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First Flush Phenomenon and Its Application for Stormwater Runoff Management

M. Kayhanian[1], M. K. Stenstrom[2]

1. Prof. Emeritus, Dept. of Civil and Environmental Engineering, University of California, Davis, CA 95616
(Corresponding Author) mdkayhanian@ucdavis.edu
2. Prof., Dept. of Civil and Environmental Engineering, University of California, Los Angeles, CA 90095-1593

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Abstract

This paper summarizes the results of the comprehensive first flush characterization study performed on three highly urbanized highway sites in Los Angeles, California. The study was performed from 2000 through 2005 and a total of 97 storm events were monitored ranging from 0.5 to 137 mm with an average rainfall of about 25.5 mm. First flush characterization was performed based on contaminant concentration and mass loading. To determine the first flush effect, multiple grab samples were obtained throughout the storm event with an emphasis on collecting additional grab samples during the first hour of storm event. Topics presented and discussed in this paper include: (1) meaningful definition of first flush characterization, (2) strategic method of collecting first flush sampling, (3) uniform method and interpreting first flush results, and (4) the implication of first flush results for urban stormwater runoff management.

Keywords: Flush Phenomenon, Stormwater, Runoff Management.

1. Introduction

1.1. Background

First flush characterization of pollutants from urban roads and highway runoff is not new and has been investigated by several investigators (Bertrand-Krajewski et al., 1998, Charbeneau and Barrett, 1998, Deletic, 1998, Geiger, 1987, Gupta and Saul, 1996, Larsen et al., 1998, Legret and Pagotto, 1999, Saget et al., 1995, Sansalone and Buchberger, 1997, Thornton and Saul, 1987). However, in most cases, monitoring was performed for one season or based on limited water quality parameters or chemical constituents.

The review of first flush monitoring among these investigators revealed that there is no standard protocol to collect samples, present the results and interpret them, and utilize the results for potential optimum best management practice[1] treatment application. To date, the most comprehensive first flush runoff characterization study was commissioned by the California Department of Transportation, Division of Environmental Analysis[2] that was jointly performed through a collaborative effort between the Departments of Civil and Environmental Engineering at the University of California, Davis (UCD) and the University of California, Los Angeles (UCLA). This joint first flush monitoring study was performed at three highly urbanized highway sites in Los Angeles, California over five years (2000-2005) and the result of this study was presented in a final report. The interested reader can find additional detail information on this study from (Stenstrom and Kayhanian, 2005).

1.2. Focus of the paper

This paper is prepared with the following objectives: (1) to present a meaningful definition of first flush characterization, (2) to establish a strategic method of collecting first flush sampling, (3) to present a uniform method and interpreting first flush (concentration- or mass-based) results, and (4) to discuss practical implication of first flush results for urban stormwater runoff management.

2. Methods

2.1. First flush monitoring sites

First flush characterization study was performed from 2000 through 2005. The first three years of the study were focused on first flush characterization of water quality parameters and chemical constituents; followed by two additional years focusing on particle size distribution and toxicity evaluation. For this study, three highly urbanized highway sites were selected in West Los Angeles, California. Selective physical characteristics of these three highway sites are summarized in Table 1.

Monitoring site 7-201 was located near the intersection of the US 101 and IS 405 highways on the south side of US 101. This site had several 50.8 cm diameter corrugated drainage pipes and they all had lengthy straight sections to facilitate flow measurement. No other drainage entered the site and there was a free waterfall as the stormwater exits the pipe to facilitate sampling. At this site 30 storm events were monitored ranging from 1.3 to 127 mm with an average rainfall of about 25 mm.

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Monitoring Site 7-202 was located near the IS 405 highway and the Getty Center exit, on the east side of the highway. Drainage was through a 60.96 cm diameter corrugated drainage pipe. The site has a single stormwater inlet with several grates along the east shoulder. Generally, during the normal and average storm events, no runoff from the hill reached the drainage inlet. Analysis of runoff rates suggests that this rarely happened. Sampling at this site was also possible at a free waterfall. At this site 32 storm events were monitored ranging from 1.8 to 156 mm with an average rainfall of about 26.4 mm.

Monitoring Site 7-203 was located on the east side of the IS 405 highway just south of the point where it passes over Santa Monica Boulevard. This site had a 60.96 cm diameter plastic corrugated pipe (smooth on the inside, corrugated on the outside) which collects runoff from the northbound, east side of the northbound highway. The curb was opened to collect runoff from the shoulder, and no runoff can enter the site in any other way, including the highway and shoulder south of the site. As the runoff exits the pipe, there was a gap of 20 cm, which creates a free waterfall for sampling. At this site 35 storm events were monitored ranging from 0.5 to 128.5 mm with an average rainfall of about 25.1 mm.

2.2. First flush sampling method

Grab samples collection during the initial stage of storm events are crucial for first flush characterization study. Strategies to collect samples for first flush stormwater runoff characterization are extremely important. First, the sampling teams must be at the sites before runoff begins; weather forecasting is important to avoid time consuming and frustrating mobilizations for storms that do not occur, as well as making sure that the monitoring

[1] Best Management Practice (BMP)

[2] Division of Environmental Analysis (DEA)

Table 1. Summary descriptions of monitoring sites

Site identification	Highway	Monitoring location/ post mile (PM)	Drainage area (m^2)	Highway grading type	Annual average daily traffic
7-201	US 101	Eastbound US 101/PM 17	12,802	Grade	328,000
7-202	IS 405	IS 405 near Getty Center exit/PM 34.8	16,918	Fill	260,000
7-203	IS 405	Santa Monica Blvd. north bound exit on IS 405/PM 30.8	3,917	Cut	322,000

Note: All three highway sites were virtually impervious, and the runoff coefficient was in the range of 0.9 to 0.95.

teams are prepared for the real events. Highway sites and other sites that are highly impervious are "flashy" and runoff occurs within minutes of the onset of rainfall. Generally, when forecasts suggest that a storm probability is greater than 50%, the sampling teams are mobilized to sampling site in advance of storm event. Secondly, in order to properly detect and quantify the first flush, discrete samples must not only be collected in the early part of the storm but also at the end of the storm. This requirement means that sampling to characterize the first flush will be more resource intensive than ordinary stormwater sampling. Grab samples can be collected manually or with automated samplers having multiple bottles. For our first flush characterization study manual grab sampling was chosen for several reasons including: (1) collecting representative sample from water column outfall, (2) allowing larger sample volumes collection, and (3) providing greater flexibility for collecting special samples using different bottles or preservation techniques.

In general, we followed the grab sampling collection method depicted in Fig. 1. As can be noted, five grab samples are collected in the first hour with the first grab sample being collected as soon as adequate runoff volume reaches the sampling point. The additional four samples were collected during 15-min intervals. After the first hour, one grab sample is collected per hour for the next 7 hours, providing a total of 12 grab samples. For storms lasting less than 8 hours, fewer grab samples will be collected. For storms lasting longer than 8 hours, an additional one or two grab samples were collected in the period from 8 hours to the end of the storm. The runoff volume was continuously monitored and recorded during the entire storm. This sampling strategy was successful in our five-year study to characterize the initial runoff as well as the later runoff, and especially for long storms with lengthy periods of light rainfall.

Runoff samples were collected by a polypropylene scoop, and then transferred to 4-L amber glass bottles. When collecting samples from free waterfall, the entire water column from waterfall should be represented, especially when the particle size distribution and particle-bound pollutant characterization are desired. The sample volume depended on the types of analysis being

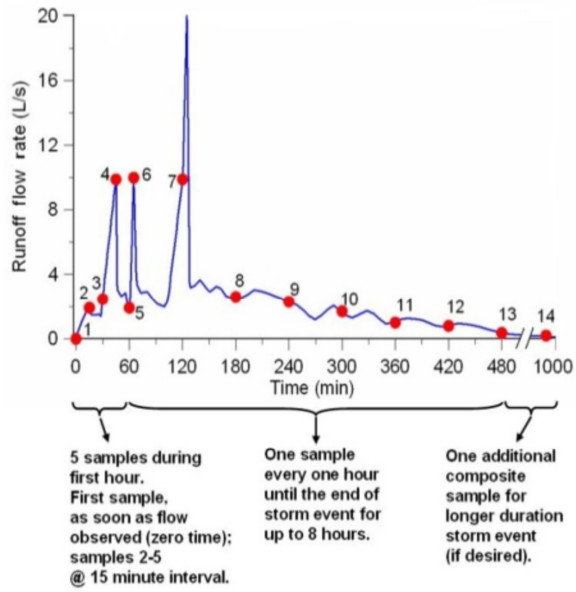

Fig. 1. Sampling strategy to evaluate first flush characterization

performed. To avoid problems with holding time, the collected samples were delivered to lab and appropriate preservation and filtration were implemented to meet the necessary analytical test requirements. This aspect of sampling method became particularly important when we initiated the first flush investigation of particle size distribution[1]. For example, the changes in PSD were observed after 10 to 12 hours of storage. Therefore, a holding time of 6 hours was established for particle size distribution analysis (Li et al., 2005).

Each site was equipped with an American Sigma rain gage and flow meter. The flow rate and the amount of rainfall were recorded automatically at one-minute intervals. In addition, Autosamplers (Sigma 900MAX, American Sigma) were installed at each site to collect flow-weighted composite samples. Data from each site were downloaded into a Windows-based laptop computer after the end of each storm.

These data were used to prepare hydrographs, pollutographs and any other related stormwater runoff

[1] Particle Size Distribution (PSD)

Table 2. Summary of constituents monitored and the related analytical methods

Water quality parameters	Units	Reporting limits	Analytical method	Holding time and preservation
Conventional				
Total suspended solids	mg/L	2	EPA[1] 160.2	7 days; refrigerated at 4°C
Turbidity	NTU	1	EPA 150.1	48 hours; refrigerated at 4°C
Conductivity	µmho/cm	1	EPA 180.1	28 days; refrigerated at 4°C
pH	-	0.01	EPA 120.1	Analyze immediately
Hardness	mg/L as $CaCO_3$	2	EPA 130.2	6 months; acidify with HNO_3 to pH < 2
Chemical oxygen demand	mg/L	2	EPA 410.0	Analyze as soon as possible
Dissolved organic carbon	mg/L	1	EPA 415.1	7 days; acidify to pH <2 with H_3PO_4
Nutrients				
Ammonia	mg/L	0.01	EPA 350.3	Analyze as soon as possible
Nitrite[2]	mg/L	0.01	EPA 354.1	48 hours; refrigerated at 4°C
Nitrate[2]	mg/L	0.1	EPA 300.0	48 hours; refrigerated at 4°C
Total Kjeldahl Nitrogen[2]	mg/L	0.1	EPA 351.4	7 days; refrigerated at 4°C, acidify to pH <2 with H_2SO_4
Orthophosphate	mg/L	0.1	EPA 300.0	48 hours; refrigerated at 4°C
Phosphorus (dissolved and total)	mg/L	0.03	EPA 200.7	48 hours; refrigerated at 4°C
Organics				
Particulate PAHs	µg/L	$1–5 \times 10^{-3}$	EPA 3535	7 days; refrigerated at 4°C
Dissolved PAHs	µg/L	$1–5 \times 10^{-3}$	EPA 3546	7 days; refrigerated at 4°C
Oil and grease	mg/L	1	C18 SPE[2]	28 days; acidify to pH < 2 with HCl
Metals (total and dissolved)			EPA 200.7	Filter immediately, acidity to pH < 2 with HNO_3
Cadmium, chromium, nickel, zinc	µg/L	1		
Copper	µg/L	3		
Lead	µg/L	5		
Microbiological				
Total coliform	MPN/100 ml	2	SM[3] B9221	24 hours
Fecal coliform	MPN/100 ml	2	SM C9221	24 hours

[1] EPA methods are based on the USEPA (1999) Methods and Guidance for Analysis of Water
[2] Lau and Stenstrom (1997)
[3] SM = Standard Methods

first flush characterization and data analysis. Individual grab and flow-weighted composite samples were analyzed for the suite of water quality parameters and chemical contaminants.

2.3. Sampling analysis and analytical methods

Table 2 shows the selected water quality parameters and their corresponding analytical methods used for the first flush characterization study. To the extent possible, most analyses were performed as soon as the samples were delivered to the lab, and within the recommended holding time. For those samples that could not be analyzed on time, the samples were preserved and refrigerated for later analysis. As can be noted in Table 2, polynuclear aromatic hydrocarbons[1] were also monitored, but not as routinely as the other constituents and hence the results of PAHs are reported elsewhere (Lau et al., 2009). In addition, during year 4 and 5 the

[1] Polynuclear Aromatic Hydrocarbons (PAHs)

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first flush effect of particle size distribution (PSD) and runoff toxicity were evaluated. The results of these studies are beyond the scope of this paper but are reported by (Li et al. 2005, Kayhanian et al. 2008), respectively.

2.4. Meaningful definition of first flush based on the concentration and mass of water quality contaminants

The "first flush" phenomenon is generally assumed for single rainfall events and can be described as a concentration first flush or a mass first flush. A concentration first flush occurs when the first portion of runoff has a higher concentration relative to the later portion of the runoff in the storm event. A mass first (concentration times flow rate) is flow dependent and it occurs when both concentration and the initial runoff is high relative to mass emission rate in the later runoff. Concentration first flushes have been frequently reported, but mass first flushes have rarely been quantified.

For example, most of the water quality parameters monitored for all the events in our first flush characterization study had higher concentrations at the beginning of the runoff than later in the runoff. Mass first flushes were usually observed but with lower magnitudes. This is due to the nature of the runoff, which generally has lower flow rate at the beginning of the storm than in the middle of the storm. Therefore, the mass emission rate in the middle of the storm event may be greater than at the beginning of the storm event, in spite of lower concentrations in the middle of the storm. The concept can be applied to any particular constituent or water quality parameter, particle size distribution, and toxicity. A definition sketch of concentration first flush is shown in Fig. 2. As shown, the concentration of chemical constituent in early runoff can be 10 times higher than the concentration of runoff at the end of storm event.

The concept of first flush can also be applied to a rainfall season. In many regions of the world, rainfall occurs over distinct periods. For example, the bulk of the rainfall in California occurs from approximately November to April, with the months of January and February usually having the greatest rainfall. The long dry period from May to October allows contaminants to build up on roads and building roof surfaces. The first large rainfall of the season, occurring any time from late October to January, generally mobilizes the built-up contaminants, creating a larger discharge of pollutants to the receiving waters. Therefore, the term seasonal first flush only applies to discharge of a higher mass or concentration of contaminants associated with the first storm or the first few storms of a rainy season (Lee et al. 2004).

Various ways have previously been proposed to quantify mass first flush by different investigators and they all in some way suggest a higher early pollutant mass emission rate (up to 80%) associated with 20 to 50% of the initial runoff volume (Thornton and Saul, 1987, Geiger, 1987, Vorreiter and Hickey, 1994, Saget et al., 1995, Gupta and Saul, 1996, Sansalone and Buchberger, 1997, Bertrand-Krajewski et al., 1998, Larsen et al., 1998, Sansalone et al., 1998, Deletic, 1998). Instead of choosing an arbitrary mass and volume fraction, it might be better to develop a universal method which quantitatively describes the mass first flush and is sufficiently broad to apply to any initial portion of the storm and leave the selection of mass and volume fraction to the stormwater management authorities and BMP designer. To facilitate this universal method, under our study we have proposed a mass first flush[1] ratio. A definition sketch of mass first flush ratio is shown in Fig. 3. Based on this definition, sketch users can determine the mass first flush for any chemical constituent based on a selected normalized cumulative mass and runoff volume.

It is possible to have a concentration seasonal first

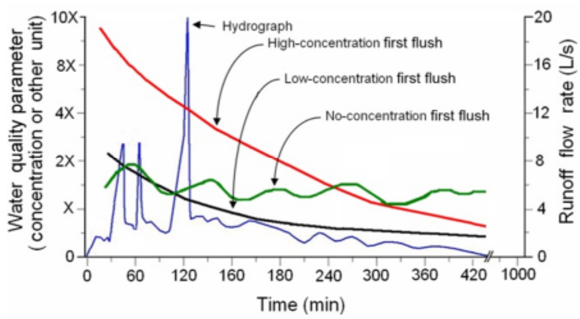

Fig. 2. A definition sketch of concentration first flush

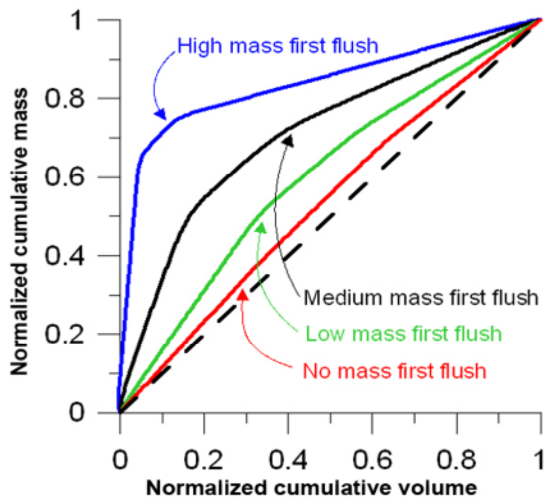

Fig. 3. A definition sketch of mass first flush

[1] Mass First Flush (MFF)

flush as well as a mass seasonal first flush. The techniques used to describe a mass first flush can also be used to describe a mass seasonal first flush. Occasionally, when investigators are describing both the first flush of a single storm and an entire season, they may use the term "storm first flush" to emphasize that the first flush is for a single storm event. To be consistent and to remove confusion, we recommend just use the term first flush for a single storm event and when it is intended to describe the first flush effect of the first storm event of the season use the term "seasonal first flush".

It is important to note that both concentration and mass first flush may occur more frequently within smaller, more impervious watersheds or drainage areas. Hence, first flush phenomenon may be less frequently observed within a larger watershed or drainage areas. The lack of mass or first flush occurrences in a large watershed means that stormwater must be transported a great distance to a single discharge point, or mouth of the watershed. Therefore, the time of travel of the runoff from various places in the watershed to the monitoring point is different (time of travel is the elapsed time for a quantity of stormwater to flow from the point of generation to the monitoring point). In this case, the first flush from each small area in the watershed arrives at the mouth of the watershed at different times, which mixes the smaller first flushes of each area into a broad discharge pattern. Therefore, the first flush from one area is mixed with runoff from other areas that occurred much later in the storm. The definition of large watershed for this context is a function of the time of travel. The first flush of pollutants observed in our study was generally within the first few minutes to the first hour after observable runoff. More important, most BMPs are designed to collect and treat smaller drainage areas rather than big watershed.

2.5. Computation of partial event mean concentration from grab samples

Mathematically, EMC[1] can be defined as total pollutant mass (M) discharged during an event divided by total volume (V) discharge of the storm event

$$\mathrm{EMC}=\frac{M}{V}=\frac{\int C(t)Q(t)dt}{\int Q(t)dt} \qquad (1)$$

Where

C(t) is a smooth real-valued function of time that represents the pollutant concentration curve, and Q(t) is also a smooth real-valued function of time that represents the stormwater flow rate curve. However, in practice, the integrals are not continuous functions of Q(t) and C(t) but approximations created by discrete measurements of Q(t) and C(t). If we assume the concentration and the flow rate measurement based on equal time-interval in a storm event, the EMC can be estimated as

$$\mathrm{EMC}=\frac{\sum_i c_i q_i}{\sum_i q_i} \qquad (2)$$

where

q_i and c_i are the measurements for the discharge rate and pollutant concentration in the ith interval. From the point of view of approximating the continuous functions in Eq. (2), the more measurements we take, the more accurate approximation we can obtain by Eq. 2. When we view the measurements of the flow rate as the weights, Eq. (2) becomes the discharge-weighted average throughout the storm event, as follows

$$\mathrm{EMC}=\sum_i w_i c_i \qquad (3)$$

$$w_i=\frac{q_i}{\sum_i q_i} \qquad (4)$$

Where

w_i is the flow weight, and $\sum_{i=1}^{n} w_i = 1$. In practice, one common situation is the number of concentration measurements does not match the number of flow measurements. Generally, there are fewer concentration measurements, because concentration measurements are much more expensive and time consuming; flow measurements can be easily and automatically obtained by most auto samplers with velocity probes. For most situations the weights must be adjusted for each concentration measurement in Eq. (3). One of the reasonable ways to adjust the weights is to use the discharge volume. One approach (Charbeneau and Barrett, 1998) splits the discharge volume from the mid-point between two consecutive concentration measurements. Fig. 4 shows this approach, and the adjusted weight can be written as

$$w_i=\frac{V_i}{\sum_i V_i} \qquad (5)$$

Where

V_i is the corresponding discharge volume for the ith concentration measurement. This mid-discharge splitting method can also be applied for measurements at unequal time-interval bases. Alternatively, if the concentration measurements are based on constant discharge volume, the weighted average of $w_i c_i$ form is reduced to the arithmetic average. Ideally, automated

[1] Event Mean Concentration (EMC)

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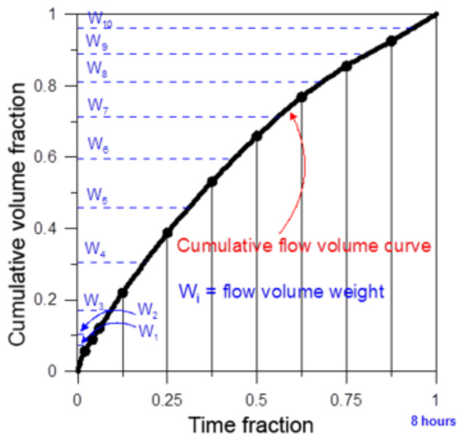

Fig. 4. Definition sketch of EMC calculation from series of grab samples

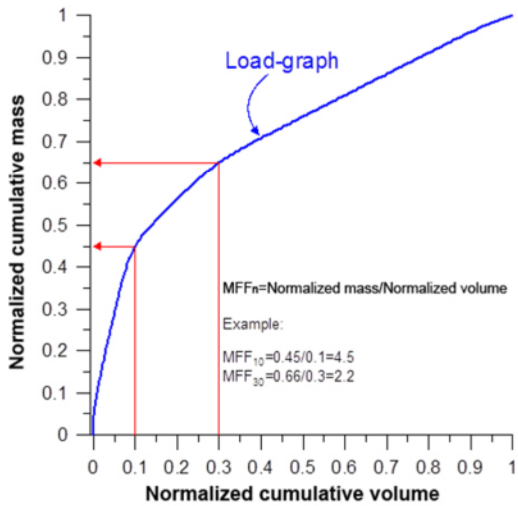

Fig. 5. Definition sketch of computing mass first flush ratio

samplers collect samples in proportion to discharge volume. Thus, a partial and complete EMC can be calculated using a series of flow-weighted grab samples. When the concentration of grab samples and the related flow rate measurement throughout the entire storm event is available, we can determine the partial EMC (i.e., EMC that is related to the early portion of the storm event) as well as the overall EMC (i.e., EMC that is related to the entire storm event). The calculation of partial EMC relative to the overall EMC will allow us to determine concentration first flush effect of a specific contaminant.

2.6. Computation of mass first flush ratio

The mass first flush can be quantified as the normalized mass of emitted pollutants (ranging from 0 to 1) as a function of the storm progress, as indicated by the normalized runoff volume (e.g., 0 to 1 and it can be defined as follows

$$MFF_n = \frac{\dfrac{\int_0^{t_1} C(t)Q(t)dt}{M}}{\dfrac{\int_0^{t_1} Q(t)dt}{V}} \quad (6)$$

where

MFF = mass first flush ratio, dimensionless

n = index or point in the storm, corresponds to the percentage of the runoff (0 to 100%)

M = total mass of emitted pollutant

V = total runoff volume,

C(t) = pollutant concentration as functions of time

Q(t) = runoff volume as functions of time

To compute mass first flush ratio, plot cumulative normalized mass (y-axis) vs. normalized cumulative volume (x-axis) similar to that shown in Fig. 5. This plot is known as load-graph. The mass first flush ratio for n fraction runoff volume (MFF_n) can easily be produced from load-graph. For example, the mass first flush ratio for 10% of runoff volume (MFF_{10}), determines the normalized mass from the plot and then the normalized mass is divided by normalized volume. The example calculation for MFF_{10} and MFF_{30} is shown on this plot. The higher MFF ratio represents a larger mass first flush effect.

The MFF ratio can also be related to partial EMC (PEMC[1]). The PEMC is a flow weighted composite sample, collected from the storm beginning to a point in the storm, as described in the above. Therefore, the MFF ratio can be defined as Eq. (7), which is numerically the same as calculated from Eq. (6)

$$MFF_n = PEMC_n/EMC \quad (7)$$

3. Results and Discussion

The first flush effect of water quality parameters and chemical constituents can be evaluated both qualitatively and quantitatively. The qualitative first flush evaluation of certain water quality parameters and contaminants such as turbidity, litter, and oil and grease may be evaluated through visual observation. As an example, Fig. 6 shows the color and turbidity of water samples obtained as storm event progresses. As shown, clearly the first few samples are more turbid, and the color is darker. However, the darker color and higher turbidity by itself is not indicative of higher organic and inorganic pollutant concentration. Therefore, the quantitative assessment of first flush is needed. Quantitative first flush effect of pollutants can be presented based on concentration and mass loading as presented below.

[1] Partial Event Mean Concentration (PEMC)

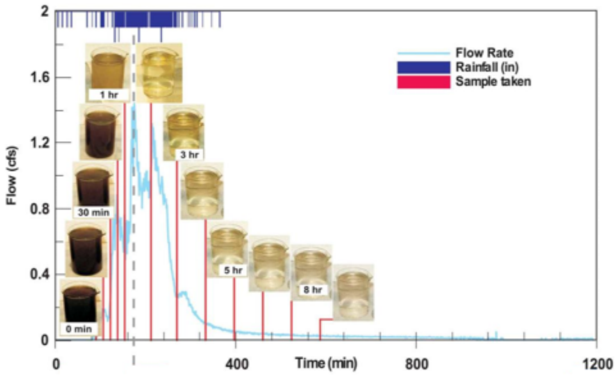

Fig. 6. Visual observation of first flush effect

3.1. Concentration-based first flush results

One method to show the concentration first flush effect of pollutants is through pollutographs. Pollutographs are representations of the variability of water quality parameter concentrations throughout storm events. A practical pollutograph is a plot showing both the plot of water quality parameter concentration and hydrograph on the same plot. A higher concentration in early storm event compared with the later period is an indication of concentration first flush. Presenting all pollutographs in this paper is not practical.

However, an example pollutograph for COD, TOC, and Oil & Grease is shown in Fig. 7. As shown, from these plots it can be noted that the concentrations of COD, TOC, and Oil & Grease are generally 3 times higher during the first 100 minutes compared to the concentration of the same contaminants toward the end of storm event. The higher concentration of these contaminants at the early stage of storm event is an indication of concentration first flush effect. In addition, it can be noted that a pollutograph is not bonded to a single contaminant. A pollutograph can show multiple number of water quality parameters for a single storm event in a single plot, which can also be helpful in visualizing relationships among parameters.

In addition, it is important to note that pollutographs can be produced for all water quality parameters including those with units other than volumetric concentrations (e.g., turbidity, conductivity). For these pollutographs, a correlation relationship with other water quality parameters having volumetric concentration will be used.

Concentration first flush can also be reported based on the ratio of the PEMC to the overall EMC. As noted before, PEMC is calculated in the same fashion as EMC, except that the runoff volume is applied to only the first part of the storm. PEMC can be calculated for the first 60, 90, or 120 minutes of rainfall and hence will be reported as $PEMC_{60}$, $PEMC_{90}$, or $PEMC_{120}$. Table 1 presents the $PEMC_{60}$/EMC for wide ranges of water quality parameters. Evidence of concentration first flush is present as long as the PEMC/EMC is larger than 1.

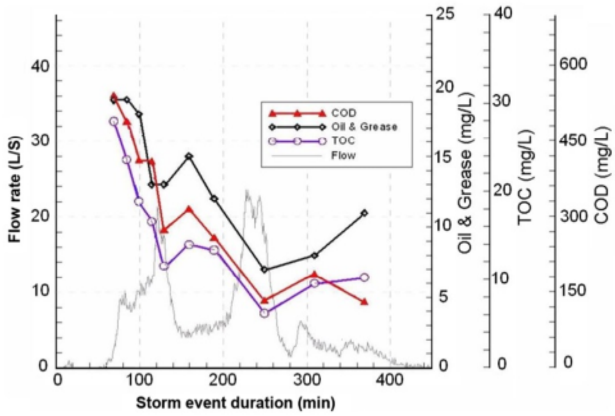

Fig. 7. Multiple pollutographs showing the concentration first flush effect for COD, Oil&Grease, and TOC

The higher the ratio, the larger the concentration first flush. Hence, the values of PEMC/EMC ratio can be used in ranking the water quality parameter based on their concentration first flush. Based on the results presented in Table 3, DOC, ortho P, COD, and TKN contribute the highest concentration first flush effect.

3.2. Mass-based first flush results

The mass first flush effect of pollutants can be reported based on the mass first flush ratio proportion to a specific runoff volume. The results of mass first flush ratio of selective water quality parameters based on the first twenty percent of runoff volume (MFF20) for three highway sites is summarized in Table 4. Similar mass first flush ratio results can be prepared for other runoff volume proportions (i.e., 10, 30, 40, 50, etc..). As shown, the summary results are presented based on their descending magnitude order and generally, the chemical oxygen demand (COD) or organics indicating pollutants (DOC, O&G, TKN) have the highest MFF ratios. The higher mass first flush ratios among these organic indicating pollutants are expected, since a strong correlation exists between them (Khan et al., 2006). The higher mass first flush rations among these contaminants suggests that they are washed or scoured from the highway surfaces early in the storm.

The range or statistical variability of the MFF ratios is also important. As shown, in Table 4 only the median values are reported. Additional statistical information can be presented in summary table or alternatively the results can be presented as a notched box plot that usually provides the range of values, mean, median, and standard deviation. As an example, the MFF_{10} to MFF_{50} ratios for combined sites for COD, TSS and the four metals (Ni, Pb, Cu and Zn) are presented in Fig. 8. The bar plots show the 25% and 75% percentiles (edges of the bar), the median (notch of the bar), confidence intervals (5%, upper and lower knees), fences and outliers. Differentsoftware produces slightly different notch bar plots. Systat 10.2 (Richmond, CA) software

Table 3. Mean $PEMC_{60}/EMC$ ratios for selective water quality parameters

Water quality parameter	Symbol	Mean $PEMC_{60}/EMC$ ratio	First flush ranking
Dissolved organic carbon	DOC	5.43	1
Ortho phosphate	PO_4^{3-}	4.58	
Chemical oxygen demand	COD	4.49	
Total Kjeldahl nitrogen	TKN	4.34	
Dissolved phosphorus	D-P	3.49	2
Oil and grease	O&G	3.46	
Total phosphorus	T-P	3.07	
Dissolved lead	D-Pb	2.74	3
Hardness	Hard.	2.74	
Dissolved cooper	D-Cu	2.59	
Dissolved zinc	D-Zn	2.59	
Nitrate nitrogen	NO_3-N	2.35	
Total suspended solids	TSS	1.99	4
Particulate phosphorus	P-P	1.88	
Particulate zinc	P-Zn	1.69	
Particulate cooper	P-Cu	1.49	
Particulate lead	P-Pb	1.36	

T = total, D = dissolved, P = particulate

Table 4. Median mass first flush ratios of selective water quality parameters relative to twenty percent of runoff volume (MFF_{20}) on descending ranking order

Median mass first flush (MFF_{20}) ratios						Combined sites	
Site 7-201		Site 7-202		Site 7-203			
Parameters	Median	Parameters	Median	Parameters	Median	Parameters	Median
COD	1.74	Dissolved Ni	2.09	DOC	2.51	Dissolved Ni	1.94
Total P	1.71	DOC	2.01	Dissolved Ni	2.40	DOC	1.94
Dissolved P	1.69	NH_3-N	2.00	COD	2.33	TKN	1.89
TKN	1.59	Total Zn	2.00	TKN	2.18	COD	1.88
Dissolved Ni	1.58	Dissolved Cu	1.98	Dissolved Cu	2.12	NH_3-N	1.88
Oil & Grease	1.57	COD	1.95	NH_3-N	2.01	Dissolved P	1.75
TSS	1.56	TKN	1.94	TSS	1.98	TSS	1.72
NH_3-N	1.56	Dissolved Zn	1.93	Total Ni	1.86	Total P	1.72
DOC	1.52	Dissolved P	1.87	Total Cu	1.79	Oil & Grease	1.70
Total Ni	1.49	Total Ni	1.85	Oil & Grease	1.79	Dissolved Cu	1.68
Total Zn	1.48	Total Cu	1.71	Dissolved P	1.75	Total Ni	1.68
Dissolved Zn	1.43	Oil & Grease	1.71	Total P	1.75	Total Zn	1.67
Conductivity	1.42	Total P	1.70	Conductivity	1.74	Dissolved Zn	1.66
Dissolved Cu	1.40	NO_3-N	1.49	Dissolved Zn	1.66	Total Cu	1.64
Total Cu	1.40	Total Cd	1.46	Total Zn	1.65	Conductivity	1.54
NO_2-N	1.39	Turbidity	1.43	Hardness	1.61	Hardness	1.48
Total Cr	1.36	TSS	1.42	NO_3-N	1.57	NO_2-N	1.37
Turbidity	1.30	Dissolved Pb	1.38	NO_2-N	1.37	NO_3-N	1.35
Total Pb	1.23	PO_4-P	1.37	Dissolved Pb	1.34	Turbidity	1.29
Hardness	1.20	Dissolved Cr	1.35	Total Cd	1.27	Total Cd	1.26
Dissolved Cr	1.15	Total Pb	1.32	Total Cr	1.22	Total Pb	1.23
Total Cd	1.07	Dissolved Cd	1.31	Total Pb	1.13	Total Cr	1.22
Dissolved Cd	1.00	NO_2-N	1.25	Turbidity	1.09	Dissolved Pb	1.21
Dissolved Pb	1.00	Hardness	1.23	Dissolved Cd	1.09	Dissolved Cr	1.17
PO_4-P	1.00	Conductivity	1.21	Dissolved Cr	1.04	Dissolved Cd	1.09
NO_3-N	0.98	Total Cr	1.20	PO_4-P	1.00	PO_4-P	1.00

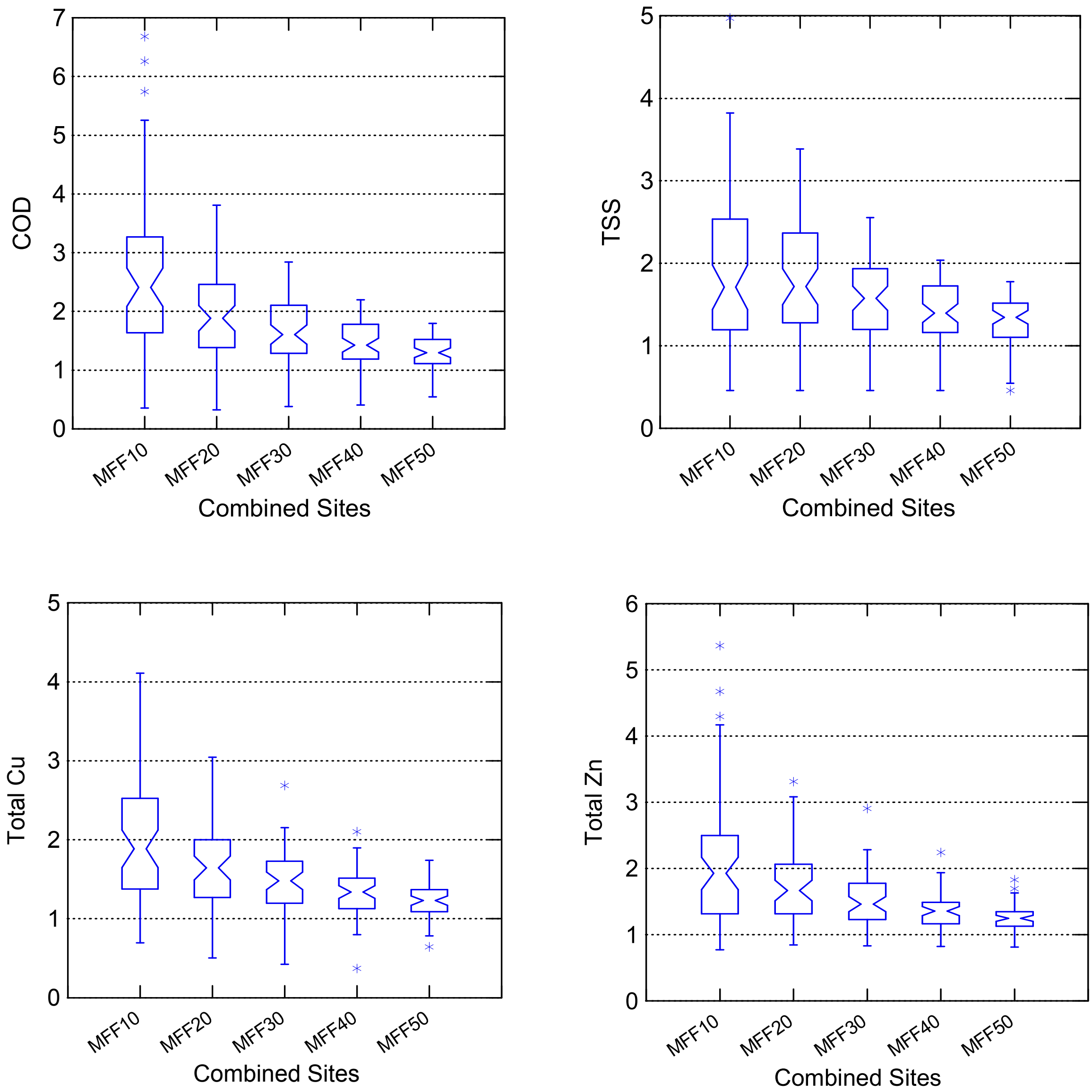

Fig. 8. Notched bar graphs for MFF ratios (10 to 50%) for COD, TSS, Total Cu and Total Zn for the combined sites (The number of storm events data used for this analysis include 58 for COD and TSS, and 62 for metals) [note: The bar plots show the 25% and 75% percentiles (edges of the bar), the median (notch of the bar), confidence intervals (5%, upper and lower knees), fences and outliers]

was used to produce all the notched bar plots in this report. The advantage of notched bar plots over standard bar plots is the ability to observe statistical differences in categories. If the knees of the notches do not overlap, there is a significant difference in the categories.

3.3. Discussion and practical implication of the first flush results

Results obtained from first flush characterization study can be used for multiple practical stormwater runoff management issues. The management issues addressed include, but are not limited to: (1) special monitoring assessment, (2) sampling issues, and (3) BMP design and treatment optimization.

3.3.1. Special monitoring assessment

The pollutograph results and stormwater rainfall and flow data obtained from first flush characterization study can be used to estimate certain pollutant concentration when only grab sampling is required. One common pollutant that is required to collect grab sampling for analytical analysis is oil and grease (O&G). Sampling of O&G using automated samplers is not recommended due to interactions with tubing and pumps or holding time, which often biases the measured concentration (Stenstrom et al., 1984, Stenstrom et al., 1986, Fam et al., 1987). Therefore, to measure the event mean concentration (EMC) of O&G without autosampler interferences, a series of grab samples must be collected. Each individual sample most be chemically analyzed and be averaged to produce the EMC. To avoid the cost of collecting many grab samples, a single grab sample is often substituted for most monitoring studies, which may not be representative.

The data collected from our first flush characterization study examined over 20 O&G pollutographs and showed a large variability in O&G concentration throughout the storm event. Samples collected early in the storm event, under one hour after the beginning of runoff, overestimated the EMC by as much as 20 mg/L.

Samples collected at the end of the storm had similar error, but were usually biased low compared to the EMC. In general, samples collected mid-way through the storm event better represent the EMC. Therefore, if a single grab sample is taken for O&G analytical analysis, we recommend tracking the storm duration in advance and taking single sample during the midway of storm event.

The first flush characterization data also revealed that the O&G EMC can be estimated by other practical methods. For sample, it was determined that there is a strong correlation (R_2=0.90) between O&G, chemical oxygen demand (COD) and dissolved organic carbon (DOC) (Khan et al., 2008). When the EMC of these two constituents are known, the following mathematical relationship can be used to estimate the O&G EMC without any sampling or analytical analysis

$$O\&G_{EMC} = 3.70 + 0.037\ COD_{EMC} \qquad R^2 = 0.90 \qquad (7)$$

$$O\&G_{EMC} = 0.15 + 0.28\ DOC_{EMC} \qquad R^2 = 0.90 \qquad (8)$$

In addition, further multiple regression analyses showed that $O\&G_{EMC}$ could be estimated directly from event or site characteristics. Best results were obtained with only ADD and T_RAIN as shown with the following mathematical relationship

$$Log_{10}\,(O\&G_{EMC}) = 0.37 + 0.64\ Log_{10}\,(ADD) - 0.17\ Log_{10}\,(T\_RAIN) \quad R^2 = 0.86 \qquad (9)$$

Where,
ADD = antecedent dry days indicating number of dry days between storm events, days
T-RAIN = total rainfall, mm

The above estimation strategy is completely predictive and does not even require any sample taking and analytical analysis.

3.3.2. Sampling issues

Stormwater runoff monitoring can be expensive and depending on the site characteristics it can also be challenging. In general, nowadays, majority of the stormwater runoff monitoring from urban areas is conducted through flow-weighted automatic samplers. However, due to the extreme cost, some municipalities may choose to take only one or a few samples to evaluate the pollutants characteristics and to use it as a basis for determining the related discharge pollutant load. It is generally known that flow weighted composite samples provide more accurate and precise information than a grab sample or multiple grab samples. Since our monitoring sampling program includes both auto samplers and grab sampling, questions were raised about the accuracy of flow-weighted automated composite samplers, and whether they provide better information than a series of composite samples that are flow-weight averaged to produce a calculated composite sample.

To answer the above question, a series of simulations were performed to “mimic” the runoff flow rate and concentrations observed in the first two years of our study (Ma et al., 2009). Random noise was added to simulate the stochastic nature of stormwater. The degree of noise was selected to match the variability in the actual observations. Next an automated sampler and flow weighted grab samples were simulated. The automated sampler was simulated by rapidly sampling the runoff at short intervals, simulating the “squirts” that the automated composite samplers collect in proportion to flow rate. Grab samples were simulated in a similar fashion, but at randomly timed intervals.

More than 1000 simulations were performed, and the result showed that EMC estimated by averaging 10 grab samples will have a mean error of 42 % difference as compared to a flow weighed composite sample, collecting small sample volumes every minute. The error decreases with the number of samples and approaches 12% for 100 grab samples. In general, however, it is shown that a large number of grab samples is needed to approximate the flow weighted composite sample (Ma et al., 2009). Thirty grab samples per storm event provided a good estimate of a composite sample. To detect a first flush, it is necessary to take even more samples or to weight the samples towards the beginning of the storm. The superiority of the automatic sampling equipment is demonstrated, and the results show that investigators using only a few grab samples to characterize an event would not be able to observe a first flush.

3.3.3. BMP design and treatment optimization

As previously shown, a strong to low first flush effect based on the concentration and mass has been observed for most water quality parameters investigated on three smaller highway drainage (e.g., paved) watersheds. The existence of a first flush may present opportunities for managers and regulators to affect better stormwater management and pollutant reduction programs. Treating early runoff that has higher contaminant concentrations or mass may be a better policy than treating a similar fraction of the entire runoff volume (Kayhanian and Stenstrom, 2005; Li et al., 2008; Abrishamchi et al., 2010). This is true for two reasons: (1) the cost of treatment is generally more dependent on the volume of water to be treated than the contaminant concentration, (2) the way the stormwater BMPs function; removal efficiency is greater at higher concentrations. Treatment efficiency at low concentrations can be nearly zero, but significant removal can be obtained at higher concentrations as this effect has been demonstrated with ASCE database on BMP trials (Strecker et al., 2001).

The MFF ratios presented earlier can be very useful in estimating potential removals of pollutants mass from BMPs. For example, most water quality regulations in the United States require that all constructed BMPs must capture or treat 80% of a stormwater runoff. Based on the rainfall probability data shown in Fig. 9 for our three first flush sites, the above requirement means that storms as large as 35 mm (≈1.4 inch) rainfall must be treated.

For storms larger than 35 mm (80% probability), some portion of the flow must be bypassed. For very large storms, only a portion of the flow can be treated. One possible way to take advantage of first flush optimization treatment strategies is to divide the existing or future BMP such as detention basin or sedimentation basin into two compartments. An example flow diagram

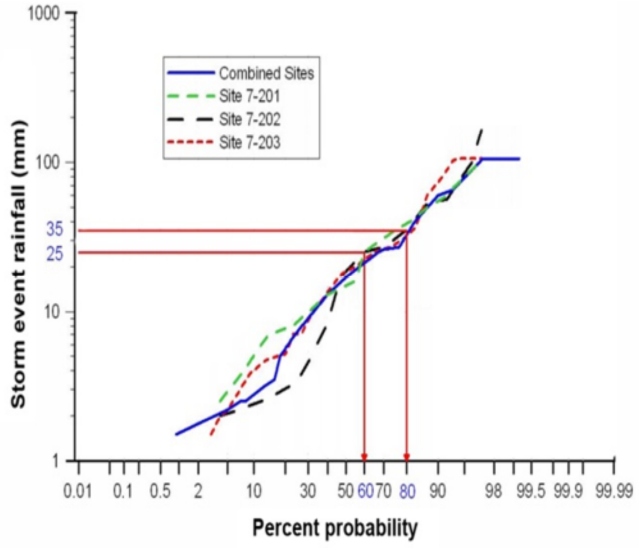

Fig. 9. Rainfall probability plots for three highway sites

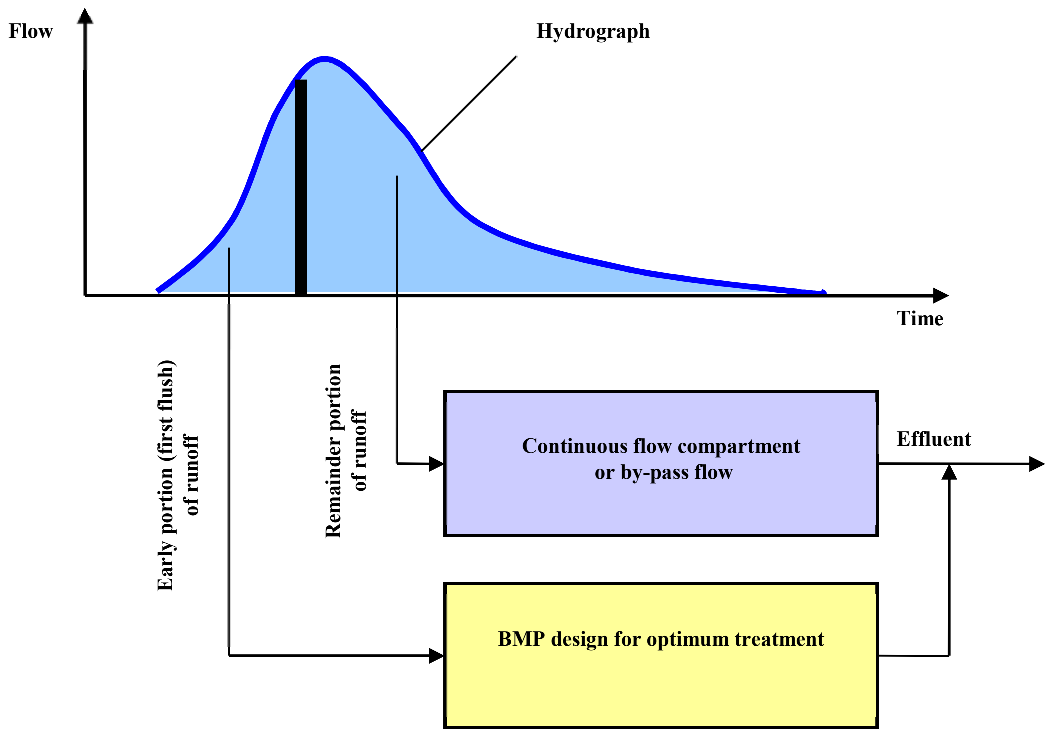

Fig. 10. Two-compartment sedimentation or detention basin design

for two-compartment design concept is shown in Fig. 10. As shown, the first compartment captures the initial runoff and then after, filling bypasses to a second compartment, which functions as a continuous flow clarifier. The runoff cut-off can be determined based on the first flush effect of a specific contaminant. The two-compartment design takes advantage of the first flush as well as other factors such as higher initial concentrations. This design is especially beneficial for removing particles and the associated particle-bound pollutants (Li et al., 2008).

Under the first flush treatment optimization, the treatment BMP can be designed to capture and treat 50% of the flow and bypass the rest of the runoff. With this treatment concept, the BMP has an opportunity to remove not just 50% of the mass of pollutants, but 50% times the MFF_{50} ratio of the pollutants. For example, based on our study the MFF_{50} for total Zn from the combined three highway sites was found to be about 1.67 (see Table 4). Therefore, a BMP that treats 50% of the flow would in fact treat 83.5% of the total Zn mass. In fact, based on the data presented in Table 4, a BMP that treats only 50% of total runoff will meet the 80% capture and treatment requirement for nearly 60 percent of the pollutants.

The two-compartment design presented above can also be applied to a detention basin. Under the first flush treatment concept, the first compartment of the detention basin will have lower overflow rate (i.e., longer detention) to remove smaller particle size and the associated contaminants. Under larger storm events, much cleaner water will be discharged from the second compartment. The treated water from both compartments can be discharged from the surface which is usually much less contaminated. The combined treated and by-pass stormwater can be used for various potable and non-potable water reuse programs (see for example, Kayhanian and Tchobanoglous, 2018 parts I, II, III).

4. Conclusions

From the results presented in this paper it can be concluded that: (1) first flush effect can be functionally defined based on specific contaminant concentration and load, (2) concentration first flush effect can be presented through pollutograph plots, which shows the change of concentration during storm duration while presenting the hydrograph on the same plot, (3) higher concentration during the early stage of the storm event is indicative of concentration first flush, (4) mass first flush effect can be presented though load-graph to compute mass first flush ratio, (5) mass first flush ratio higher than 1 is an indication of mass first flush; the higher the mass first ratio, the higher the mass flush effect, (6) both concentration and mass first flush effect were observed for nearly all water quality parameters, (7) the highest concentration and mass first flush effect were observed for organic indicator contaminants such as TKN, COD, DOC, and TKN, (8) the first flush characterization data was used to address the following stormwater management issues: (a) it was determined that a single grab sample and analysis is not a good representative measurement of oil and grease concentration in highway runoff and it is best to be estimated through the EMS of DOC or COD. Alternatively, it was determined the oil and grease EMC could be estimated from antecedent dray days and total cumulative rainfall; both of which do not require any sampling and analytical analysis, (b) treating early runoff that has higher contaminant concentrations may be a better policy than treating a similar fraction of the entire runoff volume for two reasons: (i) the first reason is the cost of treatment is generally more dependent on the volume of water to be treated than the contaminant concentration, (b) the superiority of the automatic sampling equipment was demonstrated, and the results show that monitoring program using only a few grab samples to characterize a storm event would generate huge error. Our analysis showed that to reduce the error below 10 percent, it is required to collect 100 grab samples that is impractical, and (c) the second reason relates to the way that stormwater BMPs function; removal efficiency is greater at higher concentrations.

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