Mass Loading of First Flush Pollutants with Treatment Strategy Simulations

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"First flush" is a term for the initial period of stormwater discharge from a storm event. Conventional thinking is that the first flush exhibits high pollutant concentrations. The existence of a first flush in highway runoff has been documented through a comprehensive 4-year runoff monitoring from three highway sites in Los Angeles, California. As part of this study, a numeric definition of the mass first flush ratio is developed; it characterizes the normalized mass of pollutants in the first portion of the normalized runoff volume. Mass first flush ratios have been developed for more than 30 conventional water quality parameters, heavy metals, nutrients, and organic pollutants. This study explores the improved performance that some best management practices (BMPs) exhibit when they can take advantage of the high concentrations of pollutants at the beginning of a storm event. A range of hypothetical events corresponding to the observed mass first flush ratios were simulated. These simulations demonstrate that improved mass removal rates are possible when BMPs can be managed to treat a greater volume of the early runoff. For example, it was shown that for pollutants such as total suspended solids, chemical oxygen demand, total organic carbon/compounds, and oil and grease, infiltration basins that can capture the first 20% of the storm volume and bypass the remaining volume can be twice as effective as a practice that treats 20% of the storm volume throughout the entire period of runoff. Similarly, when a seasonal first flush exists, treating the first few storms of the season entirely is more effective than treating a constant volume throughout the season.

"First flush" is a term associated with the belief that the first runoff of stormwater in a storm event is the most contaminated. Most researchers believe that the first runoff does have higher contaminant concentrations, but opinions vary as to the importance of the increased concentrations and whether the actual mass of the first flush is a significant portion of the total runoff mass (*1–11*). Lay persons generally believe that there is a first flush and associate hazardous driving conditions with the onset of rainfall. This study has devoted a great deal of effort to developing a quantitative way of defining the first flush. In areas that have distinct seasonal rainfall patterns, such as Southern California, a similar concept, called "seasonal first flush," exists (*12*). The general belief is that the first rainfall of the new rainy season is the most contaminated and washes out several months of contaminant buildup. Also addressed in this study is the storm first flush, which is not associated with the first storm of a season. Statements about first flush apply to both types unless otherwise noted.

The existence of a first flush, during either a storm or a seasonal first flush, presents opportunities for better pollutant reduction programs for two reasons. First, the cost of treatment, whether a wastewater treatment plant or a stormwater best management practice (BMP), is more dependent on the volume of water to be treated than on the contaminant concentration. Second, removal efficiency is greater at higher concentrations and nearly zero at lower concentrations. The emerging ASCE database on stormwater treatment BMP trials shows this effect (*13*). Lau and Stenstrom (*14*) demonstrated the same phenomenon using catch basin inserts, sorbers, and sedimentation devices.

As part of the larger study, various aspects of first flush characterization were investigated. Major issues examined include water quality and litter characteristics, correlations among contaminants, mass emission rates, a meaningful definition of the first flush phenomenon, first flush of organics, pollutant buildup and wash-off models, sampling strategies, particle size distribution, and toxicity. Some aspects of these research topics have been presented at national conferences and others have been submitted to or are published in peer-reviewed journals (*7, 10, 15–20*). The focus of this study is to perform various treatment simulations to demonstrate the benefits associated with treating the largest possible fraction of early runoff.

METHODS

Characteristics of Highway Sites

Three representative highway sites in West Los Angeles, California, were selected for this study. The sites are within a 10- to 15-min drive of the University of California, Los Angeles (UCLA), campus. This site selection criterion was essential because the sampling protocol required the sampling teams to arrive at the site before the storm and to be present during the entire storm. The sites were also selected to have identifiable runoff areas and distinct points for sampling. The sites had drainage pipes that discharged as a waterfall or free jet, so a well-mixed representative sample could be obtained by bailing. All three sites were highly impervious and the annual average daily traffic (AADT) ranged from 260,000 to 328,000. Additional information on AADT, sites, and equipment used can be found elsewhere (*18, 21*).

Sample Collection

A series of grab samples were collected throughout the storm events. In the first year, five to six grab samples were collected in the first hour and a manually composited sample was collected over the following

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several hours. In the second, third, and fourth years, five grab samples were collected in the first hour, followed by one grab sample per hour until the end of 8 h. When a storm lasted beyond 8 h, one or two additional grab samples were collected to characterize the tail of the runoff. A flow-weighted composite sample was also collected during the last 3 years of monitoring using an American Sigma 950 Series automatic sampler.

In general, a 4-L amber glass bottle was used for sample collection. Grab samples were transported to the UCLA laboratory after the first hour and at one or two times later in the storm. A large suite of water quality parameters was measured, such as conventional parameters [alkalinity, hardness, conductivity, temperature, pH, total suspended solids (TSS), total dissolved solids, chemical oxygen demand (COD), dissolved organic carbon (DOC), and total organic carbon/compounds (TOC)], metals (arsenic, cadmium, chromium, copper, lead, nickel, and zinc), nutrients [NH_3, NO_2, NO_3, total Kjeldahl nitrogen, orthophosphate, and total phosphate], oil and grease, fecal and total coliform as indicator organisms, and polynuclear aromatic hydrocarbons. All samples were analyzed using standard methods or the U.S. Environmental Protection Agency (EPA) procedures. Comprehensive field and laboratory quality assurance and quality control were used for all monitoring data.

Event Mean Concentrations

In most stormwater monitoring programs, a single flow-weighted composite sample is usually collected by automatic samplers and analyzed for pollutant event mean concentration (EMC). The EMC is mathematically represented as follows:

$$\text{EMC} = \frac{M}{V} = \frac{\int C(t)Q(t)\,dt}{\int Q(t)\,dt} \tag{1}$$

where

$C(t)$ = pollutant concentration (mg/L),
$Q(t)$ = stormwater flow discharged at time t (L/h),
M = total pollutant mass (mg or kg), and
V = total flow volume (L).

The EMC is the best single descriptor of stormwater contaminant concentration and is generally preferred in any monitoring study. Unfortunately, the EMC measured from automatic samplers provides no information on the temporal variability of contaminant concentrations. It cannot be used to characterize first flush. Automated sampling equipment is also not suitable for sampling specific contaminants such as oil and grease, bacteria, and some volatile organic compounds. Automated equipment may also introduce artifactual toxicity (toxicity that is introduced by the sampling or analytical method) and is generally addressed through the use of field blank samples that verify the suitability of the equipment (*22*). Preliminary particle size distribution (PSD) analysis performed by Li et al. (*15*) also revealed that composite samplers cannot be used for PSD analysis because of particle aggregation in the sample bottle during the sampling period.

It is also possible to calculate an EMC from a series of grab samples. Most samples analyzed under the first flush characterization study were grab samples. Grab samples collected at different stages of a storm event (hydrograph) may differ substantially. An EMC cannot be determined by simply averaging the measured pollutant concentrations because of the varying flow rate.

The key problem of the simple EMC equation is how to express the concentration changes, $C(t)$, reasonably. Gupta and Saul (*5*) used multiple linear regression analysis for data interpolation and Larsen et al. (*6*) calculated EMCs using the medium point method. Other researchers (*23–27*) used an applied washoff model for estimating EMCs. To calculate EMCs with a limited number of samples, the most useful method is to use finite difference equations that incorporate continuously monitored flow data and instantaneous pollutant concentrations, as follows:

$$\text{EMC} = \frac{\sum_i C_i V_i}{\sum_i V_i} = \frac{C_i V_i + C_2 V_2 + \cdots + C_n V_n}{V_T} = W_1 C_1 + W_2 C_2 + \cdots + W_n C_n \tag{2}$$

where

$W_i = \dfrac{V_i}{V_T}$,
$W_1 + W_2 + \cdots + W_n = 1$,
W_i = weight for ith sample,
V_i = fractional flow volume assigned for ith sample,
V_T = total flow volume, and
n = number of samples.

Pollutographs

A pollutograph is generally known as a plot of pollutant concentration versus time throughout the storm event. In most cases, storm event rainfall or rain intensity and flow rate are also shown on the same plot. Pollutographs can be prepared for a single pollutant or multiple pollutants. A typical multiple pollutograph for TSS, COD, oil and grease, and TOC is shown in Figure 1. As can be seen, the principal benefit associated with pollutographs is to see the change in concentration of certain contaminants as a storm progresses. For example, the first sample may have more than 600 mg/L of TSS, but the EMC may be only 200 mg/L. The reduction occurs because the first runoff concentration may be present at a low flow rate, at the beginning of the storm. Pollutographs are a useful tool to examine the first flush of constituents based on concentration and to understand the relationships among various constituents' concentration and changes related to peaks in flow or rainfall.

Load Graph and Mass First Flush Ratio

As previously shown, measurements of pollutant concentration at different stages of a storm event along with flow measurement enable the computation of the mass at any point along the hydrograph. Pollutant mass emission and runoff flow rates can be integrated and normalized as follows:

$$\frac{y}{x} = \frac{\dfrac{\int_0^{t_1} C(t)Q(t)\,dt}{M}}{\dfrac{\int_0^{t_1} Q(t)\,dt}{V}} = \frac{\dfrac{\int_0^{t_1} C(t)Q(t)}{\int_0^{t_1} Q(t)\,dt}}{\dfrac{M}{V}} \tag{3}$$

where y/x is known as the mass first flush (MFF_n) ratio.

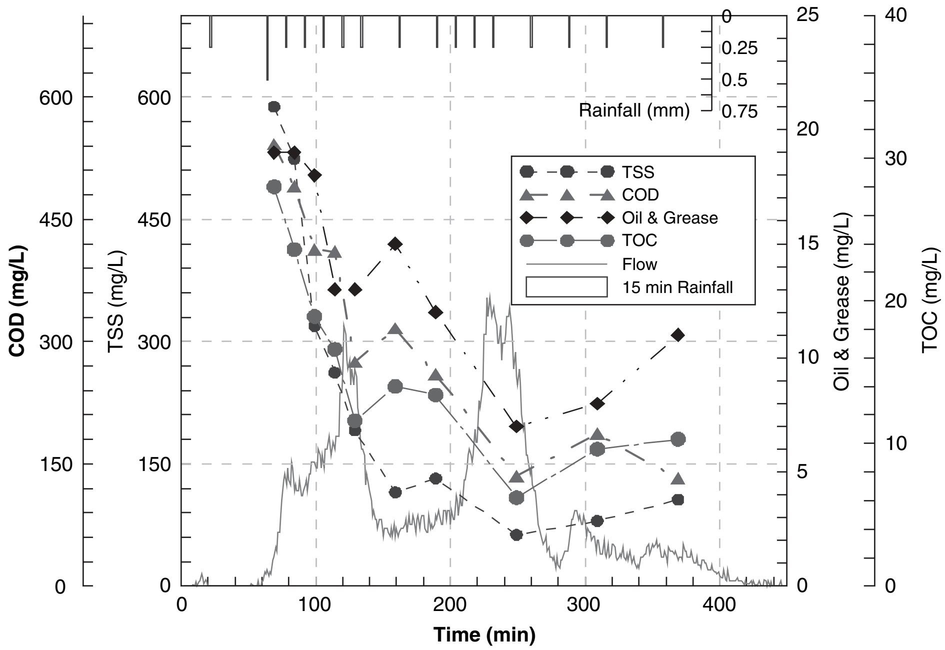


FIGURE 1 Pollutographs for TSS, COD, oil and grease, and TOC for storm event during February 2001.

The plot of normalized cumulative mass versus normalized cumulative volume is usually referred to as a load graph and can be used to examine the mass first flush phenomenon (*7*). Although the mass first flush ratio can be computed throughout the event, only the first 50% or less of the volume is usually considered to establish the mass first flush criterion. For a pollutant to have a true mass first flush, the ratio of *y*/*x* for the early runoff volume fraction must be much greater than 1. The greater the *y*/*x* ratio, the larger the mass first flush. A typical load graph is shown in Figure 2. The computation of MFF_{10} and MFF_{30} for a typical load graph is also illustrated in Figure 2. The MFF_{10} ratio of 4.5 implies that 45% of the pollutant mass is transported in the first 10% of the runoff volume. The MFF approaches 1.0 as the normalized runoff volume approaches 1.0.

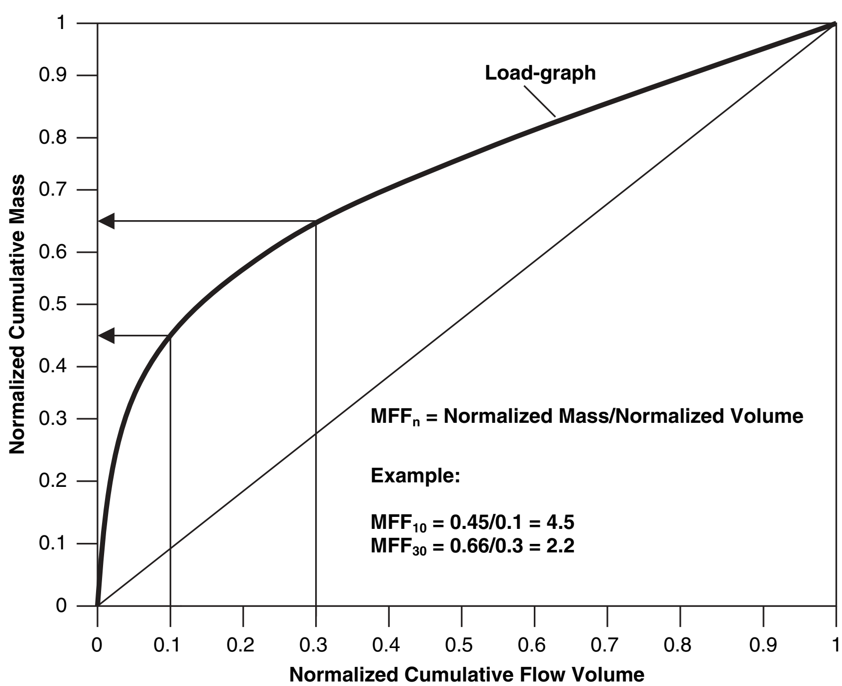


FIGURE 2 Typical load graph with illustrative method showing computation of mass first flush ratio.

RESULTS AND DISCUSSION

Hydrologic Data

A summary of storm events for the duration of the study and the monitoring sites is given in Table 1. Generally five to eight storms per year were sampled. In the first year more storms were sampled because no criteria were being used to limit sampling to longer storms. The research teams were mobilized for nearly all storms, and in a few cases samples were collected but not analyzed because the storm ended too soon. In a few cases equipment failures occurred, and the samples were either not collected or not analyzed since flow data are needed for proper interpretation of mass loading.

In general, four types of hydrographs were observed in the study area (see Figure 3):

- Type 1 hydrograph: runoff is continuous;
- Type 2 hydrograph: runoff is discontinuous, but the discontinuity can be neglected in the analysis;

TABLE 1 Storm Event Summary

Site	Monitoring Year	Number of Event	Number of Samples: Grab	Number of Samples: Composite	Rainfall [cm (in.)]
7-201	1999–2000	11	51	—	21.74 (8.56)
	2000–2001	8	63	2	55.24 (21.75)
	2001–2002	5	39	5	8.23 (3.24)
	2002–2003	6	74	5	49.58 (19.52)
7-202	1999–2000	12	83	—	29.67 (11.68)
	2000–2001	8	83	2	54.28 (21.37)
	2001–2002	8	57	8	13.56 (5.34)
	2002–2003	6	61	6	47.52 (18.71)
7-203	1999–2000	13	71	—	33.25 (13.09)
	2000–2001	8	71	4	55.68 (21.92)
	2001–2002	8	55	8	10.11 (3.98)
	2002–2003	6	73	5	55.83 (21.98)

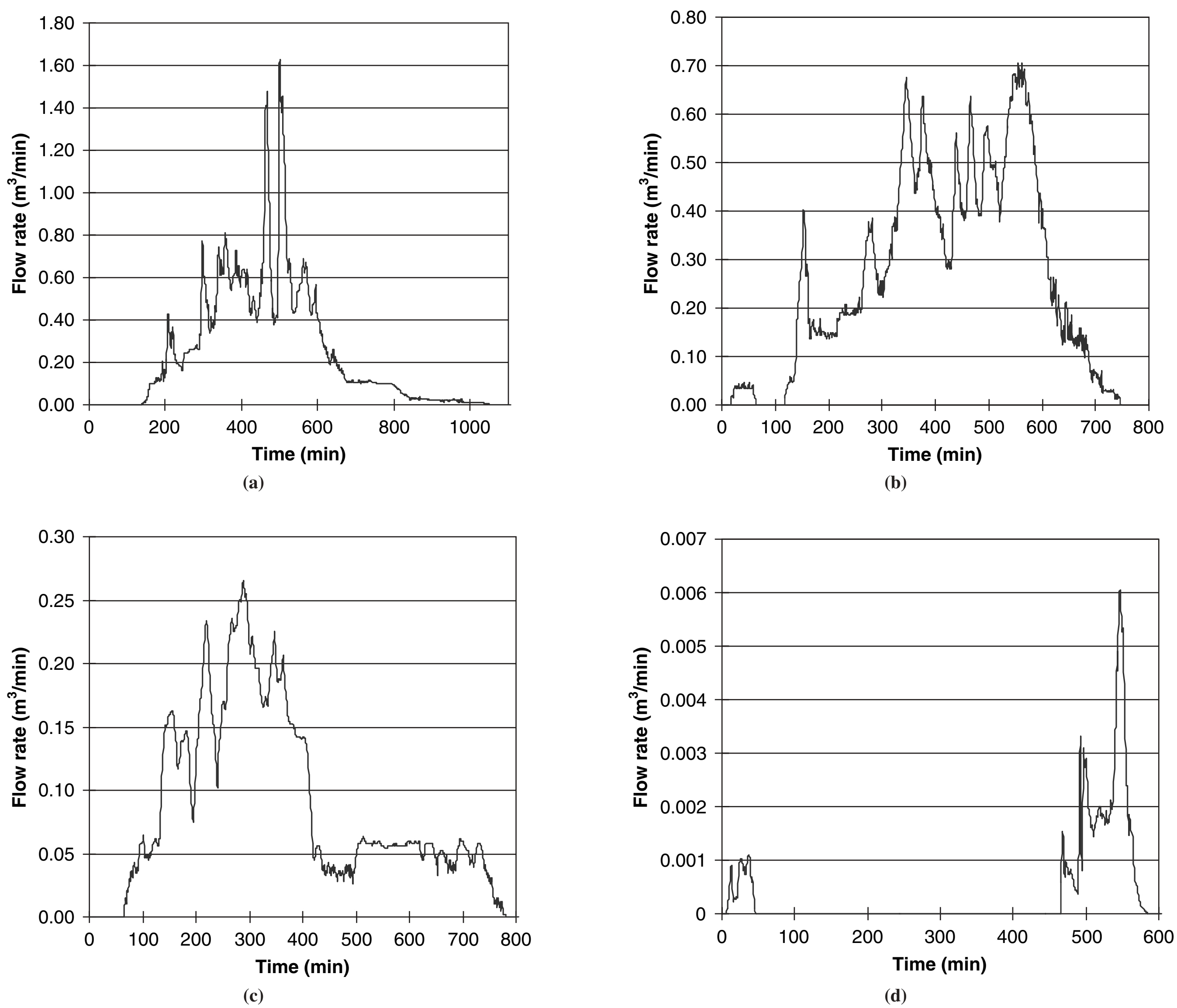


FIGURE 3 Typical hydrographs observed for study areas: (*a*) Type 1, (*b*) Type 2, (*c*) Type 3, and (*d*) Type 4.

- Type 3 hydrograph: runoff is discontinuous, and only the first part of the runoff is used in the analysis; and
- Type 4 hydrograph: runoff is discontinuous, and only the last part of the storm is used in the analysis.

A review of all hydrographs for the duration of the study and three highway sites indicates that Hydrograph Type 1 was more dominant. These hydrographs are a useful tool for the preparation and examination of pollutographs, load graphs, and EMCs and for evaluation of treatment options. For example, Hydrograph Type 4 is less useful for first flush sampling and pollutant treatment evaluation.

Concentration and Mass Loading of First Flush Pollutants

The statistical summary of the pollutant concentrations in grab samples obtained from the three highway sites for the duration of the monitoring program is shown in Tables 2 and 3. Table 2 shows the pooled average of all individual grab samples from each highway site. These data should not be used for calculating mass emission rates since they are not flow-weight-averaged. Table 3 shows the averages of the EMCs calculated from the grab samples and flow rates. As expected, the variability of the results reported in Table 3 is much less than that reported in Table 2.

Reporting of both individual grab samples and EMCs is important and can play an important role in a highway runoff stormwater management program. By reporting only the EMC concentrations, the high initial concentrations are not recognized. As will be demonstrated in the following discussion, this change in concentration may be significant for BMP selection, since BMPs generally show better performance at higher influent concentrations (*28*). Using the EMC for BMP evaluation may underestimate overall BMP removal rates. Using only the EMC may underestimate environmental effects. For example, the toxicity may be more affected by high concentration than mass emission rate. Capturing or treating the first runoff with high concentrations may be important in protecting the environment from toxic materials.

The data shown in Table 3 should be used for estimating mass emission rates, BMP design, and performance evaluations. Load graphs for the previously shown pollutographs (see Figure 1) are shown in Figure 4.

TABLE 2 Summary of Pollutant Grab Sample Concentrations for Three Highway Sites During 2000–2003 Wet Seasons

Site	Constituent	Unit	Sample Size	Mean	SD	Min	Max
7-201	TSS	mg/L	236	31.8	33.1	2.5	188.8
	COD	mg/L	236	198.7	292.7	15.19	2714.3
	DOC	mg/L	236	41.9	56.04	3.39	614.5
	O&G	mg/L	235	11.4	9.70	1.28	73.0
	Cu-d	µg/L	211	50	55	5	570
	Pb-d	µg/L	211	3	2	1	15
	Zn-d	µg/L	211	265	555	6	6489
	Cu-t	µg/L	211	67	62	10	615
	Pb-t	µg/L	211	13	10	1	69
	Zn-t	µg/L	211	341	577	36	6765
7-202	TSS	mg/L	282	102.5	136.0	4.5	1534.7
	COD	mg/L	282	347.6	702.8	7.3	8470.6
	DOC	mg/L	282	80.2	169.3	2.05	1735.8
	O&G	mg/L	268	20.5	25.6	0.7	127.9
	Cu-d	µg/L	268	103	158	1	882
	Pb-d	µg/L	268	5	7	1	57
	Zn-d	µg/L	268	596	1166	3	9920
	Cu-t	µg/L	268	139	177	9	1059
	Pb-t	µg/L	268	35	36	5	271
	Zn-t	µg/L	268	714	1222	35	10830
7-203	TSS	mg/L	283	64.3	82.7	6.3	802.3
	COD	mg/L	283	280.9	526	7.59	4000
	DOC	mg/L	283	77.6	189.4	0.94	1328.1
	O&G	mg/L	280	16.4	21.6	0.57	138.3
	Cu-d	µg/L	258	63	106	2	780
	Pb-d	µg/L	258	5	7	1	53
	Zn-d	µg/L	258	311	527	26	3983
	Cu-t	µg/L	258	78	112	8	809
	Pb-t	µg/L	258	26	17	4	114
	Zn-t	µg/L	258	369	546	39	4055

NOTE: O&G = oil and gas; Cu-d = dissolved copper; Pb-d = dissolved lead; Zn-d = dissolved zinc; Cu-t = total copper; Pb-t = total lead; Zn-t = total zinc.

Treatment of First Flush

As part of this study, the MFF ratios were calculated for all storms and monitored constituents. The MFF value at 20% runoff volume is shown in Figure 5. As can be seen, some pollutants tend to have a greater tendency for first flush, whereas others have a lesser tendency. The use of the MFF ratios as opposed to an arbitrary definition of first flush allows BMPs to be evaluated for a continuum of conditions. These values can be used in evaluating BMPs, especially those that are "first flush friendly," meaning that the treatment system can capture and remove nearly all of the early runoff and associated pollutant mass.

To estimate the potential benefits of treating pollutants in the early runoff, either as the first flush of a storm event or a seasonal first flush, as compared with treating the pollutants in the later runoff, the following treatment effectiveness factor (TEF_n) as a function of MFF_n is introduced:

$$TEF_n = \frac{MFF_n}{(1 - M_n)/(1 - V_n)} \tag{4}$$

where

TEF_n = treatment effectiveness factor at fraction n of cumulative runoff volume,
MFF_n = mass first flush ratio at fraction n,
V_n = normalized cumulative runoff volume at fraction n, and
M_n = normalized cumulative mass at fraction n.

Applying Equation 4 to the previously shown load graphs (see Figure 3), the TEF computed for 10% and 30% of the normalized cumulative runoff volume would be approximately 7.4 and 4.5, respectively. A TEF_{10} of 7.4 means that treating the first 10% of the stormwater runoff volume will be 7.4 times more effective than treating an equal volume of runoff at a later time in the storm event. When there is no first flush effect, the TEF is 1.0 and the concentrations of pollutants and effectiveness factor will be constant throughout the event or wet season (i.e., no storm or seasonal first flush).

Table 4 shows the TEF at five runoff volume intervals for the selected pollutants (TSS, COD, oil and gas, and TOC) that were previously shown in Figure 4. The results in Table 4 indicate that the relative treatment effectiveness is highest in the first 10% to 20% of the runoff volume for all pollutants. For most pollutants shown, the minimum treatment effectiveness at 10% of the runoff volume was greater than 2, which means that treatment of the initial 10% of the runoff volume could remove at least 2 times as much pollutant mass as treating an equal volume later in the storm. The TEF_{10} for TSS was the great-

TABLE 3 Summary of Pollutant EMCs for Three Highway Sites During 2000–2003 Wet Seasons

Site	Constituent	Unit	Sample Size	Mean	Median	SD	Min	Max
7-201	TSS	mg/L	23	29.8	23.8	19.6	8.8	86.3
	COD	mg/L	23	159.5	108.1	181.5	31.7	819.7
	DOC	mg/L	23	36.5	28.3	28.9	7.6	125.1
	O&G	mg/L	23	9.8	8.6	7.0	1.9	33.9
	Cu-d	μg/L	21	46.3	34.1	36.4	12.6	131.5
	Pb-d	μg/L	21	2.6	2.4	2.0	0.5	6.5
	Zn-d	μg/L	21	217.3	183.7	155.5	47.7	660.6
	Cu-t	μg/L	21	64.2	53.0	42.0	19.6	173.6
	Pb-t	μg/L	21	28.8	11.8	63.5	4.6	239.1
	Zn-t	μg/L	21	285.2	243.7	177.9	83.4	727.0
7-202	TSS	mg/L	27	101.7	76.0	92.4	38.5	466.4
	COD	mg/L	27	341.5	133.7	500.7	31.3	2282.8
	DOC	mg/L	27	95.8	29.7	183.0	5.4	848.8
	O&G	mg/L	27	19.6	9.1	20.3	1.5	80.2
	Cu-d	μg/L	26	108.8	44.4	162.6	8.3	735.3
	Pb-d	μg/L	26	6.7	3.6	10.2	1.2	43.5
	Zn-d	μg/L	26	755.7	200.0	1746.9	47.6	8150.0
	Cu-t	μg/L	26	152.6	78.0	194.8	26.9	920.8
	Pb-t	μg/L	26	38.4	26.6	32.8	16.7	151.6
	Zn-t	μg/L	26	893.7	280.7	1879.8	114.3	8881.3
7-203	TSS	mg/L	23	66.3	68.7	24.9	25.2	112.8
	COD	mg/L	23	243.5	129.7	342.9	19.3	1304.8
	DOC	mg/L	23	66.1	29.2	109.4	2.9	400.0
	O&G	mg/L	23	12.2	9.4	11.4	1.5	41.8
	Cu-d	μg/L	21	42.2	28.2	47.4	5.3	193.9
	Pb-d	μg/L	21	5.1	4.3	3.4	0.5	12.6
	Zn-d	μg/L	21	259.7	139.2	359.2	42.4	1689.2
	Cu-t	μg/L	21	61.5	50.9	49.8	16.2	211.5
	Pb-t	μg/L	21	31.2	27.4	9.8	21.1	51.4
	Zn-t	μg/L	21	326.0	227.9	361.0	87.4	1747.9

NOTE: For abbreviations, see Table 2.

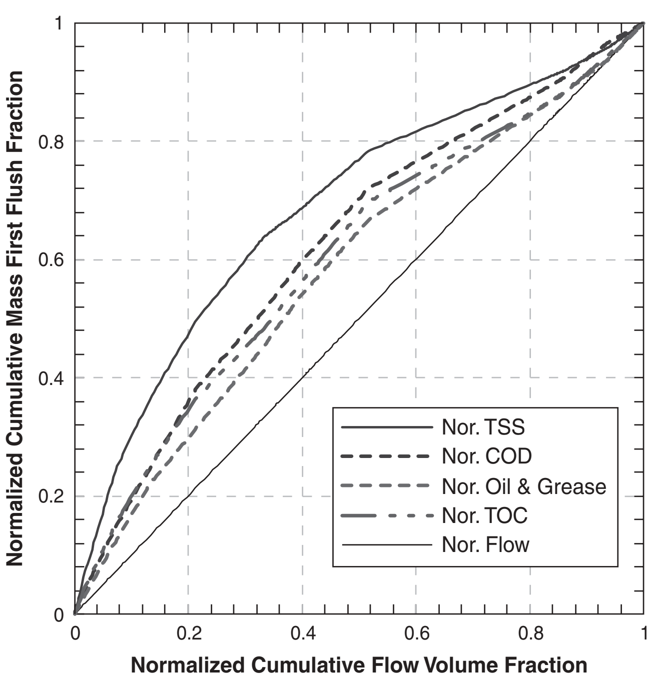


FIGURE 4 Load graphs for pollutants and storm event shown in Figure 1.

est among the four pollutants, which suggests that treatment will be nearly 4 times more effective in removing suspended particles within the first 10% of normalized cumulative runoff volume. The value of removing a large portion of the TSS from the early runoff is the removal of the pollutants bound to the TSS, such as metals and oil and grease. An additional benefit of using BMPs to treat the early runoff is the impact of pollutant concentration on BMP removal efficiency. Since BMPs are generally more efficient at higher pollutant concentrations, applying them to the early runoff will maximize pollutant removal.

BMP Simulations of First Flush

To demonstrate the advantages of using BMPs for treating early runoff with a first flush, two sets of simulations were performed. The first related to a first flush and the second related to a seasonal first flush. A general model for an event first flush pollutant treatment is shown in Figure 6. The first flush is treated by the BMP, and the later flow is bypassed.

To demonstrate the application of the event first flush treatment model, a hypothetical infiltration basin was used. The infiltration basin fills with the initial runoff and either can function as a continuous treatment system or can store the initial runoff and bypass later runoff. Figure 7 shows both scenarios; it is assumed that the infiltration basin is not large enough to capture and treat the entire runoff

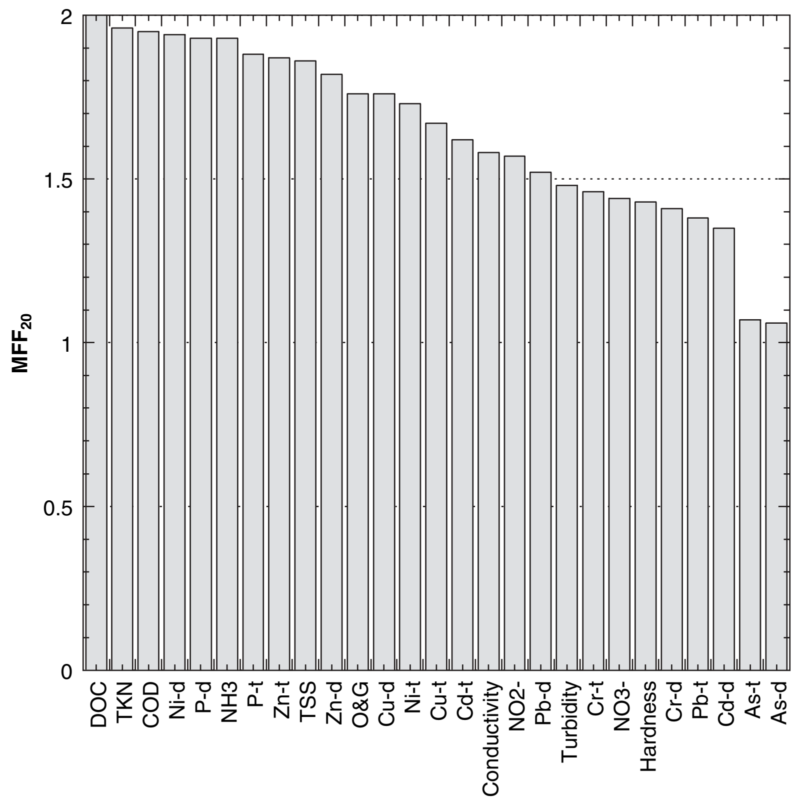


FIGURE 5 MFF ratios for selected pollutants for combined sites and monitoring seasons at 20% normalized cumulative runoff volume.

volume. In Scenario 1, the entire storm event flow enters the BMP. When filled, the extra runoff volume will discharge continuously from outflow until the end of the event. In Scenario 2, the early portion of the storm event flow enters the BMP. When filled, the inflow valve will close and the later event flow will bypass until the end of the event.

Figure 8 shows the results of both scenarios. Figure 8*a* is the pollutograph, and Figure 8*b* and 8*c* show the effluent concentrations for two basin volumes. In Figure 8*b,* the basin fills after approximately 200 min, which is equal to 20% of the total runoff volume. Scenario 1 allows the runoff to continue through the basin, which washes out the pollutants removed in the early runoff, and the combined concentration is equal to 160 mg/L. Scenario 2 bypasses later runoff and the effluent concentration is equal to the runoff concentration at 200 min, which is after the first flush. The difference between the two curves represents the improved removal of Scenario 2. Figure 8*c* shows the same results except that the basin volume is increased to 40% of the runoff volume. At the end of the storm, the infiltration basins are filled, but in Scenario 2 the concentrations in the basins are higher.

In the case of a seasonal first flush, a similar benefit occurs when BMPs are used to treat a large fraction of the early storms. Again, two alternative BMP strategies were simulated. In both cases an infiltration and detention basin capable of storing approximately 20% of the seasonal runoff volume is considered. The total seasonal runoff volume can be determined by historic rainfall data. The first strategy uses one-eighth of the volume to capture the initial portion of each of the eight storms. The second strategy captures the entire volume of the early storms until the basin is full. It is assumed that infiltration occurs slowly and the basin does not empty until after the end of the rainy seasons.

Figure 9 shows the strategies for the 2001–2002 wet seasons. For Strategy 2 the basin fills midway through the third storm. If the storm first flush is ignored, it is straightforward to calculate the removal rates. Strategy 1 removes 20% of the metal masses, since 20% of the total seasonal runoff is infiltrated. Strategy 2 removes more, since the EMCs of the early storms are greater because of the seasonal first flush. The seasonal first flush is discussed in greater detail elsewhere (*12*).

The results of this simulation analysis for dissolved and total copper and zinc for two monitoring seasons are summarized in Tables 5 and 6. Two simulations were performed, for infiltration basins able to capture 20% and 40% of the seasonal runoff volume. For nearly

TABLE 4 TEF at Five Runoff Flow Volume Intervals for TSS, COD, O&G, and TOC Constituents Shown in Figure 5

Constituent	TEF_{10}	TEF_{20}	TEF_{30}	TEF_{40}	TEF_{50}
TSS	3.9	3.7	3.5	3.2	3.0
COD	2.3	2.1	2.2	2.3	2.3
O&G	2.3	2.1	1.9	1.9	1.9
TOC	2.0	1.7	1.5	1.6	1.5

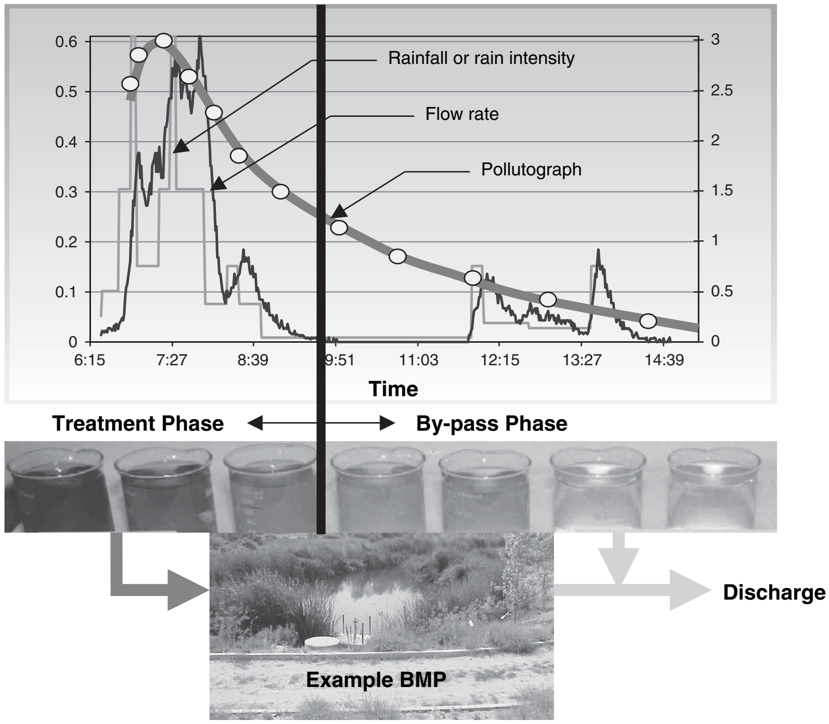


FIGURE 6 Concept for first flush pollutant treatment.

all cases, Strategy 2 removes a greater fraction of pollutants, and the magnitude largely depends on the magnitude of the seasonal first flush. In general, Strategy 2 treats about 25% to 84% of the pollutant mass depending on the year and parameter. Strategy 2 also removes 25% to 200% more pollutant mass compared with Strategy 1. It is important to note that the relative benefit of pollutant removal under Strategy 2 decreases as the volume of treated stormwater increases. For instance, the benefit of Strategy 2 was found to be marginal compared with Strategy 1 at 60% of total volume.

The two preceding examples for storm and seasonal first flush treatment strategies show that there are large potential advantages for treating the first flush of each storm or, in the case of the seasonal first flush, the first storms of the wet season. Pollutant removal rates

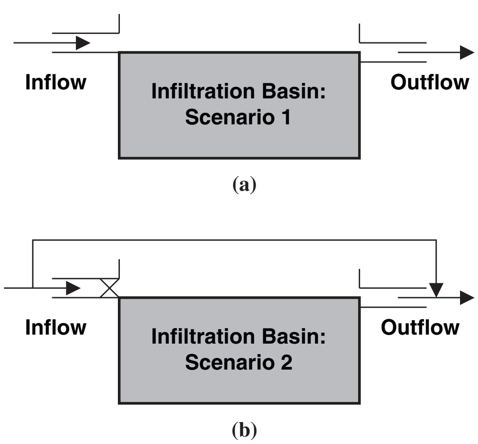


FIGURE 7 Two scenarios of infiltration basin treatment comparing treatment of first flush pollutants with conventional method.

can be twice as great when the same volume is used. The two simulations represent the authors' first attempts to demonstrate the value of treating the first flush. Additional work is under way and will be presented later.

CONCLUSIONS

Major conclusions drawn from this study are as follows:

- Collecting a number of grab samples throughout the storm event will provide a better evaluation of temporal variability of pollutant concentrations. The temporal variability of pollutants can be shown by pollutographs. It is also possible to calculate an EMC from a series of grab samples.
- The mass first flush phenomenon can be numerically defined and evaluated through a load graph and the computation of the mass first flush ratio (MFF_n).
- Using the event EMC for BMP performance evaluation may correctly indicate the actual BMP removal rate, since BMPs generally show better performance at higher influent concentrations. Using only the EMC may also underestimate environmental effects. Pollutographs can be very useful and practical since they show peak concentrations.
- By using a TEF, it was shown that for most pollutants, treating the early portion of an event can be 2 to 5 times more effective than treating the same runoff volume at a later stage in the event.
- Two first flush BMP simulations performed for both event and seasonal first flushes demonstrated that there are benefits with BMP strategies that treat the early portion of storm events and bypass the remaining runoff.

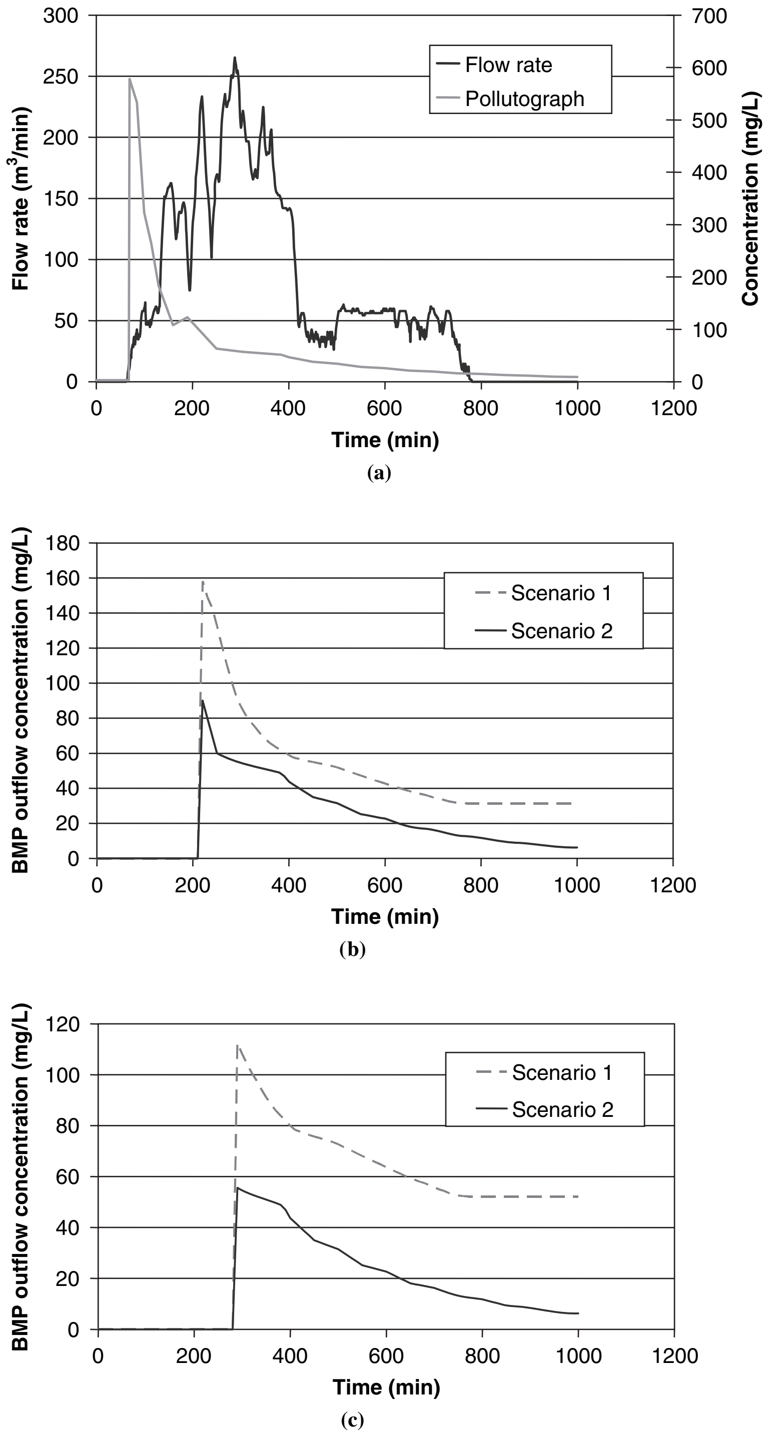
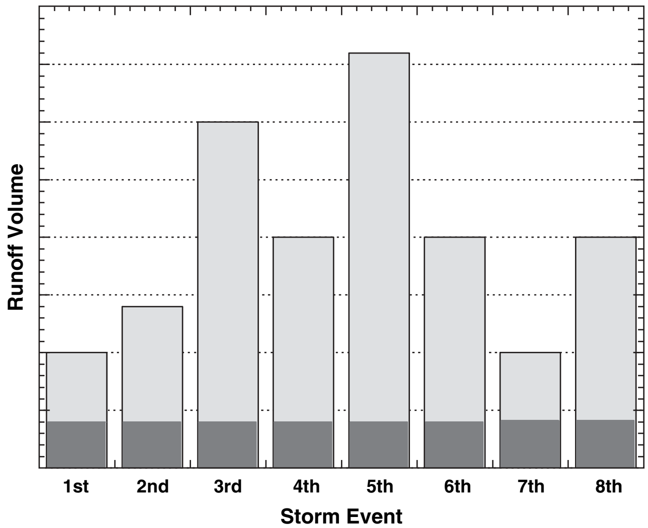
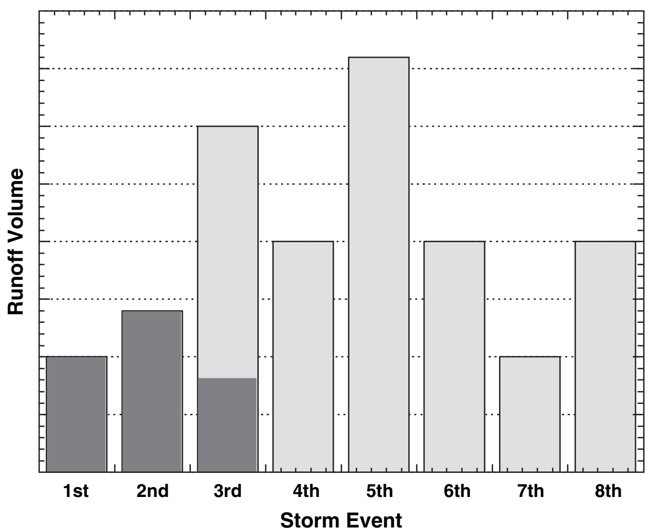


FIGURE 8 Simulation of generalized pollutant removal in infiltration basin with two scenarios presented in Figure 7: (*a*) pollutograph, (*b*) 20% total runoff volume, and (*c*) 40% total runoff volume.



(a)



(b)

FIGURE 9 Runoff volume captured for two BMP strategies with emphasis on seasonal first flush pollutant removal (dark-shaded part of bar represents runoff volume used for treatment; light-shaded part represents portion of runoff volume not treated): (*a*) Strategy 1, treatment of equal runoff volume for each storm event, and (*b*) Strategy 2, treatment of first several runoff volume equivalents to total runoff volume in Strategy 1.

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TABLE 5 Mass of Pollutants Removed on Basis of 20% of Total Runoff Volume

		Strategy 1		Strategy 2	
Year	Constituent	(g)	(%)	(g)	(%)
2000–2001	Cu-d	9.1	20	17.0	37.4
	Cu-t	22.6	20	34.0	30.1
	Zn-d	37.9	20	46.8	24.7
	Zn-t	82.3	20	117.7	28.6
2001–2002	Cu-d	19.7	20	43.1	43.8
	Cu-t	31.2	20	59.8	38.4
	Zn-d	139.9	20	426.4	61.0
	Zn-t	175.4	20	487.2	55.6

TABLE 6 Mass of Pollutants Removed on Basis of 40% of Total Runoff Volume

		Strategy 1		Strategy 2	
Year	Constituent	(g)	(%)	(g)	(%)
2000–2001	Cu-d	18.2	40	21.7	47.7
	Cu-t	45.2	40	49.2	43.6
	Zn-d	75.8	40	73.6	38.8
	Zn-t	164.5	40	182.0	44.3
2001–2002	Cu-d	39.4	40	49.5	50.3
	Cu-t	62.4	40	74.9	48.0
	Zn-d	279.7	40	458.6	65.6
	Zn-t	350.7	40	546.3	62.3

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