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Determination of cost-effective first flush criteria for BMP sizing

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ABSTRACT

Effective control of nonpoint source pollution in urban areas relies on the appropriate application of best management practices (BMPs). Many strategies are used in designing the BMPs considering efficiency, cost, benefits, etc. In Korea, the first flush criterion is typically employed to size the BMPs. However, the criterion was only adopted from foreign literature without verification of its applicability. This study was conducted to investigate the most suitable first flush design rainfall that can be used in sizing the BMPs in Korea. The data used to calculate the pollutant concentrations were gathered from a total of 22 storm events during the three-year monitoring on a paved parking lot site. The magnitude of the generated first flush at 5 mm and 7.5 mm accumulated rainfall were quantified and analyzed by means of mass first flush (MFF) ratio. The results showed that the pollutant concentration at 5 and 7.5 mm accumulated rainfall were 36% and 22% greater than the average event mean concentration (EMC), respectively. Although the BMP size could be appreciably reduced by almost 70% when 5 mm rainfall is to be used as compare to 50% size reduction for 7.5 mm rainfall, it is still better to select 7.5 mm as design rainfall. In this case, the treated mass is above 50% for 7.5 mm but only 40% for 5 mm rainfall. Therefore, "cost-effective" BMP design must not only depend on treated runoff quantity but also quality of the treated runoff.

Keywords: Accumulated rainfall; BMP; Design; EMCs; First flush; MMF

1. Introduction

For the past 30 years, the government of Korea has made tremendous advances in building water related infrastructures to clean up its aquatic environments against point source pollution. Although point source discharges have been reduced, many water bodies in Korea remain polluted. Nonpoint sources (NPSs) are the reason behind many problems. Generally, NPS pollutants are caused by various land uses. Paved surfaces such as parking lots and bridges in urban areas are storm water intensive land uses since they are highly impervious, and have high pollutant mass emission from vehicular activities [1]. To control NPS, it is necessary to understand the environmental processes within a watershed [2]. The primary characteristic of urban storm water runoff is the first flush phenomenon. It is this initial period of runoff during which pollutant concentration is higher than in later periods that is called the first flush phenomenon [3]. First flushes are usually associated with small impervious catchment such as highways and parking lots [4, 5]. Saget et al. and Bertrand-Krajewski et al. suggested that a first flush occurs when 80% of the pollution load is contained within the first 30% of runoff volume [6, 7]. Others have chosen 25% of runoff volume as a cutoff [8]. Still others have used a pollutant mass/runoff volume curve method in which slopes of greater than 45° constitutes a first flush [9].

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The first flush of the impervious runoff sites were characterized with mass first flush (MFF*n*) ratio, define as the ratio of the discharged pollutant mass to the runoff volume in the first *n*% of the runoff. It quantifies the mass of emitted pollutants as a function of the storm progress, as indicated by the normalized runoff volume. The MFF*n* is equal to zero at the beginning of the storm ($n = 0\%$) and always equals 1.0 ($n = 100\%$) at the end of the storm. MFF*n* values greater than 1 indicates that normalized mass is being discharged faster than the normalized volume or a first flush [4, 10, 11].

The existence of first flush provides an opportunity for controlling urban runoff pollution from a broad range of land uses. Considering first flush gives a more effective design of best management practices (BMPs) [12]. These BMPs are employed to capture and isolate the most polluted runoff, with subsequent runoff being directly diverted to the runoff system (as bypass), which is more economical compare to treating the whole amount of runoff. Besides, BMPs also consider cost and not only efficiency in design. Regulations for NPS pollution from small catchments often contain requirements for treating a first flush depth of runoff. BMPs used to improve water quality needs to be designed or selected to correspond to the flow rate of the first flush runoff depth [13]. The Ministry of Environment (MOE) set up guidelines for the design and installation of BMPs based on the first flush phenomenon. The design criterion for the treatable volume is to be based on an accumulated rainfall of at least 5 mm [14]. There is another criterion for the pollutant reduction facility which considers an accumulated rainfall of 7.5 mm following the first flush concept [15]. These criteria are adopted in Korea to design BMPs for paved areas.

The higher initial concentrations are associated with the removal efficiency of the BMPs due to the first flush [16]. The washed-off pollutant concentrations from NPS, including parking lots and bridges, are quantified with the event mean concentration (EMC). In spite of many EMC-related studies concerning various landuses, using the published EMC values is limited because of high uncertainties of NPS as demonstrated by the differences in total rainfall, rainfall duration and intensity, total runoff volume, catchment area, and other site-specific factors [1]. The concentration of discharged pollutants during the first flush has imposed limitations to estimate pollutant concentration using the general EMCs of the total event.

The objective of this study was to evaluate the most effective design rainfall that can be applied in sizing stormwater BMPs. To be able to accomplished this objective, the concentrations (e.g., EMC, MFF*n*) for accumulated rainfall of 5 and 7.5 mm, were calculated and compared with the event EMCs (i.e., total EMCs average). The values for accumulated rainfall selected for this study (i.e., 5 and 7.5 mm, respectively) were the typical values use in current sizing of BMPs in Korea. Nevertheless, the intention of this study is to suggest the most economical and effective criteria for rainfall that can be use to establish a general and unified sizing criteria and standard for BMP design in the country.

2. Methods

A parking lot site was selected to evaluate the runoff concentrations according to the BMP design criteria. The monitoring site is located in Yong-In City, Kyunggi Province, Korea. The parking lot is paved with asphalt and 100% impervious. It has a total catchment area of 10,700 m^2. The concentration and flow data from the 22 storm events during June, 2006 to October, 2008 monitoring period were used to calculate the pollutant EMCs of the stormwater runoff from the parking lot land use. Analyses of typical parameters (TSS, COD, BOD, TN, TP, heavy metals, etc.) were performed in accordance to Standard Methods [17].

Aside from the EMCs calculated for all of the events, the concentrations were also calculated until the rainfall of selected events reached 5 and 7.5 mm rainfall. This means that using the time until the 5 and 7.5 mm rainfall, respectively for EMC calculations, the ratio of first flush concentration for EMCs were estimated. To quantify the magnitude of first flush, the MFF*n* ratio was analyzed using the equation according to the percentage of runoff volume for all events [4, 11]. In addition, accumulated mass ratios for 5 and 7.5 mm accumulated rainfall were analyzed to express MFF*n* ratio.

3. Results and discussions

3.1. Monitored rainfall events

The summary of the monitored events is provided in Table 1. It includes antecedent dry days (ADD), total rainfall, runoff and rainfall duration, and average rainfall intensity. ADD varies from 1 to 33 days while the total rainfall ranges from 0.5 to 51 mm. The average event rainfall is approximately 16 mm. During the monitoring period, the rainfall and runoff duration has a minimum of about 1 h up to a maximum of 12 h. The rainfall intensity averages from 0.2 to 12.1 mm h^{-1}. Hydraulic characteristics seem not to be dependent on each other since events with larger rainfall occur with varying ADD.

3.2. Estimation of EMCs

The concentrations of TSS, BOD, COD, TN, TP, Turbidity, Fe, Pb and Zn were quantified by means of EMC. Fig. 1 shows the box plot results of pollutant EMCs for all events. The mean values for EMCs are 54.6 mg L^{-1} (TSS),

Table 1
Monitored event data[a].

Event date	ADD (day)	Total rainfall (mm)	Runoff duration (hr)	Rainfall duration (hr)	Avg. rainfall intensity (mm/hr)
Number of cases	22	22	22	22	22
Minimum	1	0.5	1	1.4	0.2
Maximum	33	51	11.7	12.3	12.1
Mean	7.3	15.7	4.5	5.2	2.8
Standard deviation	7.3	17.3	2.8	2.9	2.7
Coefficient of variation	1.0	1.1	0.62	0.57	0.97

[a]SD = standard deviation; CV = coefficient of variation.

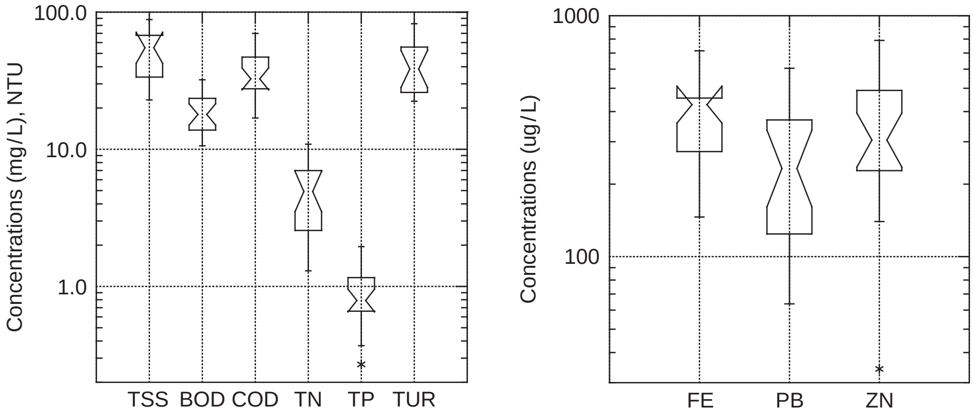

Fig. 1. Statistical summary of EMC in the facility.

15.0 mg L^{-1} (BOD), 4.0 mg L^{-1} (TN), 0.8 mg L^{-1} (TP), 398.0 µg L^{-1} (Fe), 274.4 µg L^{-1} (Pb), 370.4 µg L^{-1} (Zn). The results is lower compared to the study by [1] which have 115, 35, 4, and 1 mg L^{-1} for TSS, BOD, TN and TP, respectively. The greater the rainfall and rainfall intensity, the smaller average EMC values were obtained. Because of long rainfall duration and heavy rainfall, average EMC value is small. Rainfall intensity, weather (e.g., cumulative seasonal rainfall, ADD, etc.), and geography (e.g,. land use, degree of imperviousness, soil type and slope, etc.) therefore found to be responsible for the variations the values of EMCs.

3.3. Mass first flush ratios

Fig. 2 shows the notched box plots of the MFF_{10} to MFF_{100} ratios for TSS, TN, TP, Fe, Pb and Zn. 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. For MFF*n*, the value at the end of the storm is equal to 1. Values greater than 1 indicate the first flush. The plots show that the first 10% of the normalized volume carries the greatest mass of pollutants. Among the parameters, TSS exhibited the largest magnitude of first flush. MFF_{10} for TSS is 1.95, which means that almost 20% of the TSS mass is washed off in the first 10% of runoff (both normalized). The MFF ratio declines as the storm progressed and the MFF_{20} and MMF_{100} drop to 1.7 and 1.0, respectively. Based on the plots of the six parameters, it can be noted that the first flush peaked at about 30% of the normalized flow which means that the first flush is usually occurring in the first 30% of the total runoff volume. Nevertheless, the values of MFF_{10} were lower than other results attributed to low rainfall intensity due to small rainfall depth and short rainfall duration during the monitoring events [16].

Table 2 and 3 indicate the results of the MFF*n* value for accumulated rainfall of 5 and 7.5 mm, respectively. The MFF*n* ratio provides a quantitative measure of the value of treating the early runoff compared to the remaining runoff [16]. For 5 mm rainfall, the mean percentage of runoff volume is equal to 36.3% while the mean MMF*n* for TSS is 1.74 and the total mass load contained 63.2% of the pollutant. For 7.5 mm rainfall,

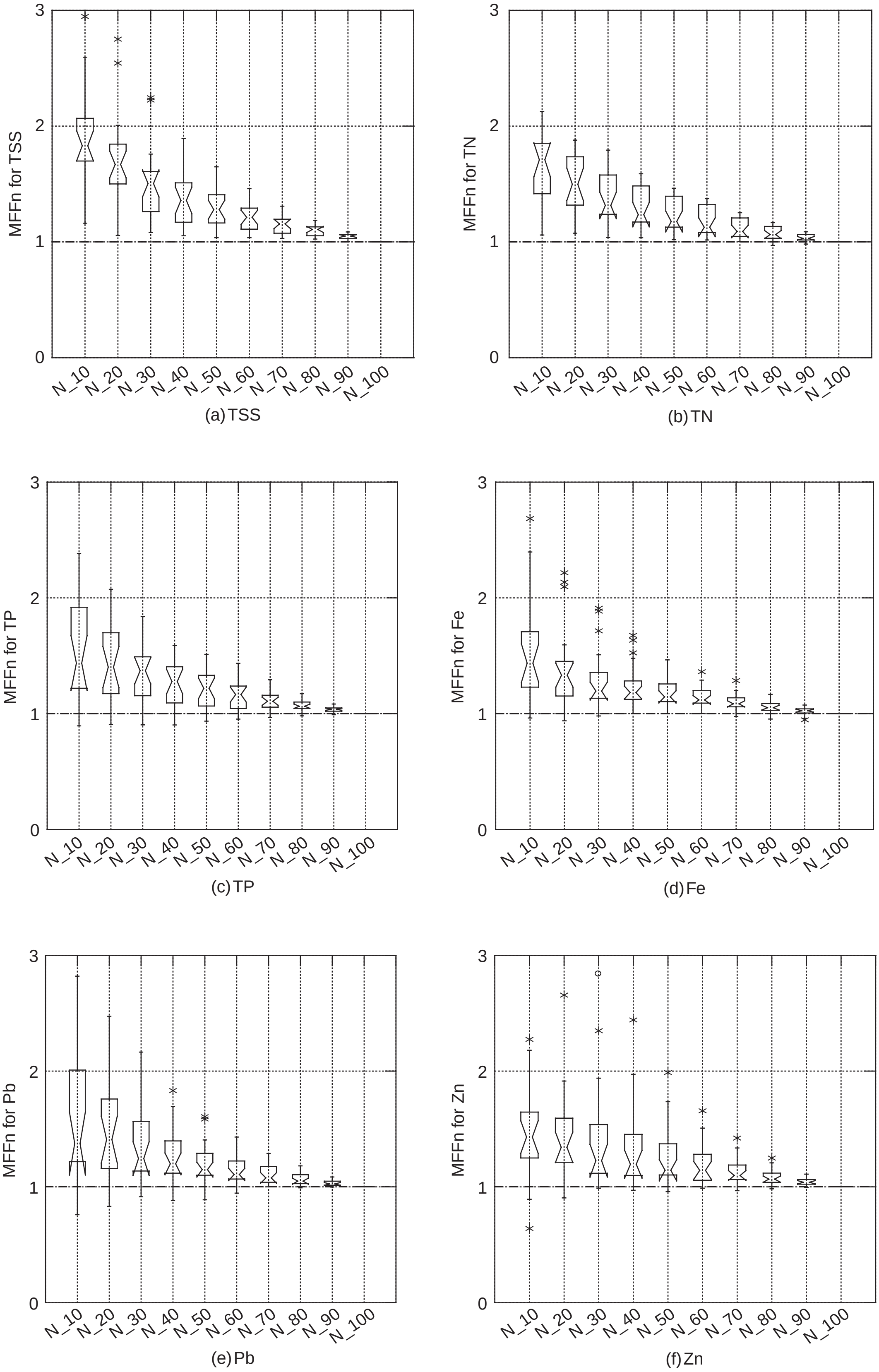

Fig. 2. Notched bar graphs for MFFn ratios (n = 10 to 100%) for TSS, TN, TP, Fe, Pb and Zn.

the mean percentage of runoff volume is equal to 41.6% while the mean MMF*n* for TSS is 1.63. The total mass load contained 67.8% of the pollutant.

3.4. First flush design runoff volume criteria

BMPs are usually designed considering water quality volume (WQV) and can be determined by several methods. In Korea, this WQV is the first flush design runoff volume in depth per drainage area multiplied by the area that is draining into the BMP. The MOE recommends a first flush capture volume of 5 mm of runoff per drainage area while the MOCT uses 7.5 mm of runoff per drainage area. These calculations are employed so that only portion of the runoff (i.e., first flush) will be treated and captured by the BMP and the remaining runoff should be bypassed. However, if treatment of the entire runoff from the site is desired, the average rainfall depth can be used as capture volume design.

Analysis on the feasibility of using the first flush rainfall criteria was incorporated to be able to investigate the most economical and practical design rainfall that can be used in sizing the BMP. Table 4 shows the comparisons of design ratio among the three rainfall depths for various parameters. The 16 mm rainfall represents the average rainfall (see Table 1) and denotes that approximately all or most of the runoff is to be treated by the BMP. It might be the "ideal design" but not in fact the "cost-effective design.". For simplification, it is assumed that the 16 mm rainfall is the limit of design, assigning the ratio of "1," accordingly.

As apparent to the BMP size ratio described in Table 4, there were extremely considerable differences when using the three rainfall depths. In comparison to using the 16 mm design rainfall, almost 50% of the BMP size was reduced if only 7.5 mm is to be use in design and greatly 70% for 5 mm. However, BMP size reduction should not be the sole condition for economical design, it is also important to note the treated mass when using the design rainfall. Based on the table, by means of using 5 mm as design rainfall 40% of the pollutant mass is treatable whereas if 7.5 mm is used, the treated pollutant mass were slightly higher treating 50% to 60% of the pollutant mass. Although the ratio of the treated mass to BMP size between the 5 and 7.5 mm design rainfall differs around 10% to 20%, it is safer to design the BMP using 7.5 mm rather than 5 mm rainfall. It implies that "cost-effective design" should not only depend on the economical aspect of WQV (BMP size) but also to the treatment efficiency of the BMP (treated mass).

4. Conclusions

The first flush runoff criterion is an important factor in designing BMPs for the proper management and control of NPS pollution especially in urban areas. MFF*n* is a useful method to evaluate the magnitude of first flush. Based

Table 2
MFF_n for accumulated rainfall of 5 mm.

Parameter	*n*	TSS	BOD	TN	TP	Fe	Pb	Zn
Number of cases	16	16	16	16	16	16	16	16
Minimum	2	1	1	0.97	0.96	1	1	1
Maximum	83	4	2.9	1.9	1.9	2.4	5.2	4
Mean	36.3	1.7	1.6	1.4	1.34	1.4	1.6	1.6
95% CI upper	51	2.2	1.8	1.57	1.5	1.6	2	2
95% CI lower	21.6	1.3	1.3	1.24	1.2	1.17	1	1.17
Standard deviation	27.6	0.8	0.5	0.3	0.26	0.4	1	0.77
Coefficient of variation	0.76	0.46	0.33	0.22	0.12	0.28	0.65	0.48

Table 3
MFF_n for accumulated rainfall of 7.5 mm.

Parameter	*n*	TSS	BOD	TN	TP	Fe	Pb	Zn
Number of cases	12	12	12	12	12	12	12	12
Minimum	5	1	1	1	1	1	1	0.96
Maximum	91	3	2.5	1.9	1.9	2.2	2.8	2.8
Mean	41.6	1.6	1.5	1.4	1.3	1.4	1.36	1.5
95% CI upper	59.7	2	1.7	1.6	1.4	1.6	1.7	1.8
95% CI lower	23.5	1.26	1.2	1.2	1.13	1.15	1	1.14
Standard deviation	28.46	0.58	0.43	0.3	0.24	0.38	0.5	0.57
Coefficient of variation	0.69	0.35	0.29	0.21	0.19	0.27	0.37	0.38

Table 4
Comparisons among the three rainfall depths (5, 7.5, and 16 mm) in terms of design criteria for sizing BMP.

Parameter	Rainfall depth (mm)	BMP size (ratio)	EMC/Avg concentration (mg/L)	Treated mass (ratio)	Treated mass/BMP size (ratio)
TSS	16	1	54.6	1	1
	7.5	0.5	66.6	*0.57*	1.2
	5	0.3	74.3	0.43	1.4
BOD	16	1	15	1	1
	7.5	0.5	17.4	*0.54*	1.2
	5	0.3	19.1	0.4	1.3
TN	16	1	4.03	1	1
	7.5	0.5	4.64	*0.54*	1.2
	5	0.3	4.99	0.39	1.2
TP	16	1	0.78	1	1
	7.5	0.5	0.89	*0.53*	1.1
	5	0.3	0.94	0.38	1.2
Tot Fe	16	1	0.31	1	1
	7.5	0.5	0.35	*0.53*	1.1
	5	0.3	0.4	0.4	1.3
Tot Pb	16	1	0.22	1	1
	7.5	0.5	0.24	*0.51*	1.1
	5	0.3	0.27	0.38	1.2
Tot Zn	16	1	0.3	1	1
	7.5	0.5	0.34	*0.54*	1.1
	5	0.3	0.37	0.39	1.3

on 22 monitored storm events in a parking lot land use site, the MFF*n* was analyzed according to runoff volume. The EMCs and pollutant concentrations at 5 and 7.5 mm accumulated rainfall were estimated for the treatable runoff. Based on the findings, the treatable runoff volume are 36.3% and 41.6% using 5 and 7.5 mm, respectively. It is also observed that the treated mass for 5 mm is approximately 40%, and 51% to 57% for 7.5 mm rainfall. It is therefore concluded that to be able to design the BMP as economically and effectively as possible, using the average rainfall is extremely unnecessary. Likewise, using 5 mm rainfall is supposedly safe but still the quality of the treated water might not produce acceptable results. It is best to design the BMP according to 7.5 mm rainfall as lower limit. This study reflects the general opinions of the authors and the recommendations stated could be use by the government or local institutions as reference in developing the standard guidelines for the design of BMPs.

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