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Seasonal first flush phenomenon of urban stormwater discharges

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Abstract

California's climate, typified by winter and spring precipitation and summer drought, is often called a Mediterranean climate, and creates a long period for pollutant build-up. The initial storms of the winter season usually have higher pollutant concentrations, which is called a seasonal first flush. To investigate the existence of a seasonal first flush, we analyzed four major data sets, collected over the 1999–2000 to 2002–2003 wet seasons. Trends in seasonal loads were quantified by plotting pollutant concentrations or cumulative pollutant load versus cumulative rainfall or cumulative runoff volume. Pollutant concentrations in the first part of the wet season were ranged from 1.2 to 20 times higher than concentrations near the end of the season, and mass emission rates were similarly higher at the beginning of the season. A seasonal first flush existed for most cases and was strongest for organics, minerals and heavy metals except lead. This result suggests that applying treatment Best Management Practices (BMPs) early in the season could remove several times more pollutant mass than randomly timed or uniformly applied BMPs.

Keywords: Best Management Practices (BMPs); Climate; Dissolved fraction; Highway runoff; Seasonal first flush; Stormwater

1. Introduction

Urban stormwater discharge during wet weather flow is a major contributor to the pollution of many receiving waters (Saget et al., 1996; Appel and Hudak, 2001; Brezonik and Stadelmann, 2002; Buffleben et al., 2002). Climatic conditions such as the existence of long dry or wet periods may greatly impact pollutant emissions from urban stormwater discharges. California has a Mediterranean climate, typified by winter and spring precipitation and summer drought. Most of western parts of California including Los Angeles are dry from May through September. Fig. 1 shows the monthly average rainfall throughout the northern, central and southern California during 1971–2000 (http://www.ncdc.noaa.gov/oa/climate/online/ccd/nrmlprcp.html). This rainfall pattern creates a long period for pollutant build-up, and therefore the initial storm of the season may have higher pollutant concentrations than in later events. This phenomenon is called a seasonal first flush.

The presence of a seasonal first flush of urban stormwater discharge as well as existence of the first flush of a storm event is important for efficient source and treatment Best Management Practices (BMPs). Many researchers investigated the first flush phenomenon to understand the characteristics of stormwater

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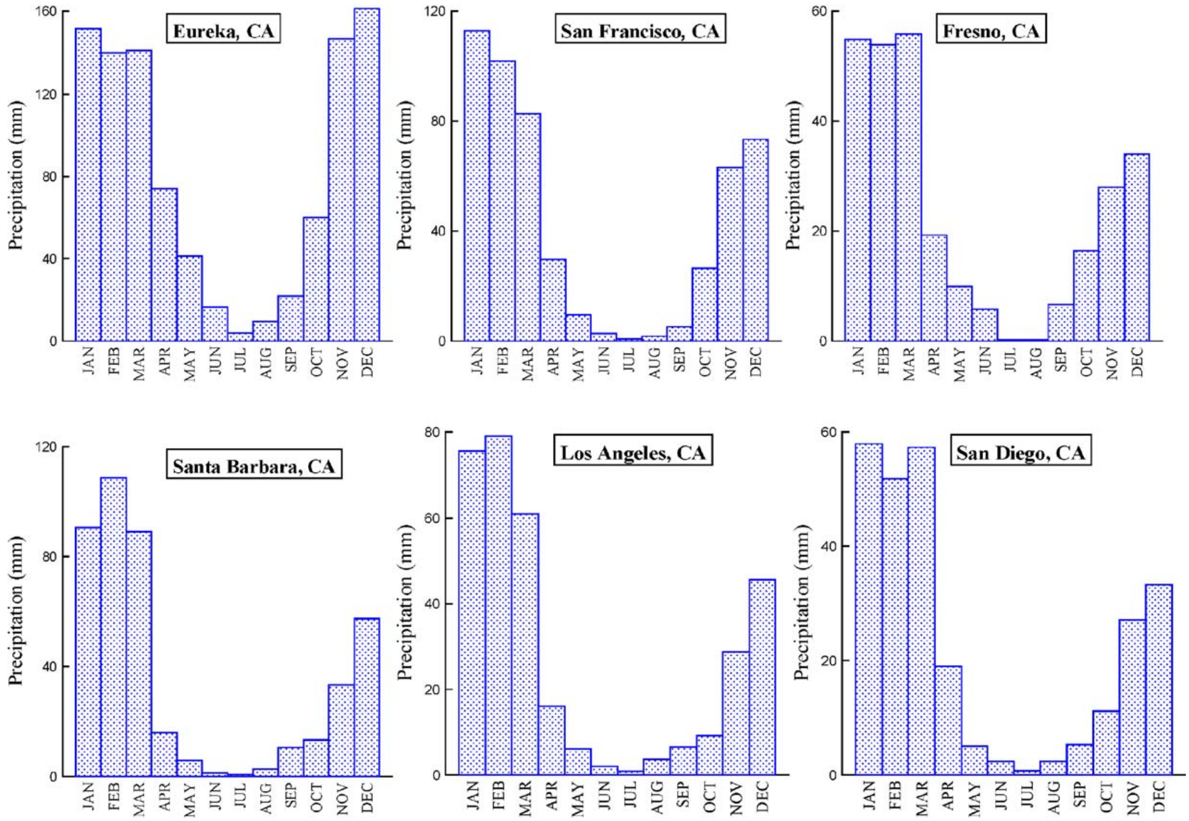

Fig. 1. Distribution of monthly average rainfall in California during 1971–2000.

runoff discharge (Bertrand-Krajewski et al., 1998; Deletic, 1998; Larsen et al., 1998; Barbosa and Hvitved-Jacobsen, 1999). The antecedent dry period is an important factor in the seasonal first flush. Few researchers determined the effect of the antecedent dry period in their study of stormwater discharge (Saget et al., 1996; Deletic and Maksimovic, 1998; Lee et al., 2002). However, the antecedent dry periods in their studies are quite short, and range from 1 to 30 days. In California, there is no precipitation in the summer in most areas, except for rare tropical storms. The existence and magnitude of a seasonal first flush of urban stormwater discharge have been rarely investigated.

Our primary objective of this study is to identify a seasonal first flush and quantify its mass loading in order to apply the information to BMPs evaluation strategies. To do this, we analyzed four major stormwater runoff monitoring programs in California. They include the Los Angeles industrial activities General Permit monitoring data, the landuse monitoring data from the Los Angeles County Department of Public Works (LACDPW), the California Department of Transportation (Caltrans) first flush highway runoff study data and the Caltrans state-wide highway runoff monitoring data.

We hope this study will assist in selecting the most effective BMPs to control stormwater runoff pollution in areas with distinct rainy and dry seasons such as California. There are five major Mediterranean Climate regions in the world: California, Central Chile, the Mediterranean Basin, Southwest and South Australia, and South Africa. These areas have similar rainfall patterns (not shown in this paper). We could expect a seasonal first flush phenomenon in these regions, with the same implications for BMP selection. Additionally, there are other areas, with less pronounced seasonal rainfall, which may benefit from this research.

2. Methodology

Table 1 summarizes the data sets used in this study. The monitoring data, with the exception of our first flush highway runoff data described in the third row in the table, were collected by others. The monitoring data sets in the table were examined to identify a seasonal first flush using the relationship between the cumulative runoff volume and the cumulative pollutant load. Pollutant concentrations were used for the two data

Table 1
Summary of monitoring data sets

Name of monitoring program	Sponsoring or managing agency	Monitoring year	Monitoring area	Drainage area (ha)	Primary landuse	Number of observations
Industrial Activities General Permit	Los Angeles Regional Water Quality Control Board (LARWQCB)	From 1992 to present	County of Los Angeles	0.0000464–14771	Industrial	~6500 events from many sites over 2 years
Land Use Monitoring	Los Angeles County Department of Public Works (LACDPW)	From 1996 to 2001	Near LAX	365	Transportation[a]	24 events from 1 site over 2 years
First Flush Highway Runoff Characterization[b]	California Department of Transportation (Caltrans)	From 1999 to present	405 and 101 freeway near UCLA (3 sites)	0.39, 1.28, 1.69	Transportation (Highway)	71 events from 3 sites over 3 years
Statewide Highway Runoff Monitoring[c]	California Department of Transportation (Caltrans)	From 1997 to present	California (statewide)	0.04–5.94	Transportation (Highway)	237 events from 25 sites over 3 years

[a]Transportation includes surface roads, while highway includes only freeways.
[b]Performed by the Civil and Environmental Engineering, University of California, Los Angeles.
[c]Part of Caltrans state-wide stormwater runoff monitoring program.

sets that had missing or inadequate runoff flow-rate data, and cumulative rainfall, which is available from publicly monitored rain gages, was used in lieu of runoff volume. Data from wet seasons over the past 4 years 1999–2000 to 2002–2003 were analyzed when available. Wet season or rainy season for California generally means October to April. Basic water quality parameters such as chemical oxygen demand (COD), specific conductance (SC), total organic carbon (TOC), and total suspended solids (TSS) were used. Additionally, when available, metals such as aluminum (Al), copper (Cu), lead (Pb), nickel (Ni) and zinc (Zn) were analyzed in both soluble and particulate phases. Additional water quality parameters exist in the data sets, and will be analyzed at a future date. For clarity, each data set is described in separate sections, with the specific information for each data set and the results of the analysis presented together. Section 4 discusses the benefit associated with preferentially treating stormwater early in the season, and the implications of metal partitioning on first flush and BMP selection.

3. Seasonal first flush results

3.1. Industrial activities general permit monitoring

On November 19, 1991, the California State Water Resource Control Board issued the statewide General Permit for discharges of storm water associated with industrial activities excluding construction activities (the General Permit). The General Permit requires monitoring by facilities that discharge storm water associated with the industrial activities. Currently, there are approximately 3000 permittees within the Los Angeles County that are covered under the General Permit. Under the monitoring requirements, permittees must collect water quality samples from two storms per year and analyzed for four basic parameters: pH, SC, TSS, and oil and grease. TOC can be substituted for oil and grease. Certain facilities must analyze for specific additional pollutants such as metals (Cu, Fe, Pb, Ni, and Zn), and permittees must analyze for pollutants that they believe are pervasive in their storm water. Industries are categorized by Standard Industrial Codes (SIC codes). For the General Permit, only grab samples, which are discrete samples taken within a short period of time, were required. Runoff flow rate was not required. Records of water quality data were obtained from the Regional Water Quality Control Board, Los Angeles.

To determine seasonal first flush, SC, TOC, TSS, and Zn were analyzed for 1999–2000 and 2000–2001 wet seasons. Among the metals, only zinc was selected for analysis because of its prevalence in observations (cases). The General Permit requests that the first storm and one later storm be sampled; no other guidance for selecting storm events is provided. In some cases the permittee missed the first sample, either because they were not prepared, or because the rainfall was small. The desire to sample large storm events means that some events have more cases than other events. We selected several events with large numbers of cases. Approximately 70% of the total cases, or 6500 cases were analyzed. Median pollutant concentrations were used to represent for the selected large events. The daily precipitation records from Los Angles Civic Center station (http://www.nwsla.noaa.gov/climate/climate.html) were used to calculate cumulative rainfall and antecedent dry days (ADD). Although rainfall is site-specific, the record from Civic Center was used as being representative of the general pattern of rainfall for the Los Angeles area. Normalized, cumulative precipitation was calculated by adding the total rainfall for each event and dividing by the season total.

Fig. 2 shows the concentrations according to the normalized cumulative precipitation during 1999–2000 (left) and 2000–2001 (right) wet season. Concentrations of SC, TOC, and total Zn were highest in the first storm event and decreased continuously during the 1999–2000 season, until the last event. In the last event, the concentrations for all parameter increased, which was probably due to the long dry period preceding the event (ADD). For the 2000–2001 season, the concentrations of all parameters were highest in the first few events and decreased as the season progressed. The first few rainfall events of this season were small (less than 41 mm or 8.29% of the total rainfall), closely spaced, and should be considered as a single event. There are several large storm events, but the concentrations of all parameters are much lower than in the first few storm events of the season.

The results show that concentrations are more influenced by antecedent dry period than the amount of rainfall. TOC, SC, Zn and TSS concentrations in the first part of the season were approximately 5.5, 4, 2.5, and 1.5 times higher, respectively, than concentrations at the end of the season. A substantial concentration peak in the initial of storm event suggests the presence of a seasonal first flush in stormwater discharges associated with industrial activities.

3.2. Landuse monitoring

The LACDPW has been monitoring stormwater under the 1990 and 1996 NPDES Municipal Permits. The 1996 Municipal Permit also requires samples from various landuses. Flow-weighted composite samples were analyzed for many water quality variables including indicator bacteria, general minerals, nutrients, metals, semi-volatile organic compounds, oil and grease, and pesticides. Results of the flow-weighted composite sample can be considered as an event mean concentrations (EMCs). Records of the stormwater quality data in various types of landuse were obtained online (http://www.ladpw.org/wmd/NPDES/report_directory.cfm) for the 1999–2000 and 2000–2001 wet seasons. For the purpose of this study, we selected the Dominguez Channel station whose primary landuse is transportation. The landuse is 75.2% transportation, 17% light industrial, 0.6% high-density residential, 0.1% retail/commercial, and 7.1% other or unknown.

Basic water quality parameters such as COD, SC, TOC, and TSS and metals such as Al, Cu, Ni and Zn were analyzed to identify seasonal first flush. A total of 24 events were analyzed for the two wet seasons. LACDPW provided precipitation and runoff volume for every monitored event. Unfortunately, in some cases the first storm was missed or runoff volume was not provided, which makes it impossible to calculate the cumulative runoff volume and pollutant load. Therefore, normalized cumulative rainfall was analyzed in lieu of runoff volume.

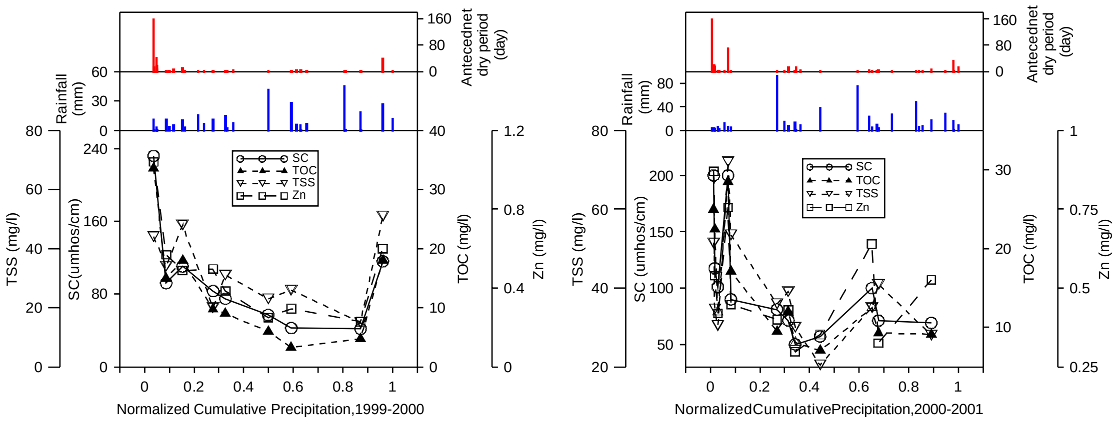

Fig. 2. Concentrations versus normalized cumulative precipitation during 1999–2000 (left) and 2000–2001 (right) wet season for industrial activities General Permit monitoring.

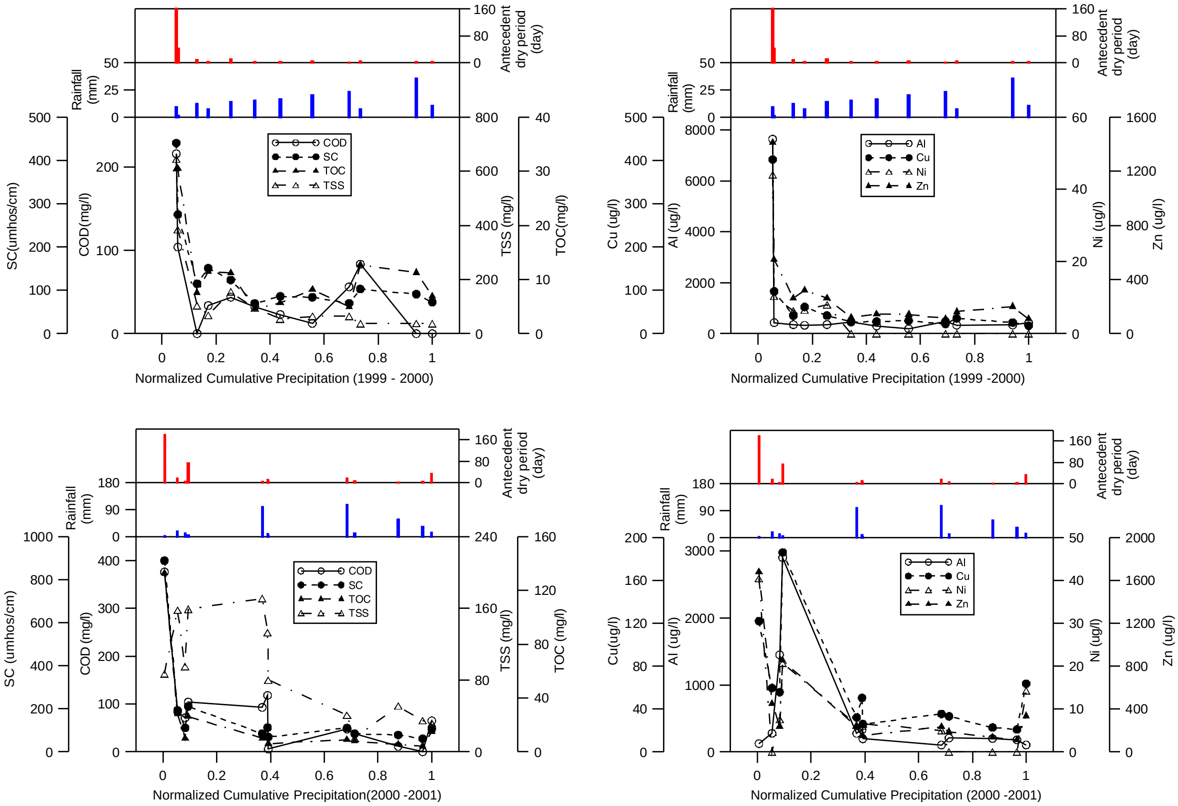

Fig. 3. Concentrations versus normalized cumulative precipitation during 1999–2000 (top) and 2000–2001 (bottom) wet season for transportation landuse monitoring by LACDPW.

Fig. 3 shows the concentrations as a function of the normalized cumulative precipitation during 1999–2000 (top) and 2000–2001 (bottom) wet season. Concentrations for all parameters were highest in the first event, dropping dramatically for the next event and generally decreasing to the last event for 1999–2000 wet season. The seasonal first flush was greater for metals than basic water quality parameters. Total Cu, Al, and Zn concentrations in the first part of the wet season were approximately 22, 18, and 13 times higher, respectively, than concentrations at the end of the season. The concentration ratios of the basic water quality parameters for COD, SC, TOC and TSS ranged from 4 to 17. The 2000–2001 season showed similar trends for COD, SC, TOC, total Ni and total Zn concentrations. The first storms were quite small, comprising less than 10% of the total cumulative rainfall, closely spaced, and should be considered as a single event. The concentrations of all parameters, except TSS, show dramatic declines as the season progressed. The ratios of the concentrations at the start of season to the end of season ranged from 1.2 to 11.2, depending on the pollutant and the method of comparison. The average ratio of the eight pollutants in the first storm to the last storm was 4.6. The average ratio of the eight pollutants for the first four storms to the last storm was 3.7. In general, there is a strong seasonal first flush in the stormwater discharges from the transportation landuse.

3.3. First flush highway runoff monitoring

The Department of Civil and Environmental Engineering at UCLA has characterized runoff from three highway sites since 1999 (Stenstrom et al., 2000, 2001, 2002). This study was conducted to assess runoff water quality and quantity from California freeways with particular emphasis on characterizing first flush. During the first hour of the storm, grab samples were collected every 15 min. After the first hour, additional grab samples were collected each hour up to 8 h. An automatic composite sampler was also used in the second and third years to collect flow-weighted composite samples. We measured a large suite of constituents including indicator bacteria, general minerals, nutrients, oil and grease, organics and metals.

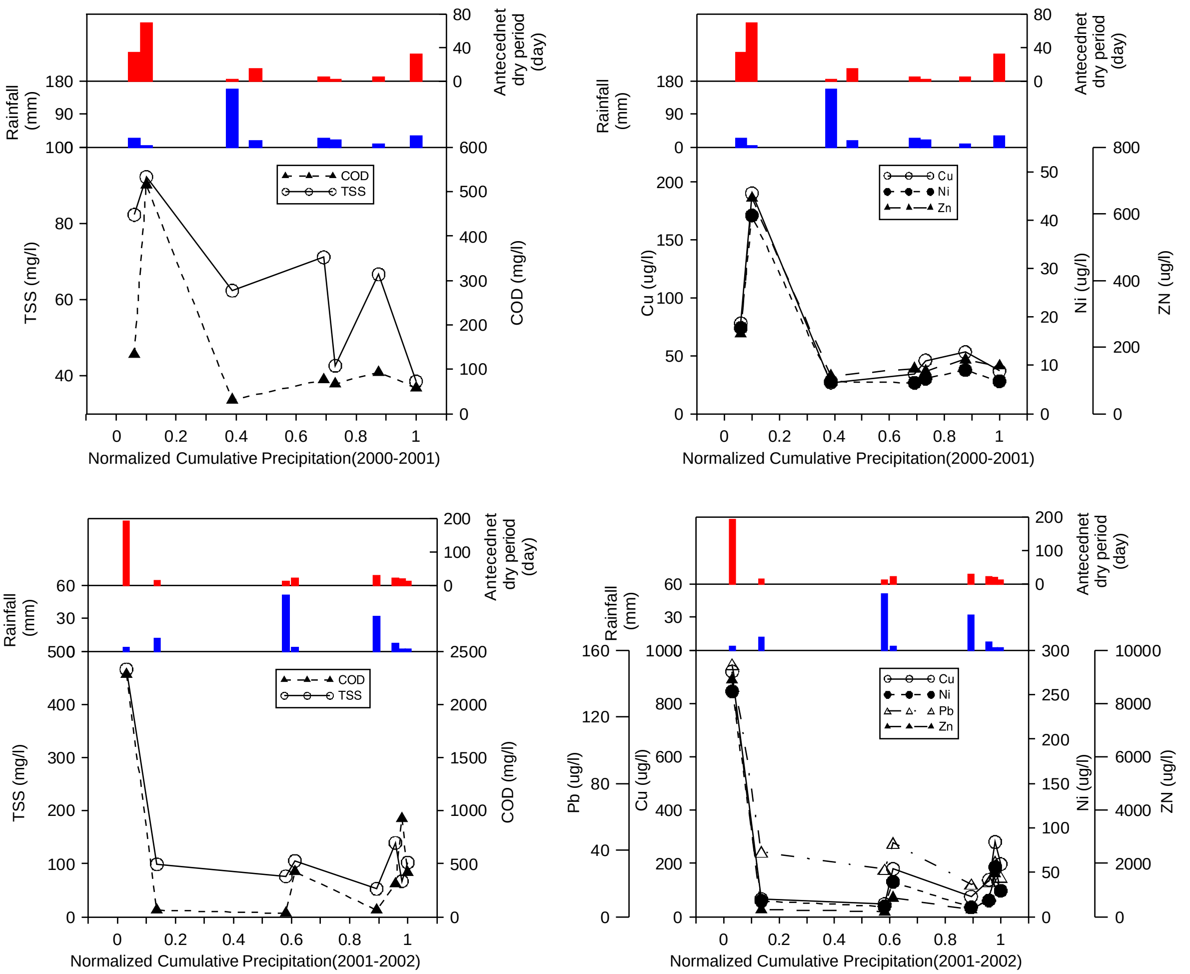

Fig. 4. Concentrations versus normalized cumulative precipitation during 2000–2001 (top) and 2001–2002 (bottom) wet season for first flush highway runoff characterization study at UCLA site 2.

EMCs were calculated from grab samples results and measured flow rate. The definition of EMCs is described by Sansalone and Buchberger (1997) and Lee et al. (2002). The calculated EMCs can be interpreted as a flow-weighted average of pollutant concentrations of a storm event. Fig. 4 shows the EMCs as a function of the normalized cumulative precipitation for 2000–2001 (top) and 2001–2002 (bottom) from site 2 located on 405 Freeway with average daily traffic of 260,000. Site 2 was selected as illustrative of all three sites. Concentrations for all parameters were highest in the first two events, which had 30 and 69 ADD. The first two rainfall events were small, (less than 54 mm or 9.96% of the total rainfall), and should also be considered as a single event. The ADD for the first storm event would normally be 100 days or more. The reason for the shorter ADD is that the very first storm of the season was too small to produce sufficient runoff for sampling. The concentrations in the 2001–2002 wet season show the clearest seasonal first flush trend for all parameters. The Zn, Ni, Pb, COD, Cu, and TSS concentrations in the first event of the wet season were approximately 9, 8.5, 6, 5.5, 4.5, and 4.5 times higher, respectively, than concentrations at the end of the season.

This monitoring project collected both flow rates and pollutant concentrations, which allows mass loadings to be computed. The normalized mass loading of a pollutant for a storm event is obtained by multiplying the calculated EMCs by the total runoff volume for the event and dividing by the total mass emission for the season. A loading graph is created by plotting normalized cumulative pollutant load versus normalized cumulative runoff volume (see Fig. 5). The diagonal line on Fig. 5 represents the loading of a hypothetical pollutant with constant concentration. The normalized loadings for COD, TSS, Cu, Ni, Pb, and Zn are plotted

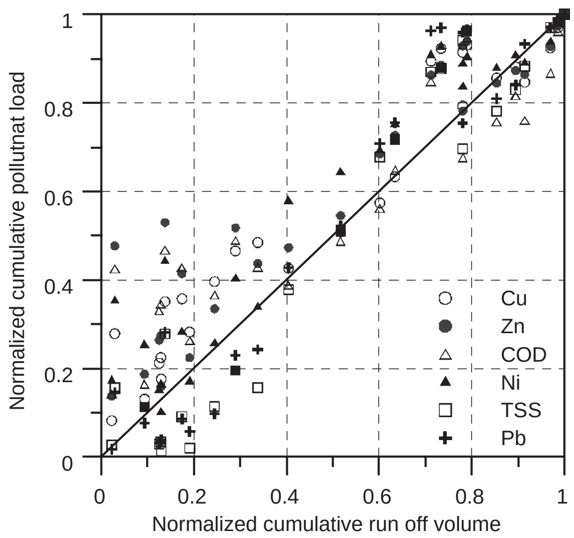

Fig. 5. Normalized cumulative pollutant load and runoff volume for UCLA sites 1, 2, and 3.

in Fig. 5 for sites 1 and 2 (1999–2000 season) and sites 2 and 3 (2001–2002 season). These 2 years were selected because they have at least seven events. Data points above the diagonal line represent a higher loading that would be expected for pollutants exhibiting a seasonal first flush. Most of the storm events show a season first flush. For events in the first 10% of the normalized runoff volume, 16 of 18 events showed a seasonal first flush. In the first 20% and 30%, 40 of 56 and 48 of 66 events showed a seasonal first flush. Only a few of the points for total Pb, TSS and Ni were below the diagonal line, which means that these pollutants sometimes did not exhibit a seasonal first flush.

3.4. State-wide highway runoff monitoring

The Caltrans has had a large monitoring program since 1997 to characterize the water quality impacts of highway runoff. A large suite of water quality constituents, such as conventional nutrients and metals, have been sampled using automatic sampler by collecting flow-weighted composite samples. Precipitation and runoff volume were also measured.

Highway stormwater runoff water quality was collected at 135 sites in California. Among them, 31 cases from 25 sites were deemed to be suitable for seasonal first flush analysis. Each case is for a single site with a minimum of five events for one wet season. In all, 237 events were analyzed. Cases with no observations from October to December were not analyzed, since the absence of observations during this period indicates that the initial rainfall events were not sampled. Cases that had initial events with ADD of less than 30 days were also not considered for this analysis. The imperviousness of the selected sites was over 90%. Based on all the selection criteria, only the events in the last 3 years, 2000–2001 to 2002–2003 wet seasons, were selected for further analysis. TOC, TSS, total Cu, Ni, Pb, and Zn were chosen for the existence of seasonal first flush analysis. These parameters were selected because they are likely to be more strongly regulated.

The total mass loading of a pollutant for a storm event is obtained by multiplying the concentration (EMC) obtained from the flow-weighted composite sample by the total runoff volume for the event. Fig. 6 shows the normalized cumulative pollutant load versus normalized cumulative runoff volume for the selected parameters.

Most data points within the initial 30% of normalized runoff volume are above the diagonal line, indicating a seasonal first flush. Table 2 shows average normalized cumulative pollutant load that fell in the 20–30% range of normalized runoff volume. The mean values ranged from 0.29 to 0.39, with maximums as large as 0.63. If no seasonal first flush existed, the mean values should be 0.25. Seasonal first flush was greatest for TOC, whose mean mass to volume ratio in the range of 20–30% of the normalized runoff, is 0.39, and only one observation fell below the diagonal line. It is weakest for total Cu with a mean ratio of 0.29.

4. Discussion

The practical implications of the seasonal first flush results presented in this study are important for selecting BMPs. Runoff from storms early in the season is more contaminated than runoff from later storms. A method for estimating the relative value of treating early runoff compared to later runoff is discussed in the next section.

4.1. BMP selection criteria

In order to estimate the potential benefits of treating early runoff as compared to runoff later in the season, we defined an effectiveness factor as a function of cumulative runoff volume. In the expected situation of having limited funding for BMP construction, applying BMPs to runoff with higher pollutant concentrations will generally be more beneficial. Also there is growing evidence that suggests that BMPs removal efficiencies are higher in runoff with higher concentrations (Strecker et al., 2001; Lau and Stenstrom, 2002).

The effectiveness factor at a specific cumulative runoff volume is calculated as follows:

$$E(V) = \frac{(Mv/v)}{(1 - Mv)/(1 - v)}, \tag{1}$$

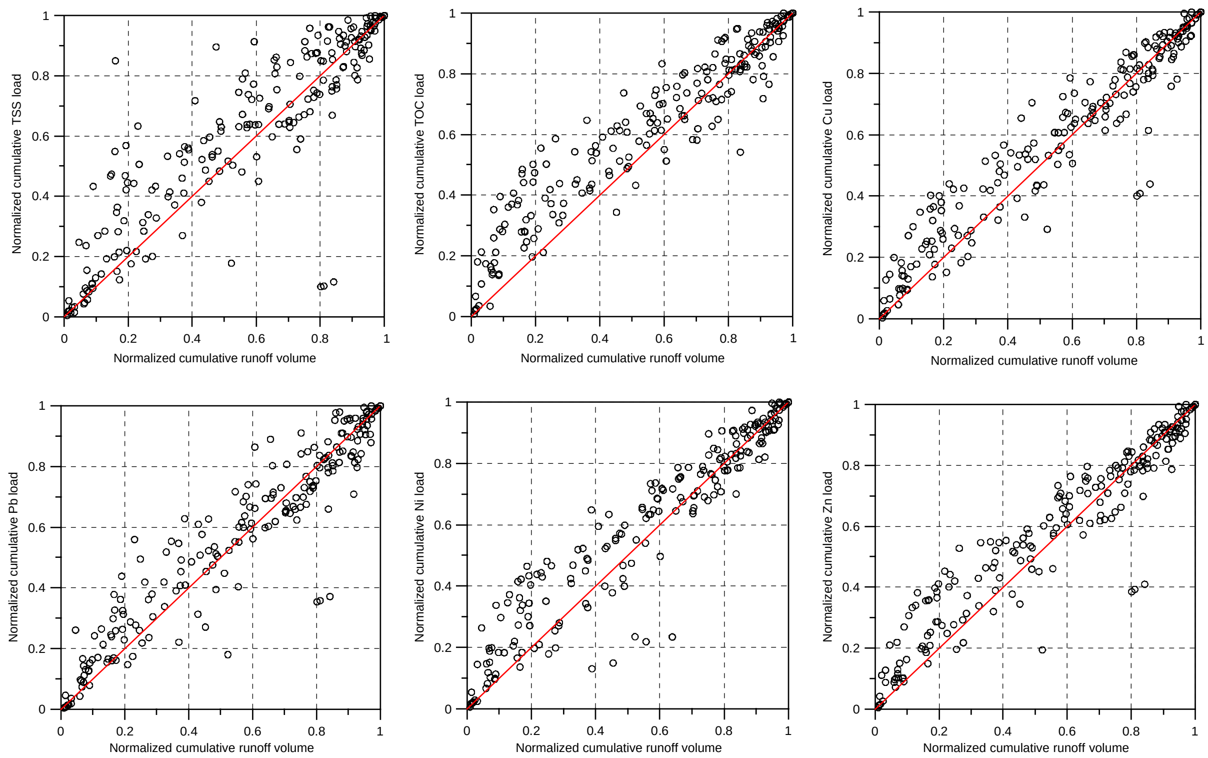

Fig. 6. Normalized cumulative pollutant load and runoff volume for 2000–2003 for the Caltrans state-wide highway runoff monitoring study.

Table 2
Normalized cumulative load at 20–30% of the runoff volume

	TOC	TSS	Pb	Ni	Cu	Zn
Minimum	0.21	0.18	0.15	0.18	0.15	0.2
Maximum	0.59	0.63	0.56	0.48	0.44	0.53
Mean	0.39	0.35	0.32	0.32	0.29	0.34

where $E(V)$ is the effectiveness factor at a specific cumulative runoff volume V, and Mv is the normalized cumulative mass at a specific normalized cumulative runoff volume, v.

Fig. 7 shows the effectiveness factor at ten intervals of runoff volume. The dashed line at 1.0 would be the relative effectiveness if the pollutants concentrations were constant throughout the wet season (i.e., no seasonal first flush). The relative effectiveness was the highest in the 10–20% range of runoff volume for all parameters. The effectiveness was greatest for TOC and weakest for Pb, with many outliers. The range for TSS was also very large. The median effectiveness for TOC at 10–20% of runoff volume was approximately 3.5, which means treatment of the initial 10–20% of runoff volume could remove the TOC load 3.5 times as much pollutant mass as treating an equal volume later in the storm. This result suggests that applying treatment BMPs early in the season could remove several times more pollutant mass than randomly timed BMPs.

4.2. Suspended and soluble pollutants

Suspended solids have often been used as a surrogate for other pollutants in stormwater runoff. This has interesting interactions for first flush, because the particle dynamics may have major impacts on emission rates of other pollutants. In the previous section we noted the existence of a seasonal first flush, and suspended solids generally showed less magnitude than other pollutants (see Fig 2 for 1999–2000, Fig. 3 for 2000–2001, and Fig. 5). This may be, in part, attributed to rainfall intensity effects on TSS emission rates. At low rainfall intensity, runoff velocity may be insufficient to mobilize particles. Therefore, if the early storms are lengthy with low rainfall intensity, suspended solids discharge may be low, which would reduce the magnitude of the seasonal first flush. Conversely, if the early storms had higher rainfall intensity compared to later storms, it would increase the seasonal first flush. We have not seen a correlation in our rainfall data between rainfall intensity and season, but it is a random effect that can produce years with reduced seasonal first flush.

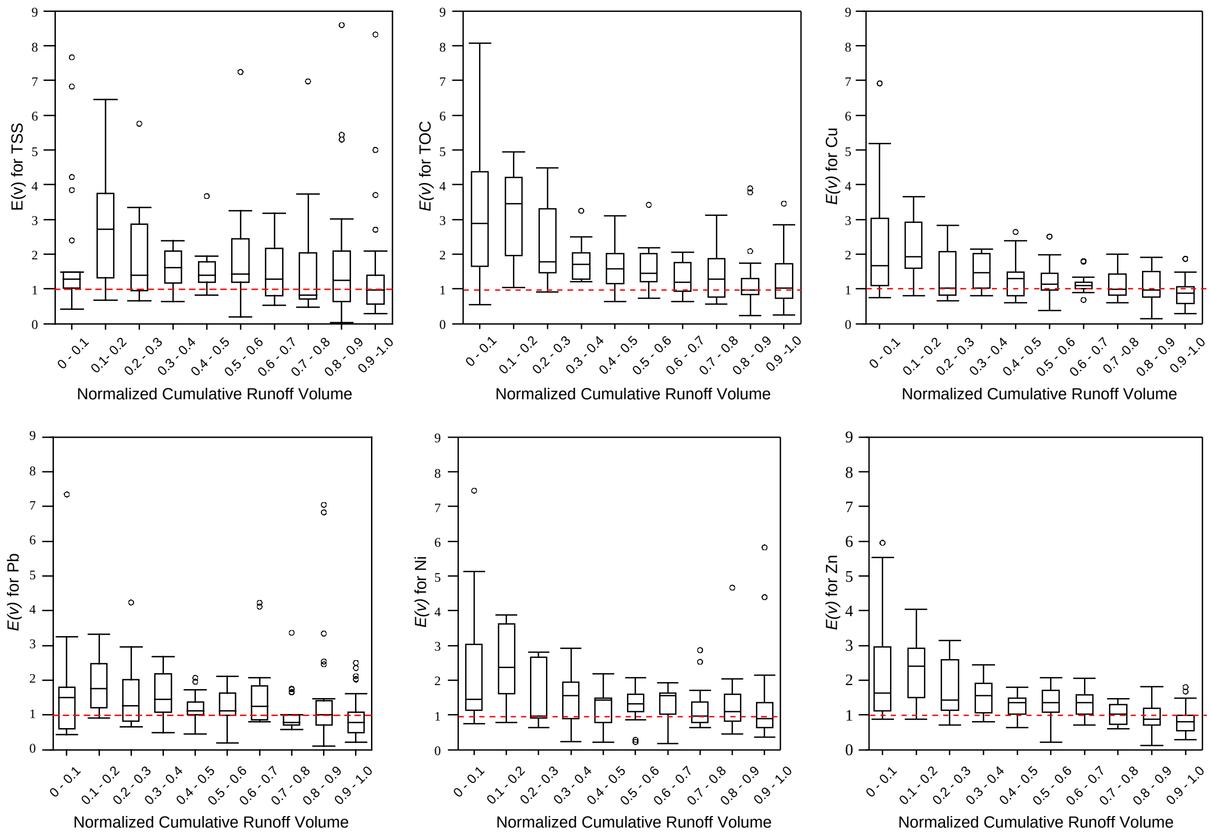

Fig. 7. Effectiveness factor, $E(V)$, for the Caltrans state-wide highway runoff monitoring study.

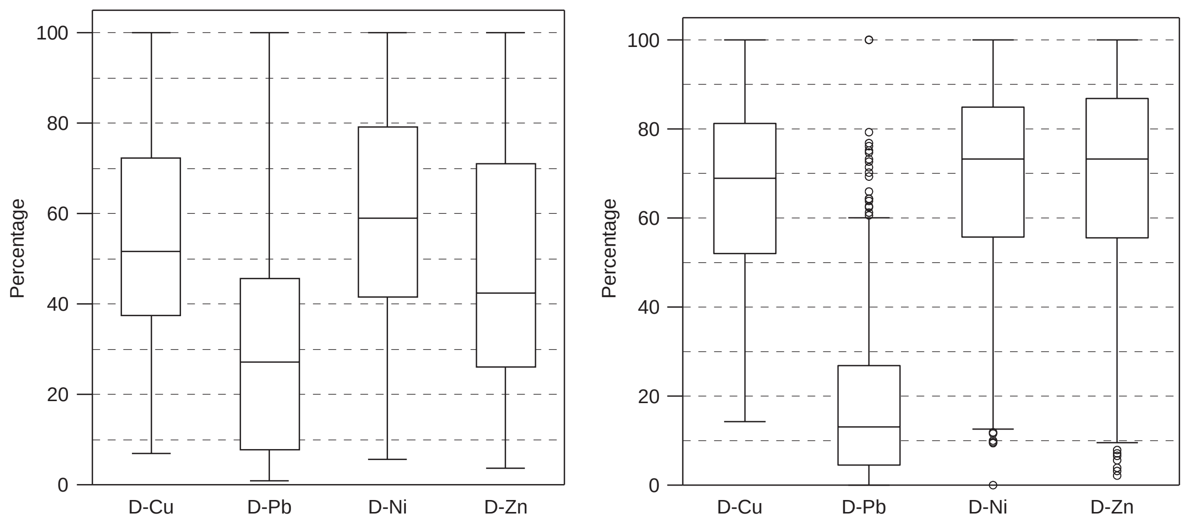

Fig. 8. Dissolved fraction (%) for Cu, Pb, Ni, and Zn for composite (left) and grab (right) samples.

An important question is the state of the metals: dissolved or adsorbed to suspended solids. Metals in the dissolved form do not require a minimum runoff velocity to be mobilized, and may be easily mobilized during storm events and exhibit a strong seasonal first flush. Metals adsorbed to solids will generally follow the trends of the suspended solids.

Metals monitored in the highway characterization studies were analyzed in both soluble and particulate forms. Fig. 8 shows the dissolved fraction, as a percent, for Pb, Ni, Cu, and Zn from the state-wide (left) and the first flush (right) highway runoff characterization studies. The state-wide study includes 237 flow-weighted composite samples for each metal for the 2000–2001, 2001–2002, and 2002–2003 wet seasons. The first flush study includes 729 grab samples per metal from three sites for 1999–2000, 2000–2001, 2001–2002, and 2002–2003 wet seasons. The composite samples show approximately equal portions in the dissolved and particulate form, except for lead, which is less than 30% (median) in the dissolved form. The grab samples show greater dissolved fractions, except for lead, which is only 11% (median) in the dissolved form. Therefore, one should expect the Pb and TSS first flushes to be related, and the emissions of Ni, Cu and Zn to be more independent of TSS. An important reason for the frequent weak seasonal first flush for Pb may be that it exists mainly in a particulate-bound form in stormwater runoff (Sansalone Buchberger, 1997; Legret and Pagotto, 1999). Analysis of the mass first flush ratios (MFFs) by event for all of the first flush highway runoff study shows that the MFFs (plotted in a fashion similar to Fig. 5; see Ma et al., 2002) are greater for soluble metals than total metals or metals in particulate form.

Partitioning between dissolved and particulate phases is potentially important in understanding the results. The time between sampling and receipt of grab samples at UCLA laboratory was less than 4 h, which means the sample holding time was shorter than the flow-weighted composite samples. The nature of the composite sample means that equilibrium processes can occur for at least the length of the storm (e.g., 6–8 h) and the allowable holding time before filtration (<24 h). Sansalone and Buchberger (1997) showed modest increases in the particulate fraction over time (0–24 h). The difference in soluble fractions between the two highway studies may be partially related to equilibrium processes that occur during sample collection or analysis. Metals partitioning will be an important consideration for BMP selection, since metal removal by BMPs is primarily due to suspended solids removal. The retention time for many BMPs, such as a sedimentation tank, is quite small compared to the time allowed for equilibrium in most monitoring programs. The time required for equilibrium merits further consideration and study.

5. Conclusions

Four major data sets, collected over the previous 4 years were examined to identify a seasonal first flush phenomenon, which occurs when the initial storm or storms of the wet season have higher pollutant concentration than storms near the end of the wet season. Trends in seasonal loads were quantified by plotting pollutant concentrations or cumulative pollutant load versus cumulative rainfall or cumulative runoff volume. A distinctive seasonal first flush existed in most cases. In general, the seasonal first flush was strong for total organic carbon (TOC), minerals as measured by specific conductivity (SC) and metals except for lead, which show frequent weak seasonal first flush and existed mainly in the particulate-bound form.

We calculated an effectiveness factor as a function of cumulative runoff volume. The parameter is intended to show the benefits of treating runoff early in the season to treating runoff later in the season. The relative effectiveness was the highest in the initial 10—20% of runoff volume for all parameters. The effectiveness was the greatest for TOC and weakest for lead (Pb), with many outliers. The median effectiveness for TOC at 10–20% of runoff volume was approximately 3.5, which means treatment of the initial 10–20% of runoff volume could remove 3.5 times as much TOC mass as a Best Management Practice (BMP) treating an equal volume later in the storm. This result suggests that applying treatment BMPs early in the season could remove several times more pollutant mass than randomly timed BMPs.

The large number of samples provided an opportunity to observe the distribution between dissolved and particulate-bound metals. The distribution was approximately equal for composite samples and about 70% dissolved for grab samples, except for lead, which was only 30% dissolved in composites and 11% dissolved in grab samples. The data supports the hypothesis that the phase of the metals is not at equilibrium at sample collection, which warrants further study to better understand BMP design or selection.

The information in this paper will be helpful in selecting better BMPs for controlling the quality of stormwater runoff in the areas with prolonged rainy and dry seasons or Mediterranean climates. Additionally, there are other areas, with less pronounced seasonal rainfall, which may benefit from this research.

Acknowledgements

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