A Stochastic Stormwater Quality Volume-Sizing Method with First Flush Emphasis

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ABSTRACT: A Monte Carlo simulation technique was applied to assess the effect of stormwater quality volume captured by best management practices (BMPs) on the frequency of discharging concentrations of constituents above certain designated threshold limits. The method used an assumption of a power law relationship between the cumulative load and flow to incorporate the first flush effect. The exponent of this relationship was considered a random variable and its frequency distribution was obtained from 78 measured pollutographs from three urban highway sites in West Los Angeles, California. Although the effect of rain depth captured by BMPs is site-specific, the method offered here provides a systematic approach to evaluate the effect of selecting various regulatory guidelines for controlling urban stormwater pollution on the overall discharge of pollutants into waterways. This allows selecting the requirements for capturing runoff volume by BMPs based on the tradeoff between the probability of concentration criteria violation and economic factors. *Water Environ. Res.,* **83,** 2025 (2011).

KEYWORDS: best management practices, water quality volume, stormwater, total maximum daily load, first flush.

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Introduction

Nonpoint sources of pollution generated from urban stormwater runoff are now deemed to be significant contributors of pollutants in waterbodies (Barrett et al., 1998; Horan, 1990; Larsen et al., 1998). This has led to the development of regulatory guidelines (e.g., RIDEM and CRMC, 2010; MPCA, 2008; NHDES, 2008; U.S. EPA, 2004) aimed at controlling or reducing the effect of non-point-source pollutants to receiving waters. These regulations mainly rely on development of best management practices (BMPs) to treat nonpoint sources or to reduce the direct discharge of polluted water into receiving waters. These BMPs can primarily be categorized into two groups: (1) methods that reduce the discharge of water into surface waterbodies by promoting infiltration into the ground or store the water so that it is never released in the form of surface runoff, such as through the use of infiltration ponds (Jefferies et al., 1999), rain gardens (Davis, 2008), rain barrels (MPCA, 2008), and permeable pavements (Balades et al., 1995); and (2) methods that remove particulate matter and the contaminants bound to them and, sometimes, nutrients through burial or denitrification. These include methods such as retention, detention (England, 2001), bioretention basins (Hsieh and Davis, 2005), sand filters (MassDEP, 1997), and constructed wetlands (Ahlfeld and Minihane, 2004; MassDEP, 1997; U.S. EPA, 2004). The effectiveness of most of these BMPs depends on the volume of storm runoff that can be captured and treated by them, which is directly related to the size of BMPs. The efficiency of BMPs also depends on whether they are able to entrap the most polluted portion of the storm runoff by taking advantage of the concept of first flush (Kayhanian and Stenstorm, 2005).

The term, *first flush,* was first introduced in the 1970s (Sartor and Boyd, 1972). The intuitive and general concept of first flush refers to the release of the greater fraction of constituent mass or concentration of pollutants at the early part of a storm event (Barco et al., 2008; Kim et al., 2005). This phenomenon was thought to be caused by the quick wash-off of pollutants accumulated during dry weather periods on the pavement surface. In general, significant factors affecting the occurrence and severity of first flush in an event include storm characteristics, size and drainage characteristics of the drainage area, the mobility and properties of pollutants, and the length of the antecedent dry period (Bertrand-Krajewski et al., 1998; Deletic, 1998; Deng et al., 2005; Kang et al., 2008). Several attempts have been made to develop empirical (e.g., Deletic and Maksimovic 1998; Gupta and Saul 1996) or physically based models (e.g., Kang et al. 2006; Massoudieh et al. 2008) to predict the first flush behavior in highway environments. Despite differences regarding the quantitative definition of *first flush* (Deng et al., 2005) and the universality and transferability of the proposed predictive models (Flint and Davis, 2007; Kang et al., 2006), the expectation of a higher pollutant concentration at the beginning of the storm has been the basis of the most practiced criteria for the design of stormwater treatment BMPs.

Various regulatory criteria have been suggested for the treatment of captured water volume by BMPs, referred to as *water quality volume* (WQV). The most widely presented and adopted rule is based on the first flush concept and requires a fixed depth of runoff to be captured (also referred to as *water quality depth* [WQD]) (e.g., MassDEP, 1997; MPCA, 2008). For example, many states throughout the United States adopt the half-inch rule, which requires the first one-half inch of runoff be treated by BMPs. However, because of regional variations of precipitation, a single WQD might not be adequate over an entire state (Chang et al., 1990). The alternative approach requires capturing and treating a certain fraction of the rain volume from each event. For example, the 90% rainfall event criterion, adopted by many states including Minnesota (MPCA, 2008) and New Hampshire (NHDES, 2008), defines *WQV* as

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being equal to the storage required to capture and treat 90% of the entire rainfall volume for 24-hour design storms on an annual basis. The third approach requires a removal rate for pollutants often surrogated by the fraction of total suspended solids (TSS) removed from the runoff (U.S. EPA, 2004). The most frequently used pollutant removal criterion requires an 80% removal of TSS on an individual storm event basis (U.S. EPA, 2004; MPCA, 2008).

Despite their limitations (Chang et al., 1990), first flush-based sizing criteria are still widely used and valued for their relative simplicity. For example, Sartor and Boyd (1972) assumed that reductions in pollutants follow an exponential decay curve and proposed a sizing equation relating the magnitude of first flush to rainfall intensity and the particle size of the constituent. Furthermore, measuring the effects of roofing material on the turbidity of first harvested rainwater and the amount of first flush and following a mass balance approach, Martinson and Thomas (2005) proposed a simple rule-of-thumb for first flush behavior that states that ‘‘for each [millimeter] of first flush, the contaminate load will halve’’. Based on this rule, a rational method was suggested for sizing some BMP devices based on first flush and the desired material intended to be removed. Attempts have also been made to define the flowrate that corresponds to the first flush runoff depth to optimize flow-through BMPs (Ahlfeld and Minihan, 2004; Froehlich, 2009). However, based on the authors' knowledge, no quantitative systematic approach for determining a WQD criterion has been offered that considers uncertainties in event characteristics and the first flush behavior of pollutants during events. Research presented in this article extends previous work by proposing a probabilistic method for assessment of the effect of sizing criteria on effluent water quality, which takes into account both the uncertainties in first flush behavior during the events and the precipitation pattern. A model based on traditional first flush formulations was developed and a Monte Carlo simulation was performed to estimate the number of times various water quality constituents in the effluent exceeded a predefined set of water quality standards as a result of capturing various depths of precipitation. Although the proposed method is developed and tested on roadway stormwater data collected from three sites in the state of California, the modeling framework is transferable to other site types and regions.

Methods

First Flush Analysis. In the traditional approach for quantifying first flush, two dimensionless quantities are used including the dimensionless cumulative flow, *V(t),* and the dimensionless cumulative constituent mass, *M(t),* as follows (Cristina and Sansalone, 2003; Lee et al., 2004):

$$V(t) = \frac{\int_0^t Q(t)dt}{\int_0^T Q(t)dt} \tag{1}$$

$$M(t) = \frac{\int_0^t Q(t)C(t)dt}{\int_0^T Q(t)C(t)dt} \tag{2}$$

Where

t = time referenced to the initiation of runoff,
T = duration of the entire storm event,
Q(t) = flowrate at time *t,* and
C(t) = constituent concentration at time *t.*

The simplest criterion for the presence of the first flush is

$$M(t) > V(t) \tag{3}$$

A graphical representation of this criterion can be obtained by plotting *M(t)* on the dependent axis against *V(t)* on the independent axis. This is also known as the *mass load graph* (Kim et al., 2005). A *first flush* exists if this curve exceeds the 45-deg line from the origin (Geiger, 1987). Bertrand-Krajewski et al. (1998) defined *first flush* as the state at which at least 80% of the pollutant mass is transported in the first 30% of the runoff volume. Based on the same concept, other similar first flush identification criterions have been reported by Stahre and Urbonas (1990) and Wanielista et al. (1977), for example.

Characteristics of the *M(V)* curves have been extensively analyzed in previous studies. A generally accepted observation is that the set of all *M(V)* curves for a constituent in one site presents a wide scatter (Bertrand-Krajewski et al. 1998; Ellis, 1986; Geiger, 1987; Saget et al., 1996; Sansalone and Buchberger, 1997). Furthermore, the set of *M(V)* curves are found to be different for different sites (Bertrand-Krajewski et al., 1998), while the mean *M(V)* curves for some constituents are found to be similar at one site (Geiger, 1987). It has been demonstrated that, in most instances, the *M(V)* curve can be fitted by a power function relatively well, as follows (Bertrand-Krajewski et al., 1998; Sansalone and Cristina, 2004):

$$M(t) = [V(t)]^b \tag{4}$$

where b is the first flush exponent that directly describes the shape of the *M(V)* curve. Based on this representation, a first flush occurs when $b < 1$ and the strength of the first flush can be determined by the magnitude of b (Bertrand-Krajewski et al., 1998; Saget et al., 1996). The variation of this parameter has also been investigated. All studies unanimously conclude that no set of parameters can sufficiently explain the variations of the constituents recorded for all catchments and events (e.g., Bertrand-Krajewski et al. [1998]). In this research, the authors used the power relationship in eq 4 to quantify the intensity of first flush.

Pollutograph Simulation. The method proposed here assumes a generic BMP capable of capturing and treating a defined depth of precipitation and bypassing the remainder without any treatment. To incorporate the effect of first flush on the performance of BMPs, the authors adopted the power law equation (see eq 4). Substituting eqs 1 and 2 into eq 4 yields

$$\frac{\int_0^t Q(t)C(t)dt}{\int_0^T Q(t)C(t)dt} = \left(\frac{\int_0^t Q(t)dt}{\int_0^T Q(t)dt}\right)^b \tag{5}$$

Considering the definition of the event mean concentration (EMC) (Bertrand-Krajewski, 1998; Charbeneau and Barrett, 1998; Huber, 1993) as follows:

$$EMC = \frac{\int_0^T Q(t)C(t)dt}{\int_0^T Q(t)dt} \tag{6}$$

and substituting the result in eq 5 gives

$$\int_0^t Q(t)C(t)dt = EMC\cdot \frac{\left(\int_0^t Q(t)dt\right)^b}{\left(\int_0^T Q(t)dt\right)^{b-1}} \tag{7}$$

Differentiating both sides with respect to time, t, and simplifying the equation provides

$$C(t) = EMC\cdot b\cdot \left(\frac{\int_0^t Q(t)dt}{\int_0^T Q(t)dt}\right)^{b-1} \tag{8}$$

Now, assuming the flow is proportional to rain intensity and the time of concentration is small compared to the rain intensity variation time scale, $Q(t)$ can be expressed as

$$Q(t) = ci(t)A \tag{9}$$

Where

A = drainage area,
c = runoff coefficient, and
$i(t)$ = rainfall intensity.

It should be noted that eq 9 is usable only for instances where the size of the basin is small enough so that its time of concentration is small relative to the time scale of rain intensity fluctuation. Also, for large watersheds, the value of c can depend on rain intensity and the area of the watershed. This dependence is neglected in this research assuming that the size of the watershed is small enough.

Incorporating eq 9 to eq 8 yields

$$C(t) = EMC\cdot b\cdot \left(\frac{\int_0^t i(t)dt}{\int_0^T i(t)dt}\right)^{b-1} = EMC\cdot b\cdot \left(\frac{I(t)}{I_{\max}}\right)^{b-1} \tag{10}$$

Where

$I_{\max}$ = the event total rainfall depth (mm) and
$I(t)$ = cumulative rain depth (mm) up to time t.

$I(t)$ can also be defined as

$$I(t) = \frac{WQD}{c} \tag{11}$$

Equation 10 implies that if the $I(t)$ depth (mm) of rainfall or WQD/c of runoff volume is captured and treated, then, depending on different possible situations, the maximum pollutant concentration ($C_{\max}$) in the released stormwater will be equal to

$$C_{\max} = \begin{cases} EMC\cdot b\cdot \left(\frac{WQD/c}{I_{\max}}\right)^{b-1} & for\ \ I_{\max} > WQD/c\ and\ b < 1 \\ EMC\cdot b & for\ \ I_{\max} > WQD/c\ and\ b > 1 \\ 0 & for\ \ I_{\max} < WQD/c \end{cases} \tag{12}$$

Equation 12 indicates that when the event total rainfall depth ($I_{\max}$) is larger than the captured cumulative rain depth, $I(t)$ or WQD/c, and when first flush occurs ($b < 1$), then eq 10 gives the maximum pollutant concentration. Conversely, when first flush does not occur ($b > 1$), the pollutant concentration will be increasing during the storm and, therefore, the maximum concentration takes place at the end of the event and thus will be equal to $EMC\cdot b$. Finally, when the event total rainfall depth is less than the captured cumulative rain depth, then all the rainfall is captured by the BMP and, consequently, there will be no released stormwater and $C_{\max}$ will be equal to 0.

In addition, the mean concentration (C_{avg}) of the discharged stormwater can be obtained from

$$C_{\text{avg}} = \begin{cases} \frac{EMC}{I_{\max}{}^{(b-1)}}\cdot \frac{I_{\max}{}^{b} - (WQD/c)^b}{I_{\max} - (WQD/c)} & for\ I_{\max} > WQD/c \\ 0 & for\ I_{\max} < \text{WQD/c} \end{cases} \tag{13}$$

Furthermore, in an instance where a total daily maximum load (TMDL) criterion should be met, the total load released to the receiving water can be obtained from

$$L = C_{avg}\cdot \int_t^T i(t)dt\cdot c\cdot A = \frac{EMC}{I_{\max}{}^{(b-1)}}\cdot \left[I_{\max}{}^{b} - (WQD/c)^b\right]\cdot c\cdot A \tag{14}$$

Depending on the type of water quality criteria used to limit the pollutant discharge, eqs 12 through 14 can be used to evaluate the frequency of exceedance of the pollutant concentration and mass loading based on specified WQD capture and treatment.

In this work, the authors demonstrate the application of the maximum and average concentration criteria (eqs 12 and 13) in evaluating the effect of WQD criteria on the exceedance frequency of a range of water quality constituents. The three parameters controlling the maximum and mean discharge concentrations, including the rain event depth ($I_{\max}$), EMC, and b, are considered random variables with frequency distribution and cross-correlations obtained from 78 measured event-wise pollutographs from three highway sites in the state of California.

Hydrologic and Pollutant Wash-Off Data. Hydrologic data and pollutant characteristics were obtained from a first flush highway runoff characterization study of three highly urbanized highway sites in west Los Angeles, California, over five wet monitoring seasons (1999 to 2004) (Stenstrom and Kayhanian, 2005). A total of 78 storm events were monitored for the three combined sites. Table 1 summarizes the basic statistics of all monitored storm events. Water quality constituents including metals, organics, nutrients, flowrate, and rain intensity were monitored over the entire hydrograph of each storm. For detailed information on the sites, storm events, and sample chemical analyses, the reader is referred to the first flush phenomenon report (Stenstrom and Kayhanian, 2005) and elsewhere (e.g., Han et al. 2006; Kim et al. 2005).

The concentration of pollutants throughout the pollutograph and the EMC for each event were obtained for numerous water quality parameters and organic and inorganic chemical constituents. For the purpose of this article, only toxic metal constituents (cadmium, chromium, copper, nickel, lead, and zinc) were considered. The first flush exponent, b, for each event was obtained using the least square method through numerical minimization of the difference between the measured and modeled cumulative normalized mass vs cumulative normalized flow curves.

Monte Carlo Simulation. A statistical analysis was performed to investigate the frequency distributions and any possible correlations among parameters b, EMC, $I_{\max}$, and several hydrograph indicators including event duration, total volume, event skewness, and temporal moments of rain intensity throughout the events. As an example, Figure 1 shows the

Table 1—Basic hydrologic statistics of monitored storm events (Stenstrom and Kayhanian, 2005).

		Drainage Area (m^2)	Annual average daily traffic	Antecedent Dry days (day)	Runoff depth (mm)	Total Rainfall (mm)	Peak flow (lit/s)	Flow Volume (m^3)	Storm Duration (hr)	Average rainfall intenstity (mm/hr)
Site 1	No. of events	12802	328000	23	23	23	23	23	23	23
	Min. / Max.			2.0 / 69.4	1.3 / 103.7	1.8 / 126.7	4.7 / 96.2	16.9 / 1327.3	2.8 / 44.1	0.6 / 10.1
	Median / Mean			15.3 / 21.2	17.9 / 22.4	23.1 / 30.0	25.0 / 36.9	228.7 / 286.3	13.6 / 14.7	1.4 / 2.1
	Standard Dev.			16.9	22.9	29.3	29.7	29.37	10.2	2.1
Site 2	No. of events	16918	260000	27	27	27	27	27	27	27
	Min. / Max.			1.0 / 192.2	14 / 260.5	1.5 / 286.8	3.9 / 154.6	23.5 / 4407.2	1.8 / 81.0	0.2 / 9.7
	Median / Mean			20.1 / 29.0	14.9 / 29.4	21.1 / 37.0	34.7 / 51.9	251.5 / 497.6	10.5 / 15.4	1.4 / 2.3
	Standard Dev.			36.9	50.7	59.7	47.4	858.5	16.9	2.3
Site 3	No. of events	3917	322000	28	28	28	28	28	28	28
	Min. / Max.			0.3 / 192.3	0.3 / 122.8	1.3 / 128.3	0.9 / 57.6	1.0 / 481.1	1.7 / 47.6	0.2 / 8.5
	Median / Mean			20.0 / 27.7	14.3 / 24.1	19.4 / 29.0	13.4 / 16.4	56.1 / 94.6	8.5 / 11.1	2.3 / 2.9
	Standard Dev.			36.8	29.7	32.4	13.7	116.4	9.9	2.2
Combined sites	No. of events	78	78	78	78	78	78	78	78	78
	Min. / Max.	3917 / 16918	260000 / 328000	0.3 / 192.2	0.3 / 260.5	1.3 / 286.8	0.9 / 154.6	1.0/ 4407.2	1.7 / 81.0	0.2 / 10.1
	Median / Mean	12802 / 11037	322000 / 302308	19.8 / 26.3	14.9 / 25.4	20.3 / 32.1	19.2 / 34.7	122.5 / 290.6	10.5 / 13.7	1.5 / 2.5
	Standard Dev.	5612	31078	32.1	36.6	42.8	36.1	554.3	12.8	2.2

histograms and scatter plots of event duration, EMC, and *b* for zinc. Similar analyses were performed for other constituents. Results generally indicate the presence of a correlation between EMC and the event total rainfall. The analysis also suggests the first flush exponent, *b,* does not have a significant correlation with event duration or with other hydrograph indicators.

The objective here was to simulate a large number of pollutographs using the power relationship between the cumulative mass and cumulative flow. The frequency distributions obtained for the exponent *b*, EMC, and the distribution of event rainfall depths and the cross-correlations between them were used to generate the pollutographs. In the Monte Carlo simulation process, the pollutographs were used in conjunction with eqs 12 and 13 to find the frequency of exceeding a predefined threshold concentration for various constituents as a result of capturing certain runoff depths.

To generate random numbers representing the parameters controlling the pollutograph for the stochastic simulations, a number of probability density functions (PDFs) were fitted to the frequency distributions of parameter *b*. A comparison of the PDFs obtained for all constituents revealed that, in general, a gamma distribution best fits the data (Table 2). Similarly, using rainfall data for the watershed region since 1951 (National Climatic Data Center), PDFs were fitted to the rainfall depth histograms. The analysis implied that an inverse Gaussian distribution with μ=4.195 and σ^2=332.764 best described the event rainfall depth.

To incorporate the dependence of EMC to the event rainfall depth, I_{max}, into the Monte Carlo simulation, a power law relationship was assumed between each constituent EMC and the event rain depth, as follows (see Figure 1):

$$EMC = K\left(\frac{1}{I_{max}}\right)^{\alpha}\varepsilon \tag{13}$$

Where

K and α = constants and

ε= a random multiplicative error component.

Taking logarithms of both sides gives

$$\ln(EMC) = \ln(K) - \alpha\ln(I_{max}) + \ln(\varepsilon) \tag{14}$$

where α was found to be a log-normally distributed random variable (see Table 2). Randomly generated values of $\varepsilon$where used in conjunction with eq 13 to generate random EMC values. For every assumed runoff captured depth (WQD), 100 000 random values for *b*, I_{max}, and *EMC* were generated from the obtained frequency density functions, and C_{max} and C_{avg} values

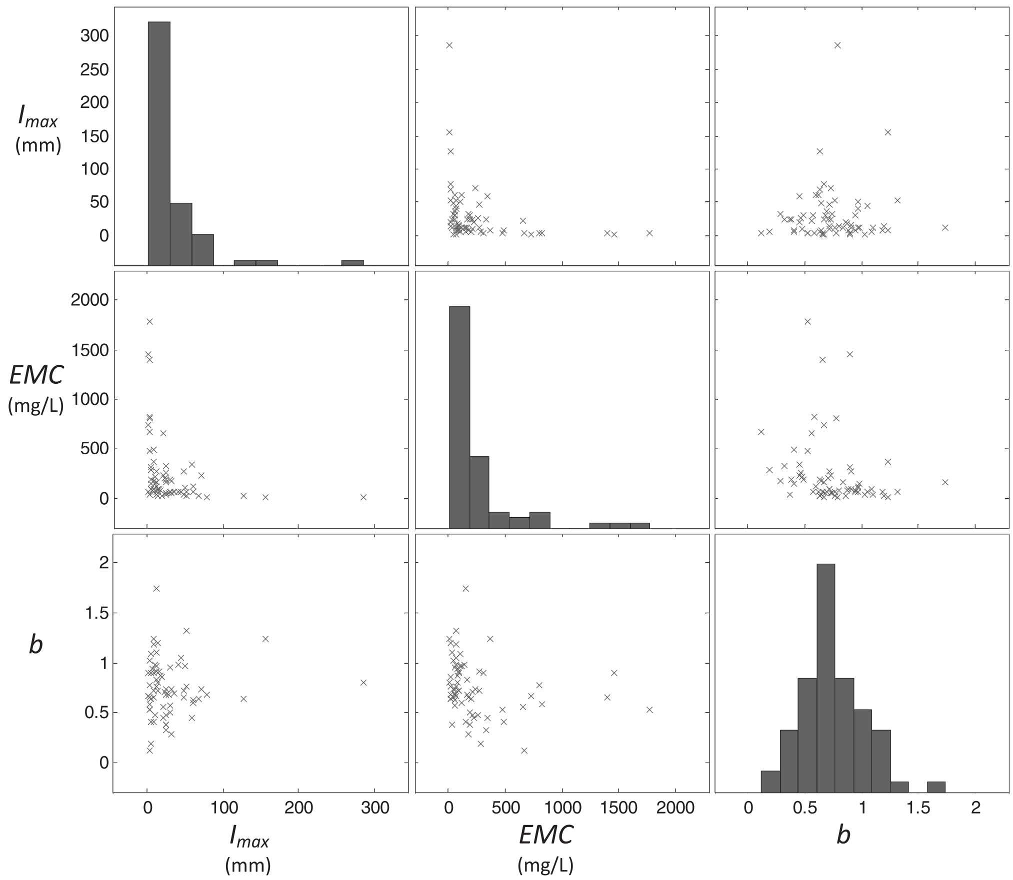


Figure 1—Histograms and scatter plots of event duration, EMC, and *b* for zinc.

were calculated using eqs 12 and 13. The exceedance probability, *P,* for the capture depth was obtained from the following relationship:

$$P = \frac{\#\ \text{simulations where } C(t) > \text{endpoint}}{\#\ \text{simulations}} \times 100 \qquad (15)$$

Once the exceedance probabilities were obtained for different capture depths, decisions could be made regarding proper capture rainfall depth.

Table 2—Predicted gamma distribution for parameter *b* and log-normal distributions for ε.

	b (Gamma Distribution)[1]		ε (log-normal distribution)[2]	
Constituent	*Shape (λ)*	*Scale (θ)*	*Mean (μ)*	*std (σ)*
Cd	7.457	0.098	−1.18815	2.107
Cr	15.014	0.059	0.00512	1.563
Cu	8.097	0.091	−0.00091	0.893
Ni	7.164	0.096	−0.00411	1.002
Pb	6.261	0.141	0.00078	1.137
Zn	6.162	0.121	0.00680	0.972

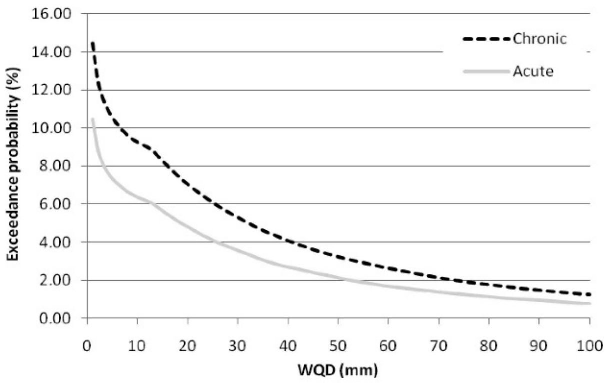
[1] Gamma distribution: $f(x;\lambda,\theta) = x^{\lambda-1}\exp(-x/\theta)/\theta^{\lambda}\Gamma(\lambda)$
[2] Log-normal distribution: $f(x;\mu,\sigma) = \exp(-(\ln x - \mu)^2/2\sigma^2)/x\sigma\sqrt{2\pi}$

Results

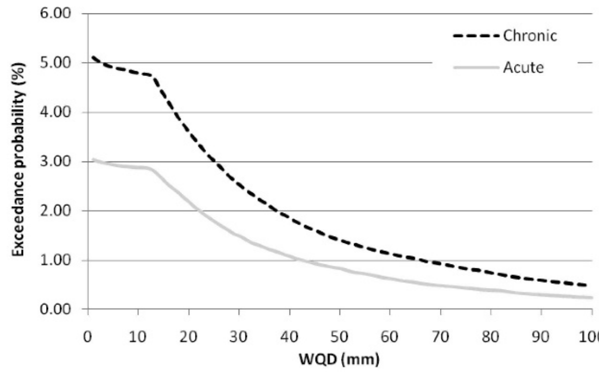
Because data were collected from a highway site that is almost completely impervious, the value of the runoff coefficient *c* was assumed to be 1.0. Various rainfall capture depths ranging from 5 to 100 mm in 5-mm increments were considered in the simulations. Furthermore, the California toxic rule (CTR) (U.S. EPA, 2000) was used to calculate endpoint values for selected metal constituents (see Table 3). Because based on certain watershed and regulatory compliance it may be prudent to use acute or chronic concentrations, the endpoint concentrations were calculated for both conditions. It is acknowledged that other water quality standards (or restrictions) and, in particular, criteria obtained from TMDL developed for the watershed might have been more relevant. However, no TMDL criterion for the

Table 3—California toxic rule water quality concentration thresholds for selected toxic metals (calculated based on an average hardness of 50 mg/L).

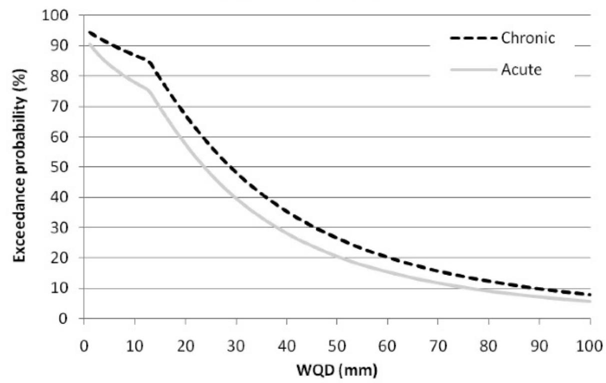
Constituent	Acute (mg/L)	Chronic (mg/L)
Cd	0.0020	0.0013
Cr	0.0160	0.0110
Cu	0.0070	0.0050
Ni	0.2605	0.0289
Pb	0.0301	0.0012
Zn	0.0651	0.0657



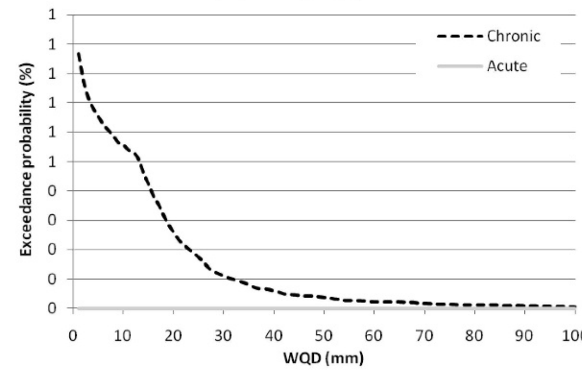
(a) Cd (C_{max})



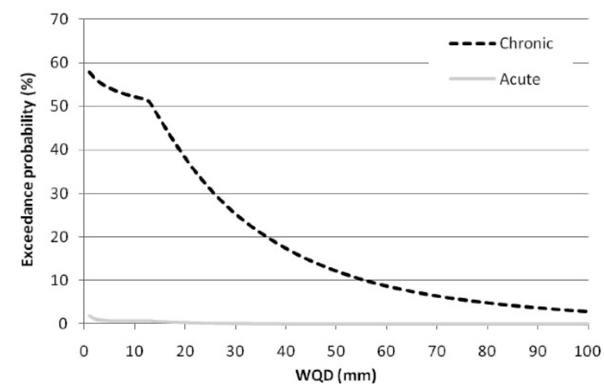
(d) Cr (C_{avr})



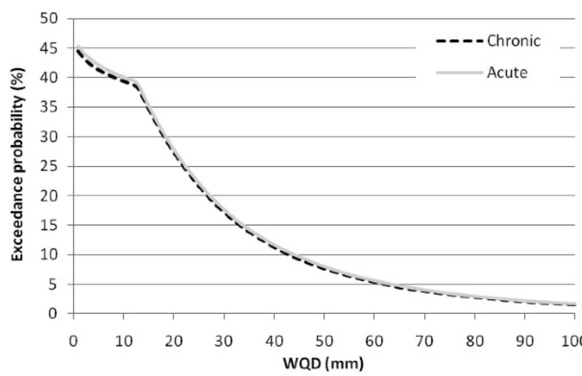
(b) Cu (C_{max})



(e) Ni (C_{avr})



(c) Pb (C_{max})



(f) Zn (C_{avr})

Figure 2—Exceedance probability of constituents' concentrations relative to CTR water quality criteria.

current highway characterization study area was available at the time of the study.

After evaluating the quality of the measured highway runoff characterization data in California, it was concluded that rainfall below 12.7 mm (0.5 in.) typically occurs in short, sporadic episodes that are not strong enough to produce sufficient runoff to quantify a pollutant's concentration from the automatic sampler (Kayhanian, 2005). Hence, the stochastic simulation procedure was only conducted for events having event total rainfall depth (I_{max}) greater than 12.7 mm (0.5 in.). Figure 2 illustrates the exceedance probability of maximum (C_{max}) and mean (C_{avg}) contaminant concentration of selected constituents from the acute and chronic endpoint values.

Based on 59 years of available rainfall data, each year the region where the sites are located experiences an average of only 5.24 events per year, with cumulative rainfall depth (I) greater than 12.7 mm. Using the obtained exceedance probability distributions, the expected value of the number of events per year in which the released constituent concentration would exceed the endpoint can be calculated from

$$\#\text{exceeding events/year} = P \times (\textit{average \#events/year}) \times 100$$

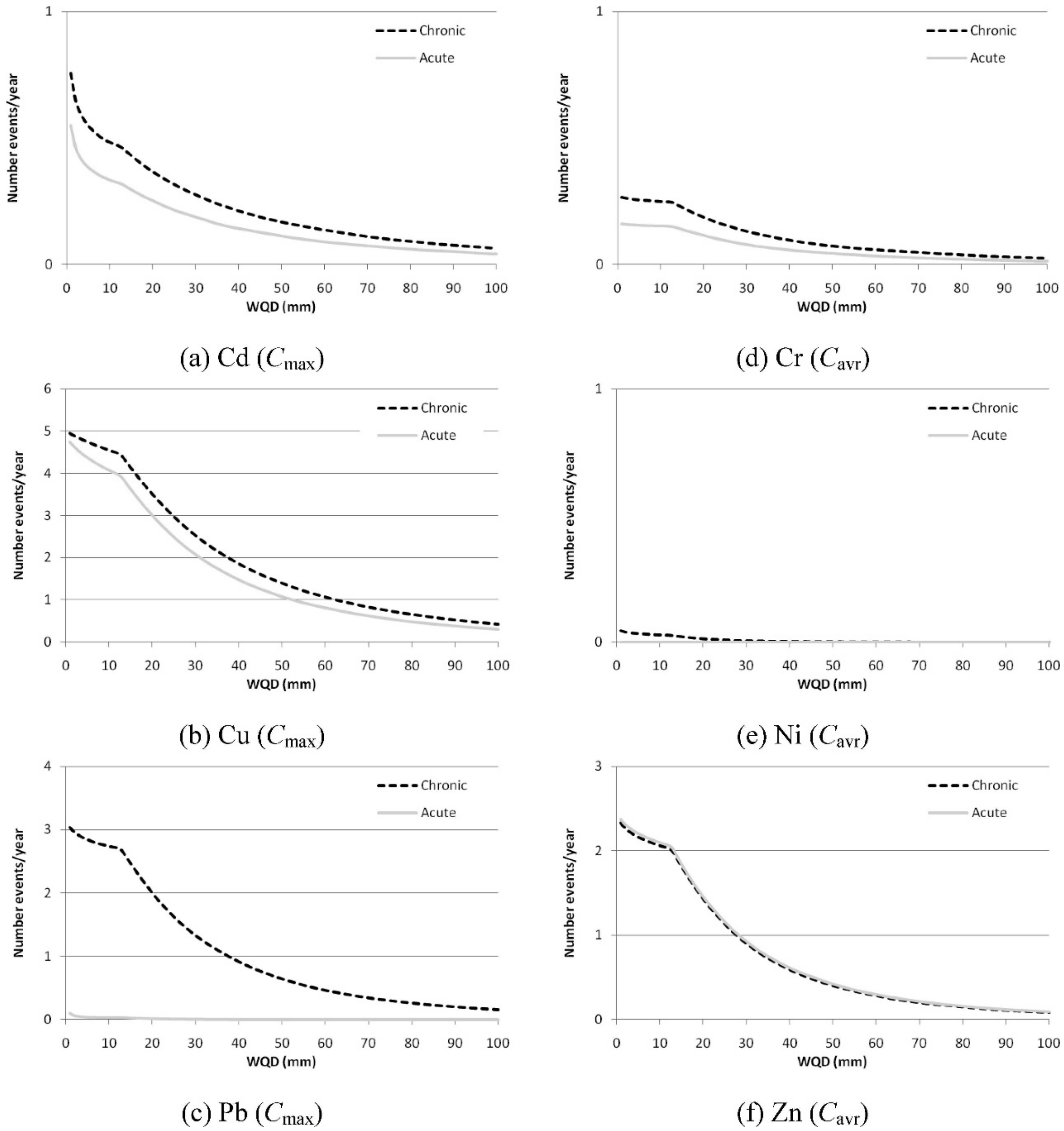


Figure 3—Number of events per year in which the released maximum constituent concentration would exceed the endpoint.

Figure 3 shows the expected value of the number of exceedances per year vs WQD for selected constituents. The results of exceedance probability based on various WQD for selected constituents are summarized in Table 4. The table presents the WQDs required for the exceedance probability of a constituent concentration from the threshold value to be less than 5% and less than 15%, and also the WQD required for having an expected exceedance frequency of single event per year. Table 4 can be used to (a) evaluate the feasibility of reducing the constituents' concentrations below the endpoint using conventional BMPs and (b) prioritize the pollutants of concern. For example, it can be seen that a WQD of approximately 30 mm can reduce the annual frequencies of exceedance to below 1 for all the metals except copper. However, in practical terms, it is not feasible to reduce the frequency of exceedance of copper to below 1. It should be noted that the endpoints here are based on the assumption that no dilution takes place as the contaminants are transported into the receiving water. The role of first flush phenomena in reducing the size of BMPs was tested by performing the simulation using a hypothetical fixed first flush exponent of 1. Setting b equal to 1 for all of the events assumes that the concentration of contaminants remains equal to EMC throughout the events. Comparisons between the probabilities of exceedance using the no first flush assumption and the instance with a randomly generated first flush exponent for four constituents are presented in Figure 4. In this instance, the role

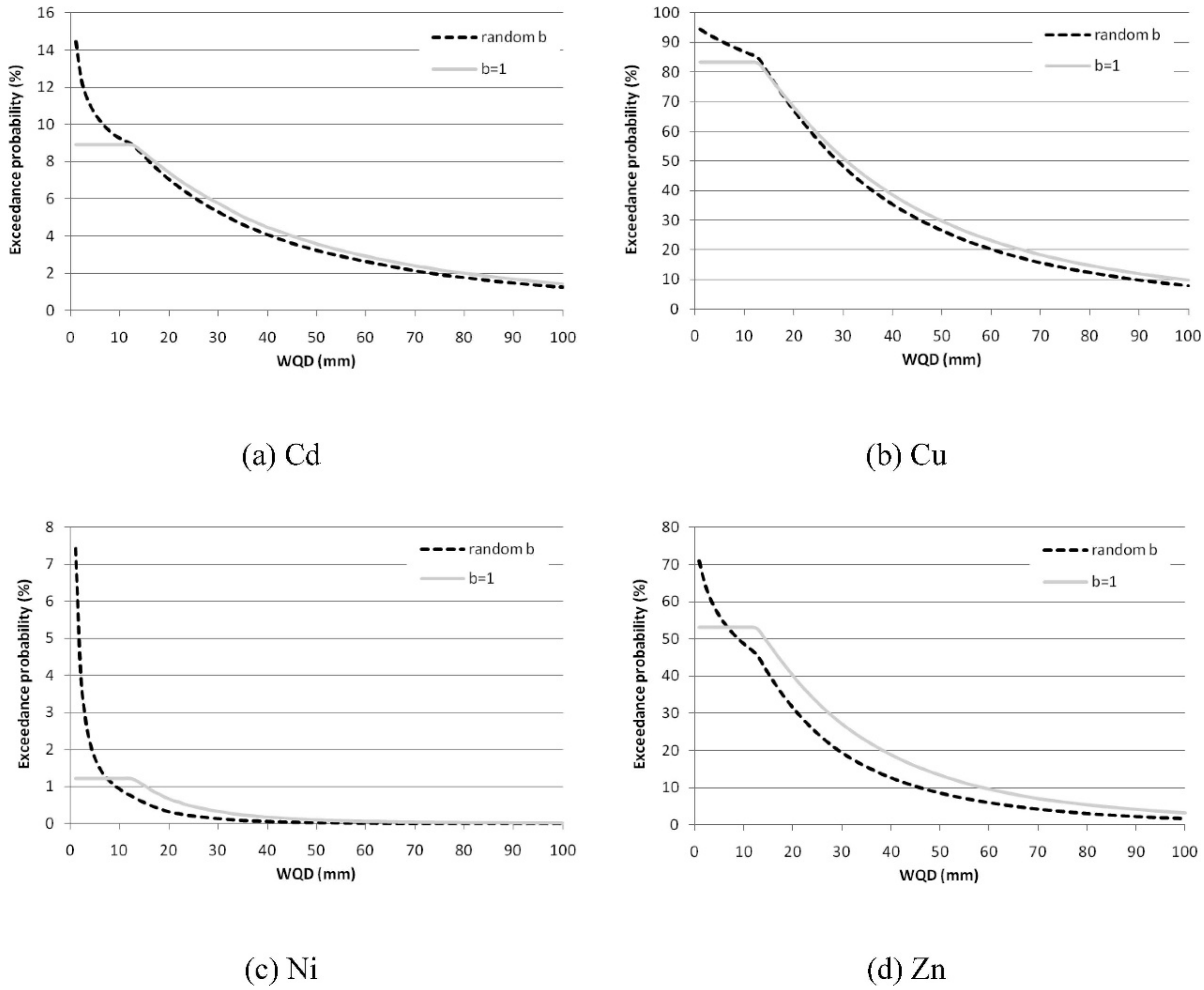


Figure 4—Comparison between exceedance probability as a result of no first flush assumption ($b = 1$) with events generated using the PDF of first flush exponent b for cadmium, copper, nickel, and zinc.

Table 4—Summary of WQDs required for achieving certain probabilities of violations of CTR criteria. *P* is the probability of violation in each event and *N* is the number of violation incidents per year.

	Required WQD (mm)											
	$P < 5\%$				$P < 15\%$				$N < 1$			
	C_{max}		C_{avr}		C_{max}		C_{avr}		C_{max}		C_{avr}	
Constituent	Acute	Chronic	Acute	Chronic	Acute	Chronic	Acute	Chronic	Acute	Chronic	Acute	Chronic
Cd	19	32	15	29	NA[2]	NA	NA	NA	NA	NA	NA	NA
Cr	2	13	NA	2	NA	NA	NA	NA	NA	NA	NA	NA
Cu	>100	>100	>100	>100	61	72	59	68	52	62	49	59
Ni	NA	2	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Pb	NA	79	NA	79	NA	44	NA	43	NA	37	NA	37
Zn	66	66	63	63	36	36	34	34	31	31	28	28

P: the probability of exceedance for each event; *N*: The frequency of exceedance per year.
[1] The required WQD is larger than 100 mm, but the exact value is not calculated here.
[2] No treatment is required.

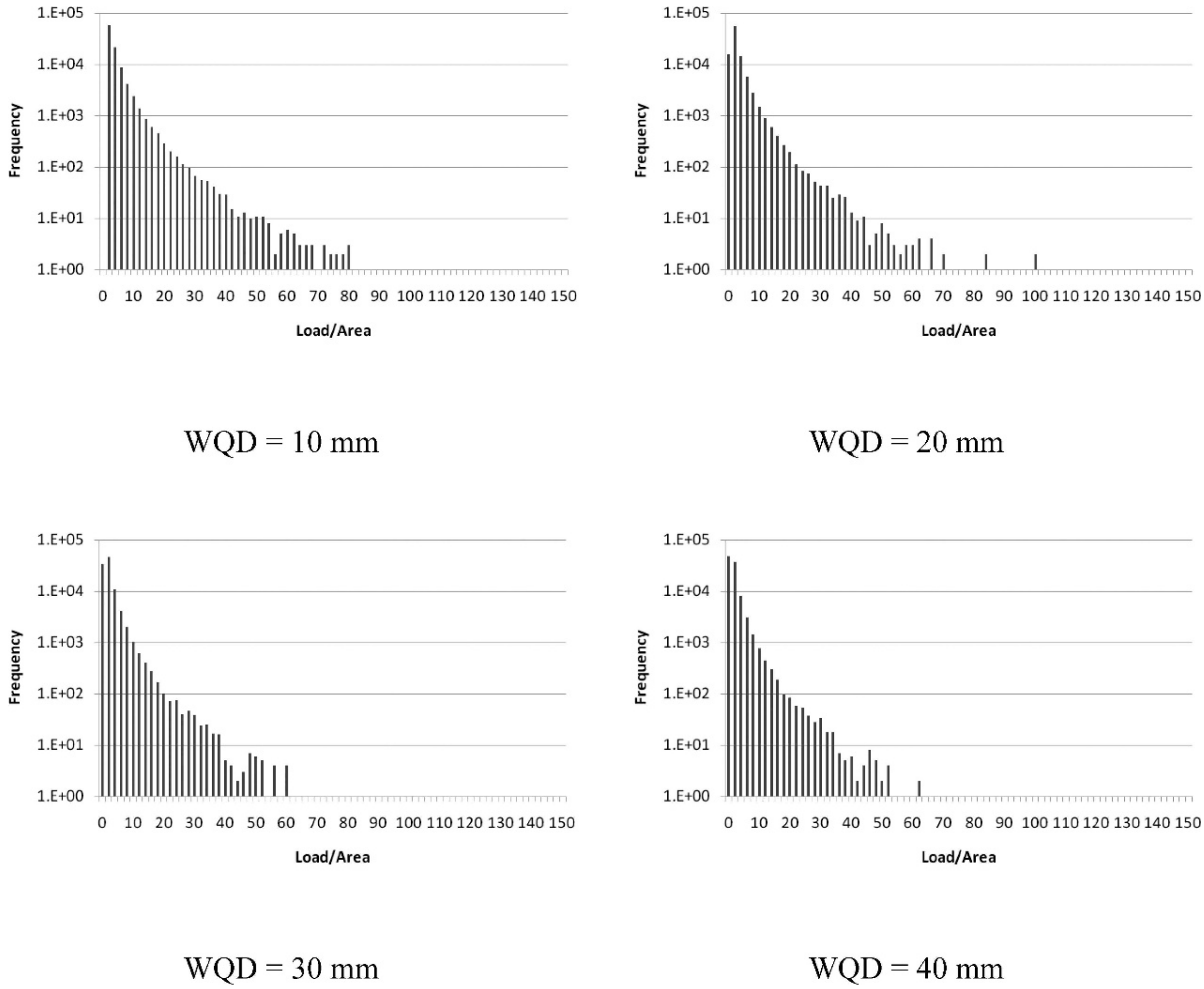


Figure 5—Frequency distribution of load and area for zinc for various water quality depths.

of first flush appears to not be substantial. This is because the variability of EMCs of events dominates the concentration variability during each event as a result of first flush. However, this conclusion is specific to the studied site and the threshold values considered and, therefore, should not be generalized.

Because there is no TMDL criterion available for the study area, the TMDL/load approach (eq 14) could not be applied to find the probabilities of exceedance from TMDL criteria. However, using eq 14, the frequency distribution of load could be obtained for each constituent for a range of WQDs. As an example, Figure 5 illustrates the frequency distributions of load per catchment area for zinc at four different WQD values. If a TMDL value and the catchment area were known, the exceedance probability of the load from TMDL could be calculated. The result shows that, although an increase in WQD reduces the loads discharged during each event, it does not eliminate all the instances of extreme loads.

Summary and Conclusions

A stochastic approach was used to quantify the frequency of stormwater discharge water quality standard exceedance as a result of water quality depth criteria (i.e., the depth of water captured and treated by BMPs). The method is based on a power relationship between the cumulative load and cumulative flow. The exponent of the power relationship (the first flush exponent), which is an indicator of first flush severity, in addition to EMC and the rain event depth, are considered to be random variables with their frequency distributions obtained from monitoring data collected from three highway sites in the state of California. A Monte Carlo simulation technique was used to find the expected value of the number of times per year the maximum or mean concentrations of various constituents exceed certain predetermined threshold limits. The method was applied to six water quality constituents using concentration-based criteria obtained partly from CTR. The method is capable of considering both concentration-based and load-based thresholds (for instances of presence of TMDL criteria). However, because of the lack of TMDL criteria for the study site, only concentration-based criteria were used for the demonstration. The required WQD to meet a certain criteria can be obtained both by limiting the probability of exceedance at each event and also by specifying an acceptable mean yearly frequency of exceedance. However, the outcome of the former method depends on the minimum rain volume required for a precipitation to be considered a rain event, whereas the second criterion is independent of the way an event is defined. Although the frequency of exceedance values obtained are site-specific and depends on the water quality endpoints chosen, the approach provides a systematic way to quantitatively evaluate the effect of the selection of water quality depth on the concentrations of various pollutants discharged into receiving waters or to meet TMDL criteria using monitoring data. In particular, the method offers a simple way to prioritize pollutants during development of TMDL implementation plans. It also offers a means to evaluate the efficacy of forcing water quality depth criteria for satisfying TMDL or concentration criteria in complicated urban settings where the use of distributed or lumped parameter watershed water quality models is difficult and involves large uncertainties. It should be noted that the method proposed here assumes that the watershed size is small enough so that its time of concentration is small relative to the rain-intensity fluctuation time scale. This assumption should be used with caution for large watersheds. Moreover, the applicability of the power relationship for approximating the normalized cumulative load vs flow curves needs to be verified with pollutograph data collected from a larger number of sites. In addition, in the model application presented here, it was assumed that the runoff coefficient c is independent of rain intensity. In applications to large watersheds, such dependencies can be incorporated by explicitly expressing c as a function of rain intensity in the Monte Carlo simulation.

The main conclusions drawn from this study are as follows:

- A half-inch WQD seems to reduce the frequency of exceeding the concentration-based criteria significantly for most constituents. However, in some instances, even much larger WQDs will not satisfy concentration-based criteria.
- The BMP design criteria based on a required water quality depth seems to be more effective in reducing the probability of exceeding load-based criteria than a concentration-based criteria.
- For the data set used in this study, it was found that the role of event first flush on the effect of water quality depth on exceedance frequencies is not significant. This is because the exceedance probability is dominated mostly by the larger variability in EMCs of events. Therefore, considering first flush will not result in substantially smaller water quality depth criteria.

Notations

A = drainage area
b = first flush exponent $M(t) = [V(t)]^b$
C = constituent concentration
c = runoff coefficient
I = cumulative rainfall depth
i = rainfall intensity
K = constant in eq 13
M = dimensionless cumulative constituent mass
P = exceedance probability
T = duration of the entire event
t = time
V = dimensionless cumulative flow
α = constant in eq 13
Γ = gamma function
ε = random error component
θ = scale factor in Gamma function
λ = shape factor in Gamma function
σ^2 = variance
μ = average

Subscripts

avg = average value
max = maximum value (at the end of rainfall)

Acronyms

EMC = event mean concentration
FF = first flush
PDF = probability density function
TMDL = total daily maximum load
WQD = water quality depth
WQV = water quality volume

Credits

Data used in this study were obtained from first flush highway runoff characterization that was funded by the Division of Environmental Analysis, California Department of Transportation. The first flush characterization study was performed under collaborative efforts between the Departments of Civil and Environmental Engineering at the University of California at Los Angeles and the University of California at Davis. The authors are especially thankful to Professor Mike Stenstrom and his graduate students and research staff for all of their efforts and contributions during the study period. Partial funding for this study was provided by the District of Columbia Water Resources Research Institute.

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