersheds, even when rainfall quantities were similar. When all watersheds were analyzed together concentrations of all three FIB decreased with increasing cumulative annual rainfall, reaching an inflection point at approximately 5 cm (average annual rainfall is 33 cm), beyond which the effect is markedly less dramatic (Figure 5). This rainfall typically corresponds to the first one to three storms of the season. For example, the early season storm from Ballona Creek in water year 2004 had an Enterococci EMC two times larger (3.0×10^4 MPN/100 ml) than the storm that occurred at the end of the rainy season in water year 2003 (1.6×10^4 MPN/100 ml), despite the early and late season storms resulting from comparable rainfall (approx. 3.0 cm). The results for *E. coli* EMCs from early and late season storms were comparable. Antecedent dry period and FIB concentrations were not strongly correlated with each other at LU sites suggesting that, unlike the larger watersheds of the ME sites, the smaller LU catchments do not exhibit the same build-up and washoff effects for bacteria.

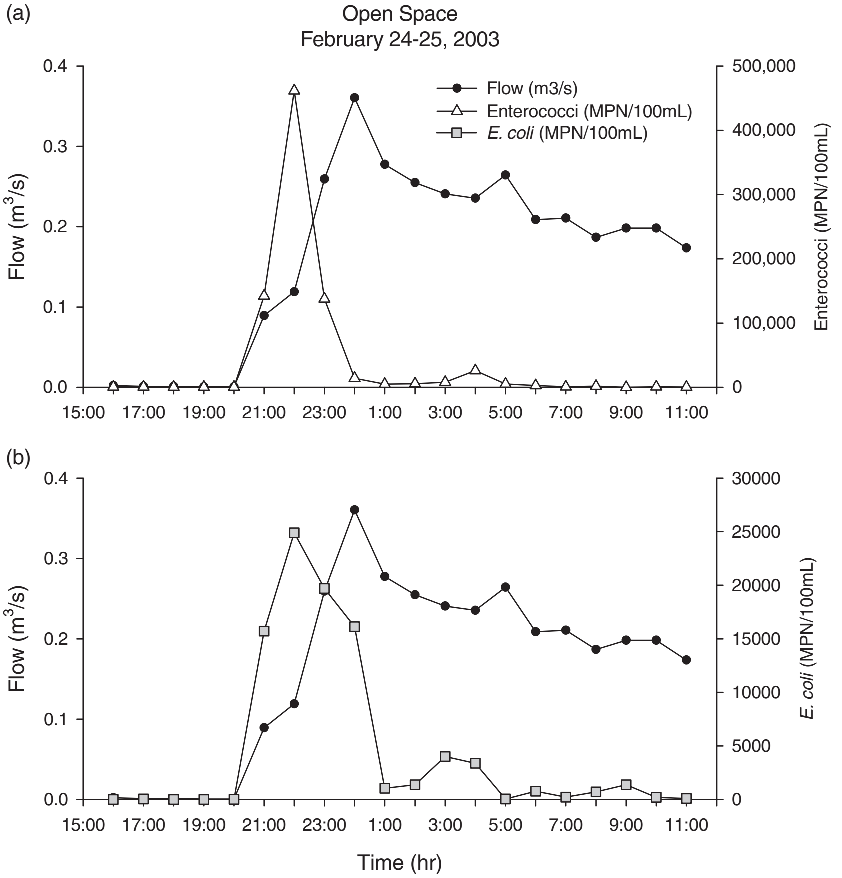

Figure 4 | Enterococci (a) and *Escherichia coli* (*E. coli*) (b) concentrations with time for a storm event from the open space land use (LU) site. Total coliforms concentrations showed a similar pattern.

DISCUSSION

Bacteria concentrations in stormwater runoff varied based on the contributing land use in the following manner: Recreational > agricultural > urban > open space. The relatively higher bacteria concentrations from recreational and agricultural LU sites may result from several mechanisms. The recreational site used in this study was an equestrian area; the heavy use by horses was likely a contributing factor to high bacteria levels from this site. This is consistent with observations from previous studies that horse use can be associated with elevated bacteria levels (Long & Pummer 2004; Airaksinen *et al.* 2007). High bacteria levels are often associated with domestic livestock. Sigua *et al.* (2010) conducted a study to assess the microbiological quality of water associated with animal-based agriculture (i.e. dairy cattle, pigs, poultry) and land uses without animals, or having crops in the rural area of Santa Catarina, Brazil. Their results indicated that the dairy cattle LU had the highest concentration of fecal coliforms and the LU associated without animal had the lowest concentrations.

The high *E. coli* and Enterococci EMCs observed at the agricultural sites during this study can be a result of bacteria from fertilizers, domestic pet and wildlife wastes that are deposited, or animal-based fertilizers stored or applied to the land. Previous studies have identified high FIB concentrations at agricultural sites associated with regular application of fertilizers (Niemi & Niemi 1991; Cook & Baker 2001). In contrast, land use sites such as industrial and residential areas have proportionately less direct sources of fecal material and have lower bacteria concentrations in stormwater than do mixed use land use and newly developing areas (i.e., recreational; Burnhart 1991; Mallin & Wheeler 2000).

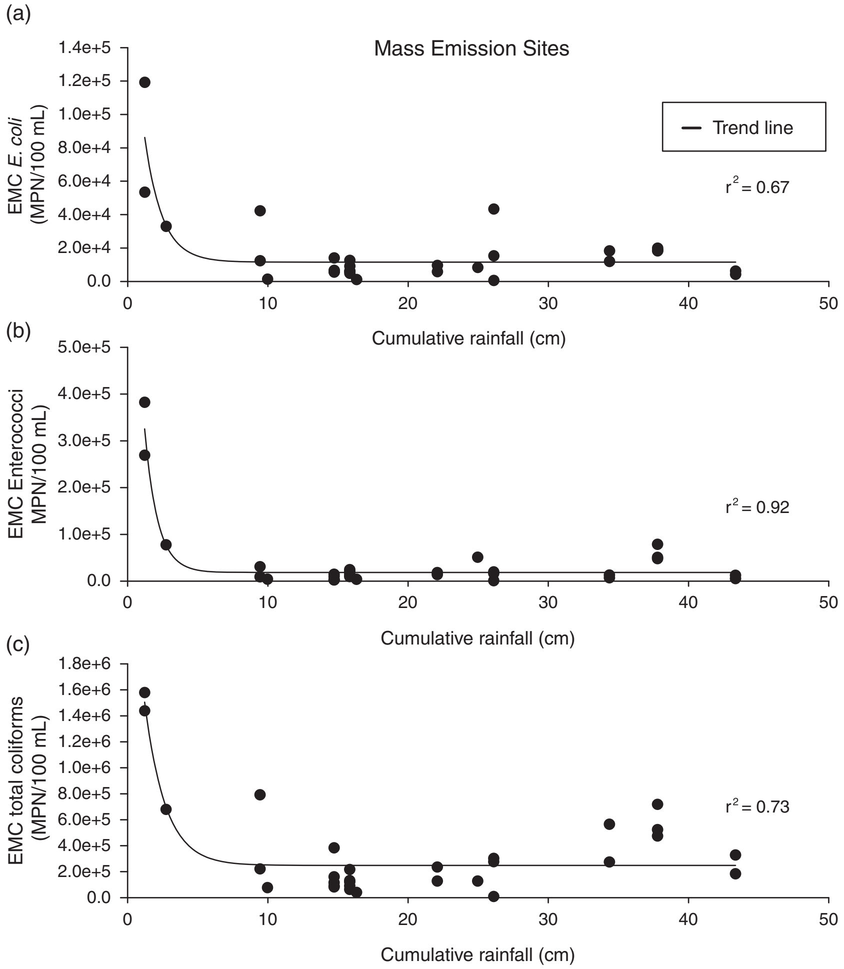

Figure 5 | Cumulative annual rainfall versus event mean concentration (EMC) for *Escherichia coli* (*E. coli*) (a) and enteroccoci (b), and total coliforms (c) during 2000–2001 through 2004–2005 storm seasons. Data shown for mass emission (ME) sites only.

The association of bacteria with sediment may also explain differences in *E. coli* and Enterococci concentrations from different LU sites. Correlations of FIB with TSS from recreational and agricultural LU sites suggest associations with particulate material, but it is unclear if the particulate material resulted from eroding soils transported to the stream from these LU sources or from erosion and resuspension of sediment already in the streambed. Other studies have implicated streambed sediment and its resuspension (Meade *et al.* 1990; Francy *et al.* 2000; Embrey 2001) as sources and principal transport vectors for bacteria. However, the high bacterial concentrations we observed in direct runoff from recreational and agricultural land use sites suggests that bacteria associated with these areas may be directly linked with site erosion. Assessing particle size distribution over the entire storm duration at these LU sites may help clarify the dynamics of bacteria-particle source associations by partitioning when the suspended sediments are settling out.

Interestingly, indicator bacteria concentrations were only significantly correlated ($p < 0.0001$) with flow at the commercial and high density residential LU sites even though bacteria in streams are commonly associated with suspended particles. One reason for this apparent difference may be that highly impervious sites (such as commercial and high density residential) have inherently less particle load than sites that have more pervious cover.

Consistently higher bacteria levels during early season storms likely reflect bacteria buildup during dry periods that flushes to rivers during early season storms. The strong relationship between FIB and antecedent dry period suggests that bacterial flux associated with stormwater runoff depends on the amount of time available for build up on land surfaces, and that storm size may be a less reliable predictor of the magnitude of bacterial loading. A seasonal pattern was observed for polycyclic aromatic hydrocarbons (PAHs) and trace metals in the Los Angeles region, (Sabin *et al.* 2004; Stein *et al.* 2006; Tiefenthaler *et al.* 2008), although the inflection point occurred later in the season than observed for bacteria in this study (~10 vs. 5 cm). Han *et al.* (2006) also reported that antecedent dry period was the best predictor of the magnitude of pollutant runoff from highways. Several researchers (Anderson & Rounds 2003; Ngoye & Machiwa 2004) have reported corresponding temporal trends for other contaminants and linked these patterns to the timing of particle washoff. This seasonal pattern suggests that focusing management actions on early season storms may provide relatively greater efficiency than distributing lower intensity management actions throughout the season.

FIB concentrations in stormwater were highly variable, with concentrations often ranging by factors of 10 to 100 during a single storm. The greatest bacteria concentrations occurred at or just before the peak in flow of the storm hydrograph for nearly every storm sampled. This early peak in concentration was also observed for PAHs (Stein *et al.* 2006) and trace metals (Tiefenthaler *et al.* 2008) in the greater Los Angeles area. Tiefenthaler *et al.* (2001) observed similar pollutographs that showed peak suspended-sediment concentrations preceding the peak in discharge for the Santa Ana River. Similar time vs. concentration relationships were also observed by Characklis & Wiesner (1997), who reported that the maximum concentrations of zinc, organic carbon and solids coincided with early peak stormwater flows.

Finally, the study compared the estimates of stormwater FIB concentrations to existing water quality standards to provide context for the magnitude of importance of stormwater to overall FIB concentrations for the region. Fecal indicator bacteria concentrations consistently and uniformly exceeded the State of California (CA) microbiological water quality thresholds at both ME and LU sites during the present study. Bacteria counts were compared to the CA single sample criterion for ocean beaches of 104 MPN enterococci/100 ml, 400 MPN *E. coli*/100 ml, and 10,000 total coliforms MPN/100 ml). The total coliform group is a large collection of different kinds of bacteria. Total coliforms are ubiquitous in the environment (i.e. soil and vegetation), and because they include fecal coliforms and *E. coli* they may indicate fecal contamination. Approximately 80% of all samples exceeded water quality thresholds at LU sites for at least one indicator (i.e., *E. coli* exceedance = 83%). Similarly, 98, 94, and 92%, respectively, of the ME stormwater samples for Enterococci, *E. coli*, and total coliforms bacteria exceeded CA ambient water quality standards. The above comparisons were based on receiving water quality standards. If compared to the proposed freshwater standards, which are approximately 60% lower than the receiving water standards, the exceedances would be slightly higher.

CONCLUSIONS

Patterns of stormwater FIB flux from developed land surfaces can inform decisions regarding how to best target BMPs. Although all urban land uses produce concentrations in excess of levels considered protective for receiving waters, the highest concentrations are associated with land uses that produce high amounts of sediment, such as active recreation and agricultural areas. This is likely due to a combination of bacteria produced as part of the land use activity itself and the erosive patterns that help deliver bacteria to the streams over the duration of the rainfall event. When runoff from multiple land surfaces is aggregated at the bottom of watersheds, clear intra-storm and intra-season patterns are seen, with highest concentrations and fluxes occurring early in storms, preceding peak flows, and early in the storm season. Targeted application of BMPs could also be improved by additional research on the relationship between FIB concentrations and particle size distributions in stormwater runoff. Because the particle size distribution, and bacteria partitioning can change over the course of a storm event (Furumai *et al.* 2002), understanding the dynamic partitioning of indicator bacteria to various size particles is important to facilitate estimation of temporal and spatial patterns of bacterial deposition in estuaries and harbors, and should be an area of future investigation.

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REFERENCES

Ackerman, D. & Weisberg, S. B. 2003 Relationship between rainfall and beach bacterial concentrations on Santa Monica Bay beaches. *J. Water Health* **1**, 85–89.

Airaksinen, S., Heiskanen, M. L., & Heinonen-Tanski, H. 2007 Contamination of surface run-off water and soil in two horse paddocks. *Bioresources Technology* **98**(9), 1762–1766.

Anderson, C. W. & Rounds, S. A. 2003 *Phosphorous and E. coli and their relation to selected constituents during storm runoff conditions in Fanno Creek, Oregon, 1998-1999. WRI 02-4232*. US Geological Services. Reston, VA.

APHA. 1992 *Standard Methods for the Examination of Water and Wastewater*, 18th Edition, 1992 Method 2540 D (pp 2–56).

Burnhart, M. 1991 *Sources of Bacteria in Wisconsin Stormwater*. Wisconsin Department of Natural Resources, Madison, WI.

Characklis, G. W. & Wiesner, M. R. 1997 Particles, metals, and water quality in runoff from large urban watershed. *J. Environ. Eng.* **123**, 753–759.

Cook, M. & Baker, J. 2001 Bacteria and nutrient transport to the lines shortly after application of large volumes of liquid swine manure. *Trans. Am. Soc. Ag. Eng.* **44**, 495–503.

Crowther, J., Kay, D. & Wyer, M. D. 2002 Faecal-indicator concentrations in waters draining lowland pastoral catchments in the UK: relationships with land use and farming practices. *Wat Res.* **36**(7), 1725–1734.

Dombek, P. E., Johnson, L. K., Zimmerly, S. T. & Sadowsky, M. J. 2000 Use of 393 repetitive DNA sequences and the PCR to differentiate *Escherichia coli* isolates from 394 human and animal sources. *Appl. Environ. Microbiol.* **66**, 2572–2577.

Edwards, D. R., Coyne, M. S., Vendrell, P. F., Daniel T. C., Moore, P. A. & Murdoch, J. F. 1997 Fecal coliform and Streptococcus concentrations in runoff from grazed pastures in northwest Arkansas. *J. Am. Water Res. Assoc.* **33**(2), 413–422.

Embrey, S. S. 2001 Microbiological quality of Puget Sound Basin streams and identification of contaminant sources. *J. Am. Water Res. Assoc.* **37**, 407–421.

Francy, D. S., Helsel, D. R. & Nally, R. A. 2000 Occurrence and distribution of microbiological indicators in groundwater and stream water. *Water Environ. Res.* **72**, 152–161.

Furumai, H., Balmer, H. & Boller, M. 2002 Dynamic behavior of suspended pollutants and particle size distribution in highway runoff. *Water Sci. Tech.* **46**, 413–418.

Griffith, J. F., Weisberg, S. B. & McGee, C. D. 2003 Evaluation of microbial source.tracking methods using mixed fecal sources in aqueous test samples. *J. Water Health.* **1**, 141–151.

Han, Y. H., Lau, S. L., Kayhanian, M. & Stenstrom, M. K. 2006 Correlation analysis among highway stormwater pollutants and characteristics. *Water Sci. Tech.* **53**, 235–243.

Hurley, M. A. & Roscoe, M. E. 1983 Automated statistical analysis of microbial enumeration by dilution series. *J. Appl. Bacteriol.* **55**, 159–164.

Inamdar, S. P. Mostaghimi, S., Cook, M. N., Brannan, K. M., & McClellen, P. W. 2002 A long-term, watershed-scale, evaluation of the impacts of animal waste BMPs on indicator bacteria concentrations. *J. Am. Water Res.* **38**, 819–833.

Jamieson, R. C., Gordon, R. J., Tattrie, S. C. & Stratton, G. W. 2003 Sources and persistence of fecal coliform bacteria in a rural watershed. *Water Qual. Res. J. Can.* **38**, 33–47.

Jones, D. L. 1997 Potential health risks associated with the persistence of *Escherichia coli* O157 in agricultural environments. *Soil Use Mangmt.* **15**(2), 76–83.

Leecaster, M. K., Schiff, K. C. & Tiefenthaler, L. L. 2001 Assessment of efficient sampling designs for urban stormwater monitoring. *Water Res.* **36**, 1556–1564.

Lewis, D. J., Atwill, E. R., Lennox, M. S., Pereira, M. D. G., Miller, W. A., Conrad, P. A. & Tate, K. W., 2010 Management of Microbial Contamination in Storm Runoff from California Coastal Dairy Pastures. *J. Environ. Qual.* **39**(5), 1782–1789.

Long, S. C. & Pummer, J. D. 2004 Assessing land use impacts on water quality using microbial source tracking. *JAWRA* **40**(6), 1433–1448.

Makarewicz, J. C. 2009 Nonpoint source reduction to the nearshore zone via watershed management practices: Nutrient fluxes, fate, transport and biotic responses. *J. Great Lakes Res.* **35**, 3–9.

Mallin, M. A. & Wheeler T. L. 2000 Nutrient and fecal coliform discharge from coastal North Carolina golf courses. *J. Environ. Qual.* **29**, 979–986.

Meade, R., Yazyk, T. & Day, T. 1990 Movement and storage of sediment in rivers of the United States and Canada. In: *The Geology of North America*, Woman, H. & Riggs, S. R. (Eds.).

Miller, W. A., Lewis, D. J., Pereira, M. D. G., Lennox, M., Conrad, P. A., Tate, K. W. & Atwill, E. R. 2008 Farm factors associated with reducing *Cryptosporidium* loading in storm runoff from dairies. *J. Environ. Qual.* **37**(5), 1875–1882.

Moog, D. & Whiting, P. 2002 Climatic and agricultural contributions to changing loads in two watersheds in Ohio. *J. Environ. Qual.* **31**, 72–83.

National Weather Service. 2005 Annual rainfall quantities. http://www.wrh.noaa.gov/lox/.

Niemi, R. M. & Niemi, S. 1991 Bacterial pollution of waters in pristine and agricultural lands. *J. Environ. Qual.* **20**, 620–627.

Ngoye, E. & Machiwa, J. F. 2004 The influence of land-use patterns in the Ruvu river watershed on water quality in the river system. *Phys. Chem. Earth* **29**, 1161–1166.

Sabin, L., Schiff, K., Lim, J. & Stozenback, K. 2004 *Atmospheric concentrations of PAH, pesticides and other semi-volatilie organic compounds in the Los Angeles coastal region*, Weisber, S. B. & Hallock, D. (Eds.), Southern California Coastal Water Research Annual Report 2003–2004. Westminster, CA, pp. 61–72.

Sigua, G. C., Palhares, J. C., Kich, J. D., Mulinari, M. R., Matt, R. M., Klein, J. B., Muller, S. & Plieske, G. 2010 Microbiological Quality Assessment of Watershed Associated with Animal-Based Agriculture in Santa Catarina, Brazil. *Wat. Soil Poll.* **210**(1–4), 307–316.

Sokal, R. R. & Rohlf, F. J. 1995 *Biometry: the Principles and Practice of Statistics in Biological Research* (3rd ed.). W.H. Freeman and Company, New York, NY.

Stein, E. D., Tiefenthaler, L. L., & Schiff, K. C. 2006 Watershed-based sources of polycyclic aromatic hydrocarbons in urban stormwater. *Environ. Toxicol. Chem.* **25**, 373–385.

Tiefenthaler, L. L., Schiff, K. C. & Leecaster, M. K. 2001 Temporal variability patterns of stormwater concentrations in urban stormwater runoff. In: *Southern California Coastal Water Research Project Annual Report 1999-2000*, Weisberg, S. B. & Elmore, D. (Eds.), Southern California Coastal Water Research Project, Westminster, CA, pp. 52–62.

Tiefenthaler, L. L., Stein, E. D. & Schiff, K. C. 2008 Watershed and land use-based sources of trace metals in urban stormwater. *Environ. Toxicol. Chem.* **27**, 277–287.

Townsend, J. (ed.). 2002 *Practical Statistics for Environmental and Biological Scientists*. Chichester, United Kingdom.

US Census Bureau. 2000 Southern California population, http://factfinder.census.gov/home/saff/main.html.

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