Evaluation of seasonal scale first flush pollutant loading and implications for urban runoff management

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Abstract

This study investigated how the occurrence and magnitude of first flush events in stormwater may influence the effective management of urban runoff pollution. To facilitate the understanding of the first flush phenomenon on a seasonal scale, the City of San Jose, CA carried out an investigation between May 1997 and April 2000 to characterize concentrations of pollutants in local waterbodies during eight storm events. The purpose of the investigation was twofold: (1) To determine if concentrations of specific constituents in stormwater runoff are elevated during the first substantial storm of the wet season, and (2) To identify the physical and environmental conditions surrounding such events. Concentration data for total and dissolved metals, pesticides, polyaromatic hydrocarbons, anions, total suspended solids, total organic carbon, conductivity, gasoline, and diesel, and volatile and semi-volatile organics were collected at over 25 sites. Monitoring data analysis focused on identifying physical and environmental conditions yielding increased levels of pollutants during the first substantial storms of the rainy season compared to other storm events. Quantitative analysis focused on metals and anions because most observations for other constituents were below detectable levels. The results suggest that first flush phenomena did not occur consistently throughout most of the stations investigated. The results further suggest that there are specific combinations of site and storm conditions that result in a first flush effect with respect to dissolved metals. Based on the results of this and related investigations, implications for urban runoff management are discussed. For example, if dissolved metals are of principal concern, it may be worthwhile to optimize existing control strategies to minimize pollutant loading from storms that are preceded by an extended dry period.

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1. Introduction

1.1. Background

Effective urban runoff management requires an in-depth understanding of the environmental processes within a watershed. To gain such understanding with respect to pollutant loading during rainfall events, urban runoff research has identified the first flush of contaminants as a potentially important watershed phenomenon. This phenomenon occurs when the initial portion of rainfall after a dry period entrains greater pollutant concentrations from catchment surfaces than that of subsequent rainfall. Urban runoff managers may be better able to mitigate urban runoff pollution with the knowledge that specific site and storm conditions facilitate entrainment of above normal pollutant loads.

Between May 1997 and April 2000, the City of San Jose, CA investigated the potential for first flush pollutant loading within two watersheds. The study investigated whether the first substantial storm of the rainy season contained increased concentrations of pollutants relative to subsequent storms. This seasonal scale investigation was employed to evaluate the potential for control measures to mitigate these seasonal scale first flush phenomena, given San Jose’s characteristically dry summer and wet winter climate. The objectives were framed by two fundamental questions: (1) are pollutant concentrations in stormwater elevated during the first substantial storm of the wet season in

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San Jose? and (2) what are the physical and environmental conditions surrounding such events? Over 25 stations within the Guadalupe River and Coyote Creek watersheds were sampled during eight storms. Stormwater samples were analyzed for total and dissolved metals, pesticides, polycyclic aromatic hydrocarbons (PAHs), anions, total suspended solids (TSS), total organic carbon (TOC), conductivity, gasoline and diesel, and/or volatile and semi-volatile organics. Subsequent statistical analysis focused on identifying the combinations of circumstances which resulted in a first flush of pollutants, as defined above.

The first flush phenomenon has been studied previously, however, it remains an important research topic due to the potential implications it may have for urban runoff management. Part of the debate surrounding the first flush concept stems from the fact that studies have defined the phenomenon in different ways. For example, a first flush event has been defined as the runoff that carries a large percentage of the pollutant load during the initial stages of a storm event (Lee et al., 2002), and as an event in which at least 80% of the pollutant mass is transported in the first 30% of the volume (Bertrand-Krajewski et al., 1998).

Previous studies report that various combinations of factors may be responsible for the occurrence of first flush events. For example, the occurrence of a first flush phenomenon has been linked to the type of pollutant, catchment area, contributing impervious area, and rainfall intensity (Lee et al., 2002). Similarly, the maximum inflow, rainfall duration and antecedent dry weather period in combination with the maximum rainfall intensity have been identified as the most important parameters influencing the occurrence of a first flush event (Gupta and Saur, 1996). Finally, the dissolved fractions of metals have been reported to exhibit stronger evidence of first flush behavior than those in particulate form (Sansalone and Glenn, 2000).

1.2. Setting

The City of San Jose is located along the east side of the Santa Clara Valley in Northern California, bordered to the east by the Diablo Range and to the southwest by the Santa Cruz Mountains. Undeveloped areas support a variety of natural communities ranging from salt and fresh water marshes to scrub brush, foothill woodlands, and coniferous forest. A number of perennial and intermittent streams in both the Coyote Creek and Guadalupe River watersheds flow northward through the valley to the South San Francisco Bay. These streams include the upper and lower Penitencia Creeks, Silver Creek, Fisher Creek, Los Gatos and Alamitos Creeks. The valley generally experiences warm, dry summers and cool, wet winters. Approximately 1,000,000 people currently live in San Jose. Residential developments comprise roughly 50% of San Jose’s developed urban land area, commercial developments cover 5%, industrial developments cover 15%, parks cover 10%, vacant land covers 5% with the remainder of land coverage (15%) serving as rights of way (City of San Jose, 1999).

2. Methods

2.1. Sampling and analytical procedures

City of San Jose staff collected stormwater samples at over 25 stations within the Guadalupe River and Coyote Creek watersheds during eight storms (Fig. 1). The sampling locations are all located on the alluvial plain of the Santa Clara Basin within either the Guadalupe River or Coyote Creek watershed. The sampling locations were distributed across a range of land use areas and stream types. The lower two sites in the Guadalupe River watershed (Oakmead and River Oaks) are located in mixed open space and industrial areas that drain into the tidally influenced reach of the river. The sampling locations between Montague and San Carlos (Guadalupe River) and between Trade Zone and Commercial (Coyote Creek) are characterized as mixed industrial and commercial land use area. The sampling locations between West Virginia/Edwards and Blossom River (Guadalupe) and Trade Zone and Commercial (Coyote) are in predominantly residential areas with small patches of commercial and light industrial land uses. The upper sites in both watersheds are characterized as mixtures of open space and residential land uses. Both creeks have low channel slopes (1–2%) and are relatively modified in the lower reaches (earth levees) with decreasing channel modification in an upstream direction.

Four samples were collected at each station during each storm and composited to yield concentrations representative of each station for each storm event. Teams of two people were each assigned 4–5 sampling stations to visit four times during each storm event. Thus, teams attempted to cycle through the stations four times, as quickly as possible (within 30–45 min), to obtain samples from the first part of each storm. All samples were collected at the catchment’s discharge point or at the nearest accessible point. The typical sampling time between the first and last sample ranged from 2 to 3 h depending on the anticipated rainfall duration.

The composited samples were analyzed, following Standard Methods or as otherwise noted, by the City of San Jose laboratory for total and dissolved metals (Cd, Cr,Cu, Pb, Ni, Se, Ag, and Zn following EPA Method 200.8 and EPA Method 1631 for Hg), pesticides (EPA Methods 614, 8141/8140, and 622), PAHs (EPA Methods 610/8310, 625, 610/8270C), anions, TSS, TOC, conductivity, gasoline and diesel, and/or volatile (EPA methods 624,601, and 602) and semi-volatile organics (EPA Method 625). Samples collected during each storm were not analyzed for every constituent, however every constituent was monitored at least once during the study period.
District and National Weather Service Forecast Office online rainfall data were utilized.

2.2. Data analysis

The means and ranges of detected constituent concentrations were computed and compared to urban runoff data previously reported for both national (US EPA, 1983) and local conditions (Woodward Clyde Consultants, 1996). The data were then statistically analyzed to determine if, when, and where a first flush of pollutants occurred. Three of the eight storms sampled were designated as potential first flush storms (first flush storm) because they were the first substantial storms of the respective 1997/98, 1998/99, and 1999/00 wet seasons (10/9/97, 11/7/98, and 11/7/99). Data from these potential first flush storms were compared to the data collected during the other five monitored storms (5/23/97, 1/18/99, 1/16/00, 4/12/00, and 4/17/00) which were not potential first flush storm events (these are referred to as baseline storms herein).

The quantitative analysis was performed on the total and dissolved metals and anions data. Graphs were created for each constituent depicting pollutant concentrations during each storm at each site. Similar graphs were then created to compare the pollutant concentrations at each site for the various storms. Spatial and temporal analysis was carried out including an outlier analysis.

Scatter plots showing the influence of land use on pollutant concentrations for each storm were created and reviewed. Storm size and antecedent dry period data were also compared to pollutant concentrations in scatter plots isolating each relationship during first flush and background storm events.

Monitoring data for organophosphorous, triazine and chlorinated pesticides, PAHs, gasoline and diesel, and volatile and semi-volatile organics were also evaluated. Similar analyses to those described above were not possible however, because the vast majority of observations were reported below detectable limits (discussed in Section 3). Those data were summarized in tables presenting the number of samples collected, the total number of compounds analyzed, the number and names of compounds detected, the number of times each compound was detected, and the ranges of the detected values.
3. Results

3.1. Comparison to previously reported stormwater concentrations

The observed results for dissolved metals from this investigation were compared to results reported previously in both local and national investigations (Table 1). Inspection of Table 1 indicates that the dissolved metal concentrations reported during this investigation are comparable to, albeit consistently at the lower end of those previously reported in stormwater except, the dissolved lead concentrations which are substantially lower than those reported previously. This observation is likely due to the elimination of leaded gasoline.

3.2. Organics

The monitoring results and ranges of analytical detection limits for PAHs, volatile and semi-volatile organics, pesticides, gasoline and diesel, and PCBs are summarized in Table 2 and discussed briefly below.

3.2.1. PAHs

A total of 57 samples from the three first flush storms were analyzed for PAHs (EPA Methods 610/8310, 625, 610/8270C). Each sample was analyzed for 16 compounds. The results indicate that 94 of the 912 total observations for PAHs were reported above detectable limits (10%).

A total of 18 samples from two of the baseline storm events were also analyzed for PAHs. Each of those samples was analyzed for nine compounds. The results indicate that 15 of the 162 total observations were reported above detectable limits (9%).

3.2.2. Semi-volatile and volatile organics

A total of 25 samples from one first flush storm event were analyzed for semi-volatile organics (EPA Method 625). Each of those samples was analyzed for 52 compounds. The results indicate that three of the 1300 total observations were reported above detectable limits (0.2%).

Butyl benzyl phthalate was detected once (21.2 ug/L) and bis-2-ethylhexyl phthalate was detected two times (20.6 and 34.6 ug/L).

A total of five samples from one first flush storm were analyzed for volatile organics (EPA methods 624, 601, and 602). The samples resulted in a total of 136 observations, none of which were above detectable limits.

3.2.3. Pesticides

Samples were analyzed for chlorinated, organophosphorous and triazine pesticides. A total of 40 samples from three first flush storms were analyzed for chlorinated pesticides. Results indicate that eight of the 1160 observations were above detectable limits (0.7%).

A total of 24 samples from three baseline storms were also analyzed for chlorinated pesticides, with five of the 696 observations above detectable limits (0.7%).

Organophosphorous pesticides were analyzed by several methods including EPA Methods 614, 8141/8140, and 622. A total of 114 samples were analyzed from the three first flush storms for organophosphorous pesticides, resulting in 171 observations. Of those 171, 58 were above detectable limits (34%).

Of 112 observations, 57 were above detectable limits (51%). The detected compounds and ranges were as follows for first flush and baseline storms, respectively: Chlorpyrifos (0.06–0.23 ug/L; 0.01–0.12 ug/L), Diazanon (0.02–2.56 ug/L; 0.01–1.22 ug/L), and Malathion (0.03–1.17 ug/L; 0.02–0.4 ug/L).

Table 1

Dissolved metals national and regional background comparison

<table>
<thead>
<tr>
<th>Constituent</th>
<th>NURP (^a) (ug/L)</th>
<th>Nationwide statistics (^b) (ug/L)</th>
<th>SF Bay area 1988–1995 (^c) (ug/L)</th>
<th>Current investigation</th>
<th>First flush events (ug/L)</th>
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<tr>
<td>Copper</td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>Mean</td>
<td>114</td>
<td>34</td>
<td>46.6</td>
<td>15.8</td>
<td>15.9</td>
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<tr>
<td>Range</td>
<td>4–560</td>
<td>12</td>
<td>46.9</td>
<td>3.4–64.5</td>
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<tr>
<td>Nickel</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
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<td>34.1–77.3</td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<td>Mean</td>
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<td>140</td>
<td>114.6</td>
<td>2.7</td>
<td>3</td>
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<tr>
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<td>3–28,000</td>
<td>51.7–151</td>
<td>0.05–18.5</td>
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<tr>
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<td>160</td>
<td>312.8</td>
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<td>Cadmium</td>
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<td>0.4</td>
<td>0.5</td>
</tr>
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<td>2.1</td>
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<td>Range</td>
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<td>NS-35.4</td>
<td>0.5–15</td>
<td>0.9–6.4</td>
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</table>

\(^a\) Pitt and Shawley, 1981.

\(^b\) Horner et al., 1994

\(^c\) Woodward Clyde Consultants, 1996.
<table>
<thead>
<tr>
<th>Type of constituent</th>
<th>Type of sample</th>
<th>Storm date</th>
<th>Analytical method</th>
<th>Range of method detection limits (ug/L)</th>
<th>No. of Stations sampled</th>
<th>No. of Compounds analyzed in each sample</th>
<th>Total no. of observations</th>
<th>No. of Detected observations</th>
<th>% Observations detected</th>
</tr>
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<td>10/09/1997</td>
<td>610/8310</td>
<td>0.02–0.15</td>
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<td>16</td>
<td>912</td>
<td>94</td>
<td>10%</td>
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<tr>
<td></td>
<td></td>
<td>11/07/1998</td>
<td>625</td>
<td>0.03–0.27</td>
<td>11</td>
<td>16</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>11/07/1999</td>
<td>610/8270C</td>
<td>0.1–0.2</td>
<td>21</td>
<td>16</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Baseline</td>
<td>01/18/1999</td>
<td>625</td>
<td>0.03–0.27</td>
<td>14</td>
<td>9</td>
<td>162</td>
<td>15</td>
<td>9%</td>
</tr>
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<td></td>
<td></td>
<td>04/17/2000</td>
<td>625</td>
<td>0.03–0.27</td>
<td>4</td>
<td>9</td>
<td></td>
<td></td>
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<td>Potential first flush</td>
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<td>625</td>
<td>1.0–4.5</td>
<td>25</td>
<td>52</td>
<td>1300</td>
<td>3</td>
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<td>624</td>
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<td>3</td>
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<td>136</td>
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<td>0.004–0.01</td>
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<td>1160</td>
<td>8</td>
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<td>29</td>
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<tr>
<td></td>
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</tbody>
</table>
A total of 36 samples from two first flush storm events were analyzed for simazine (triazine pesticide). Results indicate that one of the 36 observations was above detectable limits (3%) at a concentration of 0.69 ug/L.

3.2.4. Other constituents

A total of 25 samples from one first flush storm event were analyzed for PCBs and gasoline. None of those observations were reported above detectable limits. A total of 30 samples from one first flush storm event were analyzed for diesel. Results indicate that there were no observations above detectable limits.

3.2.5. Qualitative comparison

Because the majority of samples analyzed for organic compounds yielded results below detectable limits, a more comprehensive quantitative analysis of the data was not performed. This result is not unexpected since these compounds tend to be hydrophobic and typically associated with sediments. A qualitative comparison of the results for these constituents indicates that there was very little difference between first flush and baseline events in terms of the percent of detected observations. This general observation also holds for organophosphorous pesticides. Those compounds were detected in 34% of the first flush samples and 51% of the background samples, with slightly higher concentration ranges reported in the first flush observations.

3.3. Total and dissolved metals

Analyses were carried out for total and dissolved metals during two baseline storms (May 1997 and January 1999) and three first flush storms (October 1997, November 1998, November 1999).

3.3.1. Site characteristic analysis

A consistently strong correlation between catchment land use percentages and pollutant concentrations was not exhibited in the observed data for either total or dissolved metals. This observation is representatively illustrated by the relationship between the percent residential land use and concentrations of dissolved zinc reported for first flush and non first flush storms during this investigation (Fig. 2).

3.3.2. Storm characteristic analysis

Metal concentrations (dissolved and total) were evaluated to determine if the presence of a first flush phenomenon was influenced by storm size. No consistent relationship was found between storm size and the occurrence of a first flush phenomenon for total or dissolved metals. Representative results from this analysis are presented in Fig. 3 for dissolved lead concentrations for first flush and baseline storms.

3.3.3. Storm event evaluation

Concentrations of total and dissolved metals were compared on a storm by storm basis to identify any trends relevant to first flush phenomena. When the data from all sites were grouped together, characteristics of first flush phenomena were generally not noted. Representative results from this analysis are presented in Fig. 4, which shows dissolved zinc concentrations from two background storms (May 1997 and January 1999), and the three first flush storms.

To further investigate potential trends in the data, graphs were generated showing results from individual monitoring
stations over the course of the investigation. As an example of this analysis, dissolved zinc concentrations at representative sites are presented in Fig. 5. In general, total metals did not show a tendency for first flush behavior in the watersheds investigated. However, the concentration of total mercury in the first flush storm samples was slightly elevated relative to background storms. Results from the dissolved metals data analysis were more difficult to interpret.

As shown in Fig. 5 for dissolved zinc concentrations and Fig. 6 for dissolved copper concentrations, the May 1997 background storm event yielded relatively high dissolved metals concentrations. During this storm event, the highest concentrations for most constituents occurred at the River Oaks station. Relatively high dissolved metals concentrations were also observed for many constituents during the November 1999 first flush storm event.

Overall, the three first flush storm events resulted in concentrations of dissolved metals similar to those from the May 1997 and January 1999 background storm events. The January 1999 background storm event at most stations produced the lowest dissolved metal concentrations of all storm events. The exceptions to this observation were concentrations of dissolved zinc, nickel and lead at the Tully, San Pedro, Oakmead, Old Oakland and Lincoln stations. Observations at these stations during the January 1999 sampling event were high relative to those measured during the same storm at other stations and to those measured at the same stations during other storms. Also of note was that observed concentrations of dissolved copper, zinc, nickel and lead at the Edwards station were higher during first flush events than those during non first flush events (Figs. 5 and 6).

3.4. Anions

Data from four storms, three first flush storms and one background storm event, were compiled and analyzed for chloride, phosphate, nitrite, nitrate and sulfate in much the same manner as the dissolved and total metals. The results of this analysis did not suggest any strong relationships between anion concentrations and storm size. However, comparisons of anion concentrations with associated land uses suggested a relation between sulfate concentrations and catchments consisting partially of agricultural land uses. The data analysis indicates that the sulfate concentrations running off catchments associated with agricultural land uses are higher than those running off catchments characteristic of either commercial, residential or mixed land uses (Fig. 7). The environmental basis and interpretation of this observation is unknown. However, basic salts such as ammonium are utilized to formulate various fertilizers including ammonium sulfate and some fertilizers are sulfur coated to allow for slow release. In addition, air deposition as a source should also be investigated.

4. Discussion

The results from this investigation suggest that a first flush phenomenon did not occur consistently for those constituents detected sufficiently to carry out a statistical analysis (total and dissolved metals and anions).
This observation is consistent with a review of stormwater data from 66 municipalities in 17 states (Maestre et al., 2004). There do however seem to be specific combinations of site and storm circumstances that appear to foster an occurrence of a first flush effect for dissolved metals. A discussion of this finding is presented below along with a discussion regarding the potential limitations of the investigation.

4.1. Monitoring conditions

Although this study was designed to investigate first flush phenomena on a seasonal scale, the monitoring protocol employed may have served to offset evidence of a first flush phenomenon. Runoff quality during the initial stages of a storm has been characterized by a positive pollutant concentration–flowrate relationship (Lee and Bang, 2000). Furthermore, peak pollutant concentrations tend to precede peak runoff flowrates and thus result in the runoff of a greater pollutant load during early storm stages. Sample values reported for the purposes of our study may not have been indicative of the magnitude of the differences in pollutant concentrations found in first flush and background storms because the analysis was performed on composites of four samples taken at various times throughout the storm event. High concentrations due to the runoff of accumulated pollutants during the initial stages may have been attenuated by lower concentrations at later stages in the storm.

4.2. Pollutant characteristics

For this study, semi-volatile and volatile organics, gasoline and diesel, PCBs, pesticides, total and dissolved metals and anions were sampled and statistically analyzed. The first flush phenomenon occurred only for dissolved metals under specific circumstances and for total mercury. These dissolved metal results are consistent with previous studies, which found that the strongest evidence of a first flush of pollutants is exhibited by dissolved metals, in particular zinc, cadmium and copper (Sansalone and Buchberger, 1997; Sansalone and Glenn, 2000). Because dissolved metals are more easily eroded from impervious surfaces and entrained in surface water runoff, pollutant concentrations are less dependent upon storm duration and intensity. The reasons for the anomalous total mercury results, compared to other metals, are not known. Differences in sources and transport processes between mercury and the other metals may contribute to the observed difference. An example of one process unique to mercury in the study area is that sediments may be enriched with mercury due to cycling in the local environment because of the nearby former mercury mines. However, a more detailed explanation of this observation is beyond the scope of this investigation.

4.3. Site characteristics

Various catchment characteristics may contribute to specific urban runoff processes. Previous work indicates that the first flush phenomenon is exhibited more prominently in smaller catchments and that there is a slight correlation between occurrence and impervious coverage within the drainage area (Lee et al., 2002). This finding is due to the fact that pollutants are more easily loaded and scoured off impervious surfaces and more rapidly delivered to the point of discharge within smaller catchments. Such factors seem only to be relevant when examining the speed with which pollutants reach the point of discharge as compared to rainfall duration.

Because samples were taken throughout the duration of the storm event for this study and composited, the effects of catchment area on the occurrence of a first flush would have to be studied simultaneously with storm duration and intensity. This type of analysis was beyond the scope of the investigation. An analysis was however carried out examining the relationship between the occurrence of a first flush phenomenon and land uses associated with each catchment. The results did not show a strong relation between any land use characteristics and the occurrence of a first flush in metals. However, the concentrations of sulfate discharging from catchments associated with agricultural land uses did appear to be higher than those discharging from catchments associated with other land uses during first flush events.

Monitoring data for dissolved metals seems to exhibit first flush behavior at the Edwards station. The data suggest that a first flush phenomenon occurred for every dissolved metal at this station. Pollutant concentrations during the first flush storm events at Edwards station are high even when compared to data from the same events at other stations (Fig. 8). It is also of note that the pollutant concentrations sampled during the May 1997 and January 1999 background storms are noticeably lower than those sampled during the first flush storms at the Edwards station.
Dissolved metals data also show evidence of a distinct split between stations at which low pollutant concentrations were observed and those at which higher pollutant concentrations were observed during the background storm event of January 1999. This trend is seen most prominently in the increase in concentrations of lead, zinc and nickel at the Tully, San Pedro, Oakmead, Old Oakland and Lincoln stations. At most other stations, January 1999 pollutant concentrations are the lowest sampled of all storms. We are unable to determine why these stations show such a trend.

4.4. Storm characteristics

The five storms during which samples were analyzed for metals and anions differed widely in rainfall volume and antecedent dry period (Table 3). Previous studies note varying relationships between storm characteristics and runoff concentrations during first flush events. For example Lee and Bang identify a slight correlation between storm intensity and the concentration of pollutants entrained in runoff but do not conclude that there is a relation between pollutant concentrations and the antecedent dry period (Lee and Bang, 2000).

For this investigation, pollutant concentrations were evaluated relative to storm volume and antecedent dry period. The May 1997 storm yielded the greatest dissolved and total metal concentrations of any storm sampled. The storm was very intense and resulted in a relatively large volume of rainfall, which was preceded by a dry period of approximately 2 months. Because of the last condition, the storm may have many characteristics in common with the first substantial storm of the wet season. The observed results of this storm may be a function of high storm intensity, and long antecedent dry period (Lee and Bang, 2000).

The November 1999 storm event resulted in the second greatest pollutant concentrations. Sampled as a first flush storm, the event was rather large in volume and was preceded by a dry period of 9 days. The rain preceding event was so small in volume that pollutant entrainment is suspected to be minimal, which if true, effectively lengthens the antecedent dry period to at least 2 months. Thus, the substantial rainfall after a long antecedent dry period may have resulted in generally high pollutant concentrations.

The January 1999 storm event was the largest in volume yet yielded consistently low pollutant concentrations. Three days prior to the sampling there was a storm event, which delivered 0.26 inches of rain. Results indicate that such a preceding rain event could have washed the surfaces clean of pollutant loads and left little to be entrained during the January 18th event. During such an occurrence, the short antecedent dry period may be responsible for such low pollutant concentrations.

The October 1997 and November 1998 storm events, although different in size and associated antecedent dry periods, yielded similar pollutant concentrations. They were consistently lower than the November 1999 and May 1997 storm samples but higher than the January 1999 storm samples. It is possible that the longer antecedent period of the November 1998 storm event effectively balanced out the greater rainfall volume of the October 1997 storm event.

These results suggest the possibility of a slight relation between antecedent dry period and dissolved metals concentrations. To investigate this possibility, a literature review was carried out to better understand pollutant loading thresholds relative to dry periods. Most relevant were the studies carried out in Castro Valley, California (Pitt and Shawley, 1981) and Reno/Sparks, Nevada (CH2M HILL, 1982). Those studies reported that dissolved pollutant loads on streets reach equilibrium within approximately 1–2 weeks, after which the mass of pollutants deposited onto surfaces does not increase. It may therefore be expected that greater pollutant loads may be washed off surfaces following dry periods of more than 1–2 weeks than those during storms immediately following a substantial rainfall. The results of this investigation are consistent with those described above. Pollutant concentrations during the storm preceded by a 3-day dry period were lowest, those from storms preceded by 7–14 day dry periods were intermediate, and those during the storms preceded by 60 day dry periods were highest. This observation is illustrated in Fig. 9, which

![Fig. 9. Influence of antecedent dry period on dissolved copper concentrations.](image-url)
presents dissolved copper concentration as a function of antecedent dry period.

4.5. Urban runoff management implications

This investigation comprised a substantial data collection effort over a 3-year time period. The results of the investigation indicate that concentrations of dissolved metals in stormwater may be higher in storms that are preceded by an extended dry period than in storms preceded by a shorter time period. Other contaminants investigated either did not demonstrate first flush phenomena or were not detected in sufficient quantities to carry out quantitative analysis.

Based on the results of the investigation, it should be clear that the implications to urban runoff management are inextricably linked to the contaminants of concern for the receiving waters. For example, if total metals concentrations are the primary contaminant of concern, it would not seem prudent to alter current urban runoff management strategies to reduce pollutant loading from ‘first flush’ storm events. If on the other hand, dissolved metals are of principal concern, it may be worthwhile to optimize existing control strategies to minimize pollutant loading from storms that are preceded by an extended dry period.

5. Conclusions

From monitoring eight storm events over a three and a half-year period, the principal conclusions of this investigation are as follows:

(1) Concentrations of dissolved metals from storms surveyed in this study were consistently lower than those from previous studies.

(2) A first flush phenomenon did not occur consistently for total metals, dissolved metals or anions. There do however seem to be specific combinations of site and storm circumstances that result in a first flush effect of dissolved metals. Total mercury also exhibited a first flush phenomenon.

(3) There was no relation between metal concentrations in storm runoff and land use. One anion, sulfate, showed a relation between stormwater concentrations and agricultural land use within the catchment. The interpretation of increased levels of sulfate with agricultural land use is unclear.

(4) Urban runoff dissolved metal concentrations do not have a strong relationship with storm size, however there does seem to be a relation with the antecedent dry weather period.

(5) The implications of the findings of this investigation to urban runoff management are inextricably linked to the contaminants of concern for the receiving waters.

References


Santa Clara Valley Water District. Past Rainfall and Reservoir Status Reports, http://www.valleywater.org/water/technical_information/measures_and_readings/_Past_Rainfall___Reservoir_Reports.shtml
