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Determination of first flush criteria from an urban residential area and a transportation land-use area

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ABSTRACT

This study was conducted to identify the magnitude of first flush in a city residential area and a transportation land-use area and to provide basic information related to the criteria of stormwater runoff management. Stormwater runoff was monitored at two separate urban watersheds, which were chosen to represent the distinct types of a residential area and a transportation land-use area. 25 storm events were monitored to investigate the first flush phenomena. The first flush criterion was determined by dynamic EMC and mass-first-flush ratio (MFF_n) methods. It was assessed to be 5.5 mm in the residential area and 2.8 mm in the transportation land-use area according to the MFF_n method (median value). The magnitude of the first flush phenomenon was assessed to be 6.5 mm in the residential area and 6.8 m min the transportation land-use area according to dynamic EMC.

Keywords: Dynamic EMC; MFF_n; First flush; Nonpoint source; Rainfall; Runoff

1. Introduction

In the administration of water quality management policies, Korea has recently focused on the treatment of point source pollutants such as common sewage and factory wastewater. Though such treatments have seen considerable progress, there have been limitations regarding the improvement of the quality of river water [1]. This is presumed to be a result of pollutants of an unspecified pollution source (known as non-point sources) rather than a result of the negligent management of point sources [2].

Non-point source pollutants generated at non-point sources, as unspecified pollutants created from various types of land use, are affected by rainwater and are discharged with ground surface runoff during rainfall events. In addition, because the management and treatment of these sources are not straightforward, they are often allowed to flow directly into rivers or lakes with no specific treatment, thus affecting the water quality of water supply sources. In particular, runoff pollution loads are much higher than those of sewage treatment plants [3–5]. To cope with the negative effects of such non-point sources, recently there is massive emerging interest in environmental damage of nearby water systems and soil by non-point sources created during rainfall events. Moreover, the need for management at the government level has been demanded.

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In particular, non-point source pollutants discharged from city areas have high concentrations of detrimental substances compared to other types, containing toxic substances such as various heavy metals as well as organic matter and nutrient salts. Specifically, the increase in the number of impermeable areas in a city area, occurring due to urbanization, causes the discharge of a large amount of pollutants upon the first flush. Therefore, the treatment of such pollutants has been difficult [6,7].

Given these circumstances, this study analyzed the discharge tendencies of non-point source pollutants by monitoring an urban residential area and a transportation land-use area, while at the same time determining the first flush criteria using the MFF_n and EMC (dynamic EMC) methods. These types of survey results may be useful for those who seek to establish best management practices (BMPs) for non-point source pollutants, specifically when determining an optimal management method for non-point source pollutants.

2. Experimental Methods

2.1. Monitoring location and method

In this study, 25 monitoring activities were undertaken from June of 2006 to October of 2009. Specifically, seven sessions in a residential area of the city of Guri in Gyeonggi province, Korea, and 18 sessions on a bridge in the city of Yongin in Gyeonggi province, Korea were conducted. Fig. 1 shows the monitored locations. In these locations, rain water pipes are located within Jangja Pond Park in Guri city and the aforementioned bridges are located in Unhak dong (neighborhood) in Yongin city. Table 1 displays the characteristics of the monitored locations. Essentially, the monitored locations were an urban residential area and a transportation land-use area, with respective basin areas of 223,230 and 3200 m^2. Regarding the residential area, 83% of this area overall was classified as impermeable, whereas in the case of the transportation land-use area, the entire areaways an impermeable area. Concerning the sample collection method, monitoring preparation involved waiting in the field before a rainfall event, and to measure the flow rate, a direct measuring method was used. This method gauges the amount of discharged water as collected within a certain timeframe. Sample collections were done at 5–30 min intervals in the beginning of the runoff, and because the concentration curve varies depending on the amount of rainfall, turbidity was measured in the field and water was collected at 1–3 h intervals. The collected samples were transported immediately to a laboratory after the rainfall event and the experiment was conducted by classifying them according to their types and amounts of particle-phase substances, organic matter, and nutrient salts. Regarding the parameter measuring method, the analysis here was done in a manner equivalent to the Standard method [8].

2.2. Two methods of first flush calculation

2.2.1. Dynamic EMC calculation of runoff amounts

The pollutant concentration used when calculating the pollutant load discharged by rainfall is termed event mean concentration, that is, EMC. It is calculated using the monitoring results, as expressed by Eq. (1). The EMC

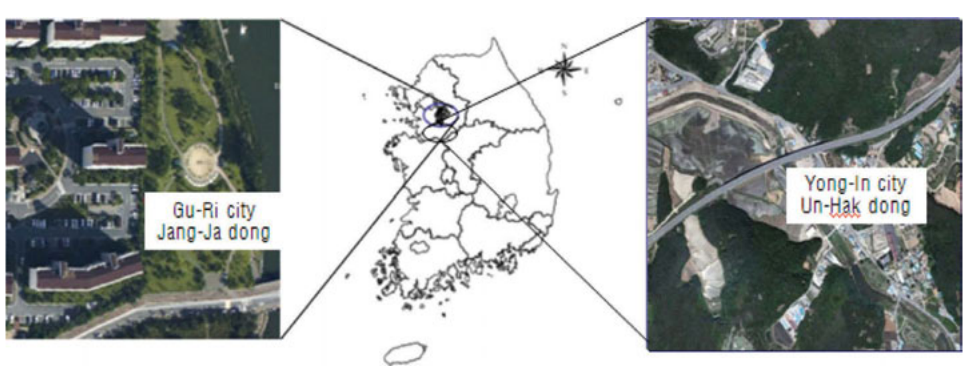

Fig. 1. Map showing the monitoring location.

Table 1
Characteristics of the monitoring location

Monitoring site	Location	Area (m^2)	Pavement type
Site 1	Guri city (Residential area)	223,230	83% impervious
Site 2	Young-In Giseongyo (transportation land-use area)	3200	100% impervious

can be calculated by dividing the cumulative amount of pollutants discharged during time "T", the entire rainfall duration time, byte entire runoff volume. This measure is crucial when calculating the average concentration of non-point sources. Here, $C(T)$ and $Q_{TRu}(T)$ indicate the concentration and the runoff rate of pollutants, respectively, for the rainfall duration time "T" [9]:

$$EMC = \frac{\int_0^T C(T) \cdot Q_{TRu}(T)dt}{\int_0^T Q_{TRu}(T)dt} \quad (1)$$

$$Dynamic\ EMC\ (mg/l) = \frac{\sum_{t=0}^{t=t} c(t) \cdot q_{run}(t)}{\sum_{t=0}^{t=t} q_{run}(t)} \quad (2)$$

However, the current method of using EMC has a shortcoming in that it cannot calculate the first flush because it shows the entire amount of pollutants discharged during a particular phase of rainfall. To calculate the first flush, a new calculation method is required, and to that end, here a method of using a dynamic form of the EMC, as exemplified by Eq. (2), is proposed. The dynamic EMC shows the EMC of the pollutants discharged for a rain duration time "*t*" [10]. In other words, EMC represents the average concentration of discharged pollutants for the entire rainfall duration, but the concept of dynamic EMC is that it measures the change in the concentration according to the duration time. With the use of the dynamic EMC, the first flush phenomena of urban residential areas and transportation land-use areas can be identified.

2.2.2. First flush ratio

The first flush ratio can be expressed based on the cumulative rainfall amount and rainfall duration with each specific water quality parameter with the use of the Mass-First-Flush Ratio (MFF_n), thus constituting the initial rainfall criteria [11]. The MFF_n can be calculated with reference to the discharged pollutant load amount, which varies widely depending on the discharge duration, the rain discharge rate, and the pollutant discharge rate at a certain time point, as expressed by Eq. (3):

$$MFF_n = \frac{\frac{\int_0^{T_1} C(t)q(t)dt}{M}}{\frac{\int_0^{T_1} q(t)dt}{V}} \quad (3)$$

Here, *n* indicates the discharge capacity at a certain time point during a discharge event over the total discharging capacity. It ranges from 0 to 100%. In addition, $q(t)$ and $c(t)$ are respectively the discharged amount at the cumulative discharge time "*t*" and the runoff concentration of the pollutants, while *M* and *V* indicate respectively the entire discharged pollutant load amount and the entire runoff flow rate volume [12]. In this paper, the first flush criteria were selected based on MFF_{20}, proposed by Deletic and Mahsimivic (1998) and Ma et al. (2002), when MFF_n was used among the two methods of selecting the first flush criteria. Subsequently, the criterion for the period until the concentration is stabilized with the use of the dynamic EMC method was selected.

3. Results and discussion

3.1. Overview of rainfall events

Table 2 shows the results of 25 monitoring events for rainfall events at the intended monitored location, including data such as the event date, the number of

Table 2
Event table for monitored events

Site	Event date	ADD[1] (d)	Total rainfall (mm)	Rainfall duration (h)	Avg. rainfall intensity (mm h^{-1})
Site 1	08-08-22	3.0	77.5	22.5	3.44
	08-10-23	27.0	6.0	7.5	0.80
	08-11-15	6.0	6.0	3.5	1.71
	09-05-11	8.0	21.0	17.5	1.20
	09-05-16	3.0	20.5	23.0	0.89
	09-08-11	3.0	127.5	28.0	4.55
	09-10-31	7.0	17.5	6.0	2.92
Site 2	06-06-22	5.0	7.5	5.6	1.35
	06-06-29	2.0	13.5	6.2	2.19
	06-08-17	18.0	6.5	3.0	2.15
	06-09-05	8.0	11.0	4.2	2.62
	06-10-22	45.0	6.0	5.0	1.20
	07-03-04	1.2	33.5	11.4	2.95
	07-04-30	9.0	16.5	10.5	1.57
	07-05-17	4.0	60.5	11.2	5.40
	07-05-28	6.0	48.0	9.9	4.86
	07-06-28	2.0	6.0	3.9	1.55
	07-07-19	1.9	49.5	7.0	7.07
	08-03-22	9.0	22.5	7.0	3.21
	08-05-28	7.0	41.0	8.0	5.13
	08-06-02	5.0	28.5	8.0	3.56
	08-06-28	7.0	5.0	0.65	7.69
	08-07-02	3.0	15.5	8.8	1.76
	08-07-19	8.0	72.0	12.0	6.00
	08-07-24	2.0	149.5	16.7	8.98

[1]ADD: Antecedent Dry Days.

antecedent dry days (ADD), the total rainfall, and the rainfall duration. Regarding the ADDs of the monitored area, for the residential areas the value ranged from 3 to 27 d, and in the case of transportation area, it ranged from 1.2 to 45 d. Regarding the total rainfall amount, the value ranged from 6 to 127.5 mm in the case of the residential area and 5–149.5 mm in the case of the transportation land-use area; the average rainfall intensity ranges were 0.80–4.55 mm for the residential area and 1.20–8.98 mm for the transportation land-use area.

3.2. Non-point pollution source discharging characteristics of the subjected watershed

To clarify the discharge characteristics of the non-point source pollutants by rainfall event, the water quality and discharged amounts were surveyed in 25 sessions. Figs. 2 and 3 show the characteristics of the non-point source pollutants with the use of the cumulative pollution load ratio. The method of expressing the cumulative pollution load amount curve was such that the ratio of the runoff flow rate over the total runoff flow rate measured with the rainfall duration during the rainfall period was taken as the "x" axis, while the ratio of the pollution load over the total pollution load for the applicable runoff flow rate was taken as the "y" axis. A slope of the graph greater than 1 indicates that the pollution load was high for a rainfall runoff amount, indicating that the first flush phenomenon occurs. If the slope is less than 1, the pollution load was low for the rainfall runoff amount, implying that the first flush phenomenon was interpreted as negligible [1,2,4,9,10,12–16].

As a result of the analysis with the use of the cumulative pollution load amount, both areas showed a slope that was greater than 1 in most of the events, with TSS as the particle substance in the rainfall runoff water, COD as the organic matter, and TN as the nutrition salt, indicating a clear occurrence of the first flush phenomena. Both areas showed the first flush phenomenon in the sequential order of TSS > COD > TN among the pollutant parameters. In a comparison of the residential area and the transportation land-use area, the 100% impermeable areas showed more first flush phenomena than the transportation land-use area. Among the pollution parameters, the TN parameter of the residential area mostly showed the first flush phenomenon, but the degrees were negligible. This most likely arose because the TN parameter of residential area rainfall runoff typically contains more NO_3-N as a dissolved substance than particle substances. Hence, the slope tended to be close to 1.

3.3. First flush ratio

With the use of the MFF ratio, the indicator of the first flush ratio, the values of MFF_n according to each

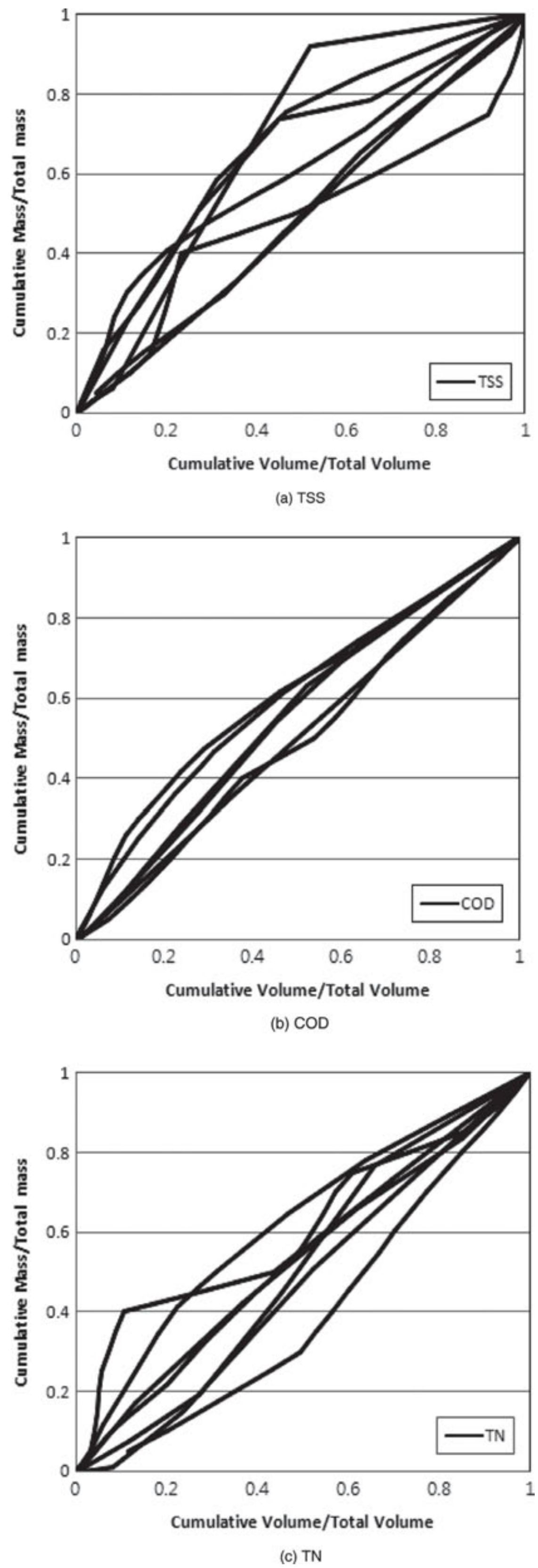

Fig. 2. Discharge characteristics of the non-point pollutants in the residential area.

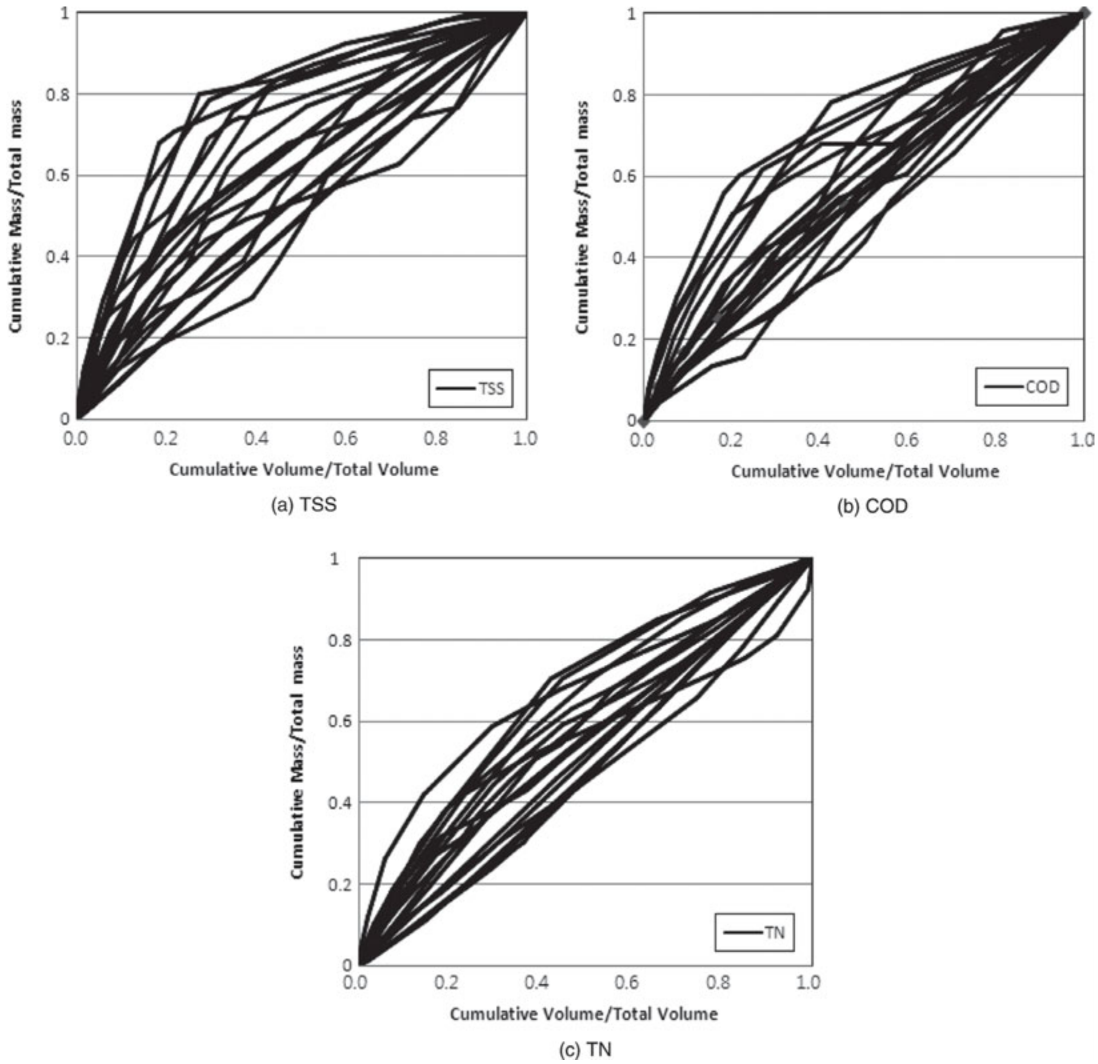

Fig. 3. Discharge characteristics of the non-point pollutants in the transportation land-use area (a) Events 4 and 6 in the residential area, (b) events 7 and 8 in the transportation land-use area.

water quality parameter of Event 4 in the residential area and Event 13 in the transportation land-use area were determined. Tables 3 and 4 show the MFF_n values calculated for each water quality parameter in Event 4 in the residential area and Event 13 of the transportation land-use area, which range from 10% to 99%. The results indicate that with the discharge time, all MFF_n values equal to existing research results tend to decrease with reference to MFF_{10}, which again indicates that among the events in the residential area and the transportation

Table 3
MFF_n for stormwater event no. 4 for various quality parameters (residential area)

Constituents	MFF_{10}	MFF_{20}	MFF_{30}	MFF_{40}	MFF_{60}	MFF_{90}
TSS	2.12	1.85	1.87	1.80	1.38	1.07
COD	2.00	1.65	1.50	1.40	1.19	1.03
TN	1.92	1.88	1.64	1.48	1.26	1.04
Mean	2.01	1.79	1.67	1.56	1.28	1.05
Elapsed time (min)	77	147	205	266	403	596
Cumulative rainfall depth (mm)	4.5	6.0	7.0	8.0	10.0	13.0

Note: Date: 09/05/11, rainfall: 21 mm, duration: 11.2 h.

Table 4
MFF_n for stormwater event no. 13 for various quality parameters (transportation land-use area)

Constituents	MFF_{10}	MFF_{20}	MFF_{30}	MFF_{40}	MFF_{60}	MFF_{90}
TSS	2.61	1.95	1.68	1.56	1.29	1.06
COD	2.83	2.41	2.07	1.80	1.34	1.04
TN	1.08	0.98	0.98	1.00	1.02	1.01
Mean	2.17	1.78	1.56	1.45	1.22	1.04
Elapsed time (min)	30	41	55	72	110	170
Cumulative rainfall depth (mm)	8.0	9.5	16.0	24.0	29.5	40.5

Note: Date: 08/05/28, rainfall: 41.0 mm, duration: 8.0 h.

Table 5
MFF_n for a stormwater events for various quality parameters in the residential area

Event no.	MFF_n	TSS	COD	TN	Elapsed time (min)	Cumulative rainfall Depth (mm)
Event 1	MFF_{20}	0.72	0.99	0.45	180	3.5
Event 2	MFF_{20}	1.87	1.14	0.66	47	5.5
Event 3	MFF_{20}	0.88	1.06	1.26	120	5.5
Event 4	MFF_{20}	1.85	1.65	1.88	150	6.0
Event 5	MFF_{20}	2.05	1.88	1.05	180	8.5
Event 6	MFF_{20}	0.91	1.06	0.35	100	7.5
Event 7	MFF_{20}	1.05	1.68	1.75	270	11.0
Minimum		0.72	0.99	0.35	47	3.5
Maximum		2.05	1.88	1.88	270	11.0
Median		1.05	1.14	1.05	150.0	6.0
Mean		1.33	1.35	1.06	149.7	6.8
Standard dev.		0.56	0.37	0.61	71.4	2.5

land-use area, the most efficient first flush selection time point can be considered as MFF_{10}, which is presumably similar to an existing result [15]. As a result of calculating the time point for MFF_{20} from the findings of existing research, the cumulative times were 147 min in the case of the residential area and 41 min for the transportation land-use area; the cumulative rainfalls were 6.0 mm for the residential area and 9.5 mm for the transportation land-use area.

Table 5 shows the values of MFF_{20}, the first flush time point calculated for each water quality parameter for seven events conducted in the residential area. For the first event, the highest value was at MFF_{30}, while in the case of the second through seventh events, the value was highest at MFF_{10}, after which it tended to decrease. At MFF_{20}, the average value among the entire amount of discharged load was 26.6% for TSS, 27.0% for COD, and 21.0% in the case of TN. At MFF_{20} for each event, the median cumulative rainfall value was 6.8 mm, while the value for the cumulative discharge time was 149.7 min.

Table 6 shows the MFF_n values for the highest first flush selection time point calculated for each water quality parameter during Event 18 conducted in the transportation land-use area. In the case of the 12th event, the highest value was at MFF_{20}, whereas for other events, the value was highest at MFF_{10}, after which it tended to decrease. At MFF_{20}, the average value among the entire load discharge amount was 39.6% for TSS while it was 31.6% for COD. At MFF_{20} for 18 events, the calculated cumulative rainfall amount was 6.2 mm on average and the cumulative discharge time was 70.4 min (median value), confirming that the average values were greater than those for all of the pollutants in the transportation land-use area and that the cumulative rainfall and cumulative time both were less than those for the residential area. These findings indicate that even in the same urban

Table 6
MFF_n for a stormwater events for various quality parameters for the transportation land-use area

Event no.	MFF_n	TSS	COD	TN	Elapsed time (min)	Cumulative rainfall Depth (mm)
Event 1	MFF_{20}	2.09	1.41	1.36	28	6.0
Event 2	MFF_{20}	2.74	0.76	0.90	11	2.0
Event 3	MFF_{20}	1.92	2.07	0.80	7	2.5
Event 4	MFF_{20}	2.96	1.57	1.74	40	2.5
Event 5	MFF_{20}	1.30	1.17	0.79	65	1.5
Event 6	MFF_{20}	0.37	0.75	1.41	260	8.0
Event 7	MFF_{20}	2.24	2.55	1.98	120	5.0
Event 8	MFF_{20}	3.28	2.79	1.94	60	8.0
Event 9	MFF_{20}	3.30	1.41	2.44	80	9.5
Event 10	MFF_{20}	1.33	1.27	1.10	7	5.5
Event 11	MFF_{20}	1.50	1.89	1.74	120	15.0
Event 12	MFF_{20}	1.79	1.76	1.66	120	5.5
Event 13	MFF_{20}	1.95	2.41	0.98	41	9.5
Event 14	MFF_{20}	2.24	2.31	2.01	72	3.0
Event 15	MFF_{20}	1.60	1.33	0.86	5	3.5
Event 16	MFF_{20}	1.71	1.27	1.36	11	1.5
Event 17	MFF_{20}	2.58	1.04	1.57	55	10.5
Event 18	MFF_{20}	0.65	0.62	0.52	165	12.5
Minimum		0.37	0.62	0.52	5.0	1.5
Maximum		3.30	2.79	2.44	260	15.0
Median		1.94	1.41	1.39	57.5	5.5
Mean		1.98	1.58	1.40	70.4	6.2
Standard dev.		0.81	0.64	0.53	66.7	4.0

area, the discharged load occurs over a shorter length of time with less rainfall in the transportation land-use area, a 100% paved area, compared to in residential area.

3.4. Calculation of the first flush using the dynamic EMC

Fig. 4 shows the dynamic EMCs of Events 4 and 6 for the residential area and Events 7 and 8 for the transportation land-use area. Regarding the dynamic EMC for Event 4 in the residential area, as soon as the discharge of TSS, COD and TN began, the dynamic EMC showed a dramatic decrease within 240 min. For Event 6, the dynamic EMC tended to decrease dramatically within 240 min as regards TSS and COD, while this occurred within 160 min for TN. As for the dynamic EMC of Events 7 and 8, conducted in the transportation land-use area, all of the pollutant parameters tended to move together; the dynamic EMC showed a dramatic decrease within 160 min during Event 7 and within 140 min for Event 8. Considering such results, the cumulative rainfall and rainfall duration time as measured by the pollutant parameters were identified. Tables 7 and 8 show their statistical values.

As a result of identifying the first flush criteria with reference to the rainfall duration time using statistical techniques, the first flush occurred 80–320 min (mean value 194.29 min) after the start of rainfall in the residential area, and 30–240 min (mean value 113.89 min) after the start of rainfall in the transportation land-use area. As a result of identifying the first flush criteria with reference to the cumulative rainfall, the first flush was measured as 5.5–10.0 mm (mean value 7.57 mm) after the start of rainfall in the residential area, and as 2.5–13.5 mm (mean value 7.53 mm) after the start of rainfall in the transportation land-use area.

As a result of calculating the first flush criteria using the dynamic EMC, despite the difference in the land-use

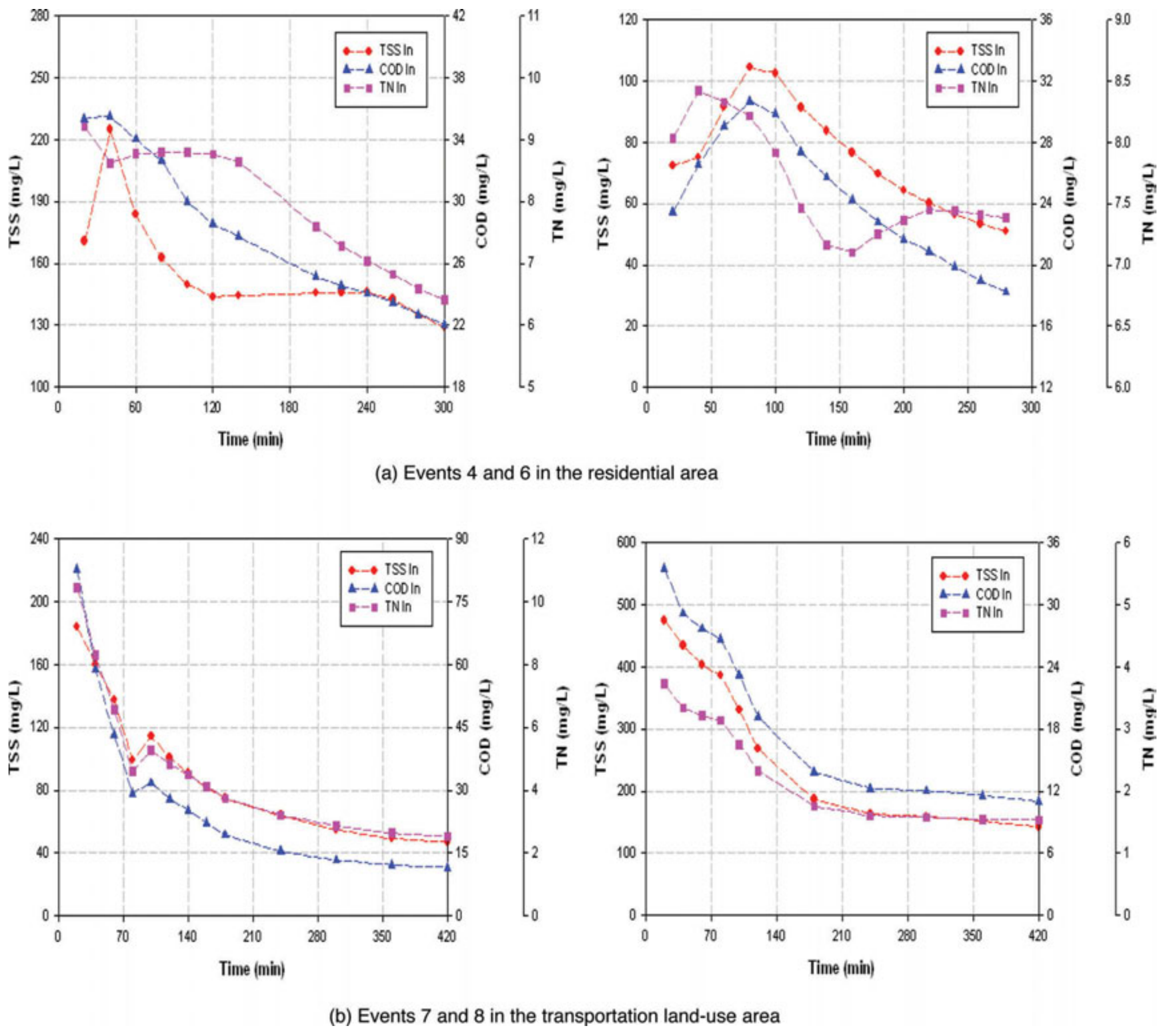

Fig. 4. Dynamic EMCs.

Table 7
Statistical summary for the residential area

Event no.	Elapsed time (min)	Cumulative rainfall depth (mm)
Event 1	320	5.5
Event 2	100	5.5
Event 3	80	6.5
Event 4	240	8.0
Event 5	240	6.0
Event 6	240	12.0
Event 7	140	9.5
Minimum	80	5.5
Maximum	320	10.0
Median	240	6.5
Mean	194.29	7.57
Standard dev.	88.48	2.44

rates, the first flush result values for the residential area and the transportation land-use area were similar; such results indicate that the first flush ends at the representative EMC of the rain event when the dynamic EMC values for the two areas become similar cumulative rainfall values. Such a high value, which is different from the optimum MFF_n value, is judged to have arisen due to the high discharge at the early stage of rainfall in the transportation land-use area with a high pavement rate. Regarding the dynamic EMC, because the time point until the dynamic EMC decreased dramatically is used as the criterion, the two areas were found to indicate the same results. The transportation land-use area with a high pavement rate showed a high load at an early stage of rainfall, but the cumulative rainfall of the time point dynamic EMC, which decreased dramatically, showed a value similar to that of the residential area.

Table 8
Statistical summary for the transportation land-use area

Event no.	Elapsed time (min)	Cumulative rainfall depth (mm)
Event 1	80	6.5
Event 2	40	2.5
Event 3	80	5.0
Event 4	140	6.0
Event 5	100	3.5
Event 6	240	7.0
Event 7	160	5.5
Event 8	140	10.0
Event 9	120	10.5
Event 10	80	6.0
Event 11	60	12.0
Event 12	240	9.0
Event 13	80	9.0
Event 14	80	11.5
Event 15	30	6.0
Event 16	180	3.5
Event 17	80	13.5
Event 18	120	8.5
Minimum	30	2.5
Maximum	240	13.5
Median	90.0	6.8
Mean	113.89	7.53
Standard dev.	60.50	3.15

4. Conclusions

- This study analyzed the EMC of non-point source pollutants for various rainfall events in an urban residential area and in a transportation land-use area and examined the discharge characteristics of the non-point sources pollutants. The following results were deduced:
- As a result of using the ratio of the cumulative pollution loads of non-point source pollutants in an urban residential area and in a transportation land-use area, it was clearly found that in both areas, TSS, denoting the particle substance of rain runoff, COD as organic matter, and TN as nutrient salt showed the first flush phenomenon. Regarding the effects according to the parameters, TSS showed the highest first flush effect, where as for the effects according to area, the transportation land-use area showed a higher ratio of the first flush effect.
- The finding of the first flush criteria of MFF_n, the time point of the highest efficiency, selected with the use of the MFF ratio indicating the first flush ratio, was MFF_{10} for both the residential area and the transportation land-use area. In the case of the residential area with-MFF20, the first flush criterion, the cumulative time was calculated as 149.7 min and the cumulative rainfall was 6.8 mm. In the case of the transportation land-use area, the cumulative time was 70.4 min, which is faster than that of the residential area. The cumulative rainfall in this area was calculated as 6.2 mm.
- As a result of analyzing the first flush criteria of the dynamic EMC with the use of statistical techniques, the criteria with reference to the rainfall duration were 194.29 min in the case of the residential area and 113.89 min in the case of the transportation land-use area. As a result of identifying the first flush criteria with reference to the cumulative rainfall amount, the criteria were 7.53 mm for the residential area and 7.57 mm for the transportation land-use area.
- Such first flush criteria were shown not to be compliant with both MFF_{20}, the criterion currently used to process 5 mm or more of rainfall for BMPs by the Korean Ministry of Environment, and the resulting value when using the dynamic EMC. In the United States, both criteria comply with the one-inch law, which is used in most of the states, but in the case of the urban area non-point processing criteria, the criteria resulted in an excessively high calculation. It is judged that the results of the present study will eventually be used as important data for calculating the first flush processing criteria.

Acknowledgments

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