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Analysis of efficiencies of runoff reduction and pollutant removal for subdividing design volume calculation in permeable pavement

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ABSTRACT

In this study, the inflow/outflow event mean concentration (EMC) and pollutant removal efficiencies were analyzed. Based on the results of the analysis, a study was conducted on the necessity of estimating the appropriate design volume according to the characteristics of the permeable pavement. Therefore, this study analyses EMC and summation of loads (SOL) reduction efficiencies based on the monitoring results pertaining to 3 y. Analysis of pollutant removal efficiency and runoff reduction efficiency of filter-type permeable and crevice-type permeable pavements showed that biochemical oxygen demand, total organic carbon, and total suspended solid values increased from 2016 to 2018 for crevice-type permeable pavement. On the other hand, the filter-type permeable pavement was found to reduce the efficiency. In the case of crevice-type permeable pavement, the proper design was based on the storage, and the reduction efficiency increased due to this, while the filter-type permeable pavement is a facility that treats non-point pollutants by continual filtering. Therefore, it should be designed as water quality flow (WQ_F), instead of erroneously designing it as water quality volume (WQ_V). The obtained results are considered to be an important derivation factor when calculating the design capacity according to the type and characteristics of low impact development (LID) facilities.

Keywords: LID (low impact development); Permeable pavement; Design volume; Crevice-type pavement; Filter-type pavement; Maintenance

1. Introduction

Increase in impermeable area due to industrialization and urbanization causes problems such as increased stream runoff and reduced natural penetration, resulting in river dryness and river pollution caused by non-point sources [1–5]. Seoul has undergone rapid urbanization since the 1960s, with approximately 48% of surfaces being classified as impervious in 2015 causing problems such as urban flooding, groundwater problems, and non-point pollution spills [6]. In order to solve these problems, studies on facilities for treating pollutants contained in the initial runoff and non-point pollution in residential and industrial complexes are being actively conducted [7]. In addition, many studies and field applications have been carried out in developed countries such as the US and Europe to reduce the distortion in water circulation and non-point pollutant spills due to urbanization and the construction of development projects [8]. In Korea, through comprehensive first and second measures have established an institutional basis and measures for non-point pollution management at the source, and has been actively promoting it every year. As part of this, we published the installation, management, and operation manual for non-point pollution reduction facilities in 2008, and a revised edition in 2014 to reflect technological changes and convenience of maintenance after the introduction of the manual [9–11]. This effort is aimed at restoring and repairing the natural water circulation system [12,13].

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For existing studies and manuals, the basis for calculating the design volume was divided into water quality volume (WQ_V) and water quality flow (WQ_F) considering the basic structure of low impact development (LID) facilities to provide factors for optimal design. WQ_V is the volume of a facility that stores and treats the rainfall runoff initially, and WQ_F is the volume of a type of facility that continuously processes rainfall runoff. However, this analysis does not take into account the detailed structure and working of the facility. Although the processing mechanism and materials differ, they belong to a large category and use a common design volume estimation criteria. This can lead to errors in proper design. Therefore, this study analyzed the results obtained from 3 y of monitoring permeable pavements which were subjected to different treatments.

2. Materials and methods

2.1. Monitoring location and characteristics

The LID facility where this study was conducted is located in Wansan-gu, Jeonju-si, Jeollabuk-do, Korea, as shown in Fig. 1. The applied LID facility is a permeable pavement, of which there are several types, but this work selected and monitored crevice-type permeable pavements and filter-type permeable pavements. There are no separate drainage areas for the two test beds, and since rainfall is introduced directly into the facility, the area of the facility is 16 m², which is the drainage area of the facility. In addition, based on the area and design volume, the capacity of each facility was estimated to be 4.2 m². Table 1 summarizes the types and characteristics of permeable pavements used in this study.

2.2. Monitoring and EMC analysis method

Since the water quality analysis of the sample obtained through monitoring depends on the rainfall and rainfall duration, turbidity was continuously measured at the site to determine whether the sample was collected. Sampling was carried out at intervals of 5, 10, and 15 min with the peak flow rate as a starting point. In addition, the samples were analyzed by total suspended solids (TSS), biochemical oxygen demand (BOD), total organic carbon (TOC), total nitrogen (TN), and total phosphorus (TP) according to Standard Methods, 20th [14] and water pollution process test [15]. In this study, the event mean concentration (EMC) was used to characterize the non-point pollutant runoff. EMC calculates the total amount of pollutant mass during an event spilled over a timespan of T hours of total rainfall duration divided by the total runoff volume. It is depicted in Eq. (1):

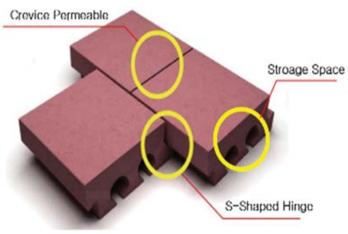
$$\text{EMC}(\text{mg/L}) = \frac{\text{Total amount of pollutant mass during an event}}{\text{Total runoff volume}} = \frac{\int_0^t C(t)\times Q(t)dt}{\int_0^t Q(t)dt} \tag{1}$$

2.3. Calculation method of reduction efficiency

In this study, the reduction efficiency of the LID facility was estimated by the summation of loads (SOL) method to estimate the reduction efficiency of the crevice-type permeable pavement and filter-type permeable

Fig. 1. Map showing the monitoring locations.

Table 1
Permeable pavement type and characteristics

Content	Permeable pavement	
	Filter	Crevice
Picture		
Runoff source	Park	Park
Catchment area (m^2)	16	16
Surface area (m^2)	16	16
Length (m)	4	4
CA/SA	1.0	1.0
Mechanism	Infiltration Sedimentation Filtration Storage	Infiltration Sedimentation Filtration
Design volume	WQ_V	WQ_V

pavement. The SOL method is a method of dividing the total amount of pollutant load during an event by the total inflow pollutant load [16]. The method for calculating the reduction efficiency is shown in Eq. (2):

$$\text{SOL}(\%) = \frac{\text{Total amount of pollutant load during an event}}{\text{Total inflow pollutant load}} = \frac{\sum_{i=1}^{N} \text{inflow pollutant load} - \sum_{i=1}^{N} \text{outflow pollutant load}}{\sum_{i=1}^{N} \text{inflow pollutant load}} \quad (2)$$

3. Results and discussion

3.1. Monitored rainfall

The results obtained from monitoring rainfall events in Wansan-gu, Jeonju-si, which is the monitoring target of this study, are shown in Table 2 and Fig. 2. Rainfall monitoring was carried out using both artificial and real rainfall and the rainfall intensity under various conditions was measured. Data pertaining to filter-type permeable and crevice-type permeable pavements were based on 3 y of monitoring results. The filter-type permeable pavement was studied based on 19 rainfall events, and the crevice-type permeable pavement was studied based on 20 rainfall events. Antecedent dry days of filter-type permeable pavement is 2~19 d (Avg.: 7.8 d), rainfall is 31.9~593.5 mm (Avg.: 121.1 mm), rainfall intensity is 1.4~172.0 mm/h (Avg.: 38.8 mm/h). Antecedent dry day of crevice-type permeable pavement is 2~19 d (Avg.: 7.4 d), rainfall is 47.5~593.5 mm (Avg.: 221.0 mm), rainfall intensity is 1.4~521.0 mm/h (Avg.: 92.9 mm/h). As such, various rainfall events were monitored. As for the runoff reduction efficiency of the permeable pavement, the filter-type permeation pavement shows an average of 62.8% of the runoff reduction efficiency, and the crevice-type permeation pavement shows a runoff reduction efficiency of 76.1%.

3.2. Analysis of inflow/outflow EMC and pollutant removal efficiency

Figs. 3 and 4 show the EMC concentration values by rainfall events of filter-type permeable and crevice-type permeable pavements. Based on rainfall monitoring data, the average inflow EMC concentration of the filter-type permeable pavement is TSS 53.7~1,111.1 mg/L (Avg.: 422.1 mg/L), BOD 2.4~29.2 mg/L (Avg.: 11.6 mg/L), TOC 2.6~23.4 mg/L (Avg.: 10.2 mg/L), TN 1.5~14.0 mg/L (Avg.: 6.6 mg/L), TP 0.3~2.7 mg/L (Avg.: 1.2 mg/L). Average outflow EMC concentrations range from TSS 6.2 to 49.0 mg/L (Avg.: 19.3 mg/L), BOD 0.3–6.8 mg/L (Avg.: 2.6 mg/L), TOC 0.1–9.7 mg/L (Avg.: 3.0 mg/L), TN 0.2–2.2 mg/L (Avg.: 1.4 mg/L), TP 0.02–0.12 mg/L (Avg.: 0.05 mg/L). In the case of the filter-type permeable pavement, the average inflow/outflow EMC showed the largest difference in the TP reduction value. The reduction of TP was found to be the best for the filter type. In the case of TOC, the inflow/outflow EMC showed the smallest difference.

The inflow EMC concentration of the crevice-type permeable pavement is TSS 55.6~463.0 mg/L (Avg.: 209.4 mg/L), BOD 2.1~21.2 mg/L (Avg.: 10.7 mg/L), TOC 2.5~21.2 mg/L (Avg.: 9.6 mg/L), TN 1.8~16.6 mg/L (Avg.: 6.3 mg/L), TP 0.3~3.5 mg/L (Avg.: 1.2 mg/L). Outflow EMC concentrations

Table 2
Statistical summary of monitored rainfall

Permeable Pavement	Minimum		Maximum		Average		SD	
	Filter	Crevice	Filter	Crevice	Filter	Crevice	Filter	Crevice
ADD (d)	2.0	2.0	19.0	19.0	7.8	7.4	5.5	5.1
Rainfall (mm)	31.9	47.5	593.5	593.5	121.1	221.0	122.0	154.1
Average rainfall intensity (mm/h)	1.4	1.4	172.0	521.0	38.8	92.9	44.6	135.0
Runoff reduction (%)	17.4	29.6	100.0	100.0	62.8	76.1	20.1	21.4

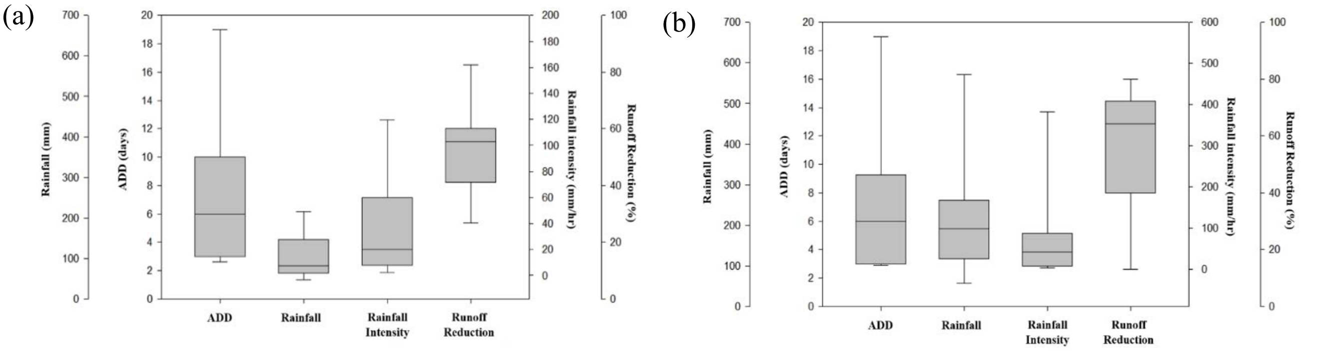


Fig. 2. Rainfall condition and runoff reduction efficiency by facility: (a) permeable pavement – filter and (b) permeable pavement – crevice.

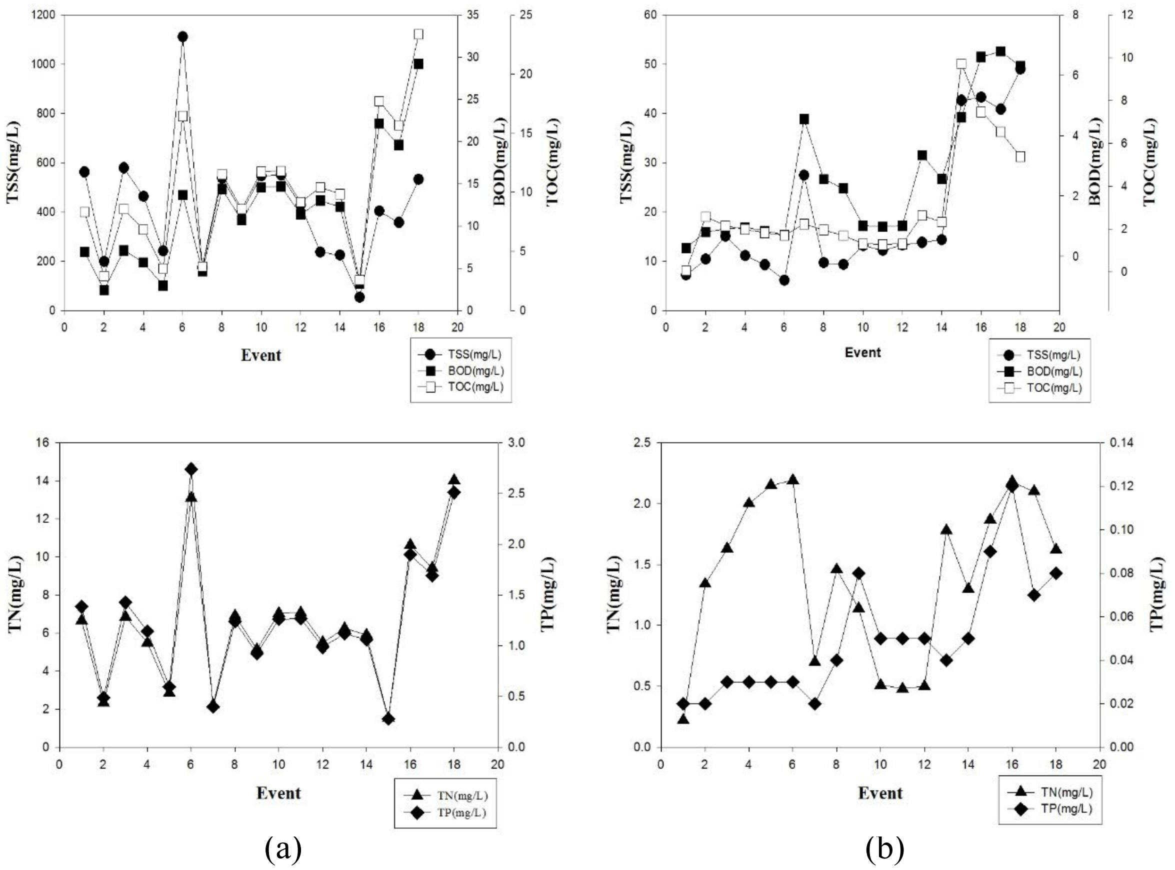


Fig. 3. Inflow/outflow EMC of filter-type permeable pavement: (a) inflow and (b) outflow.

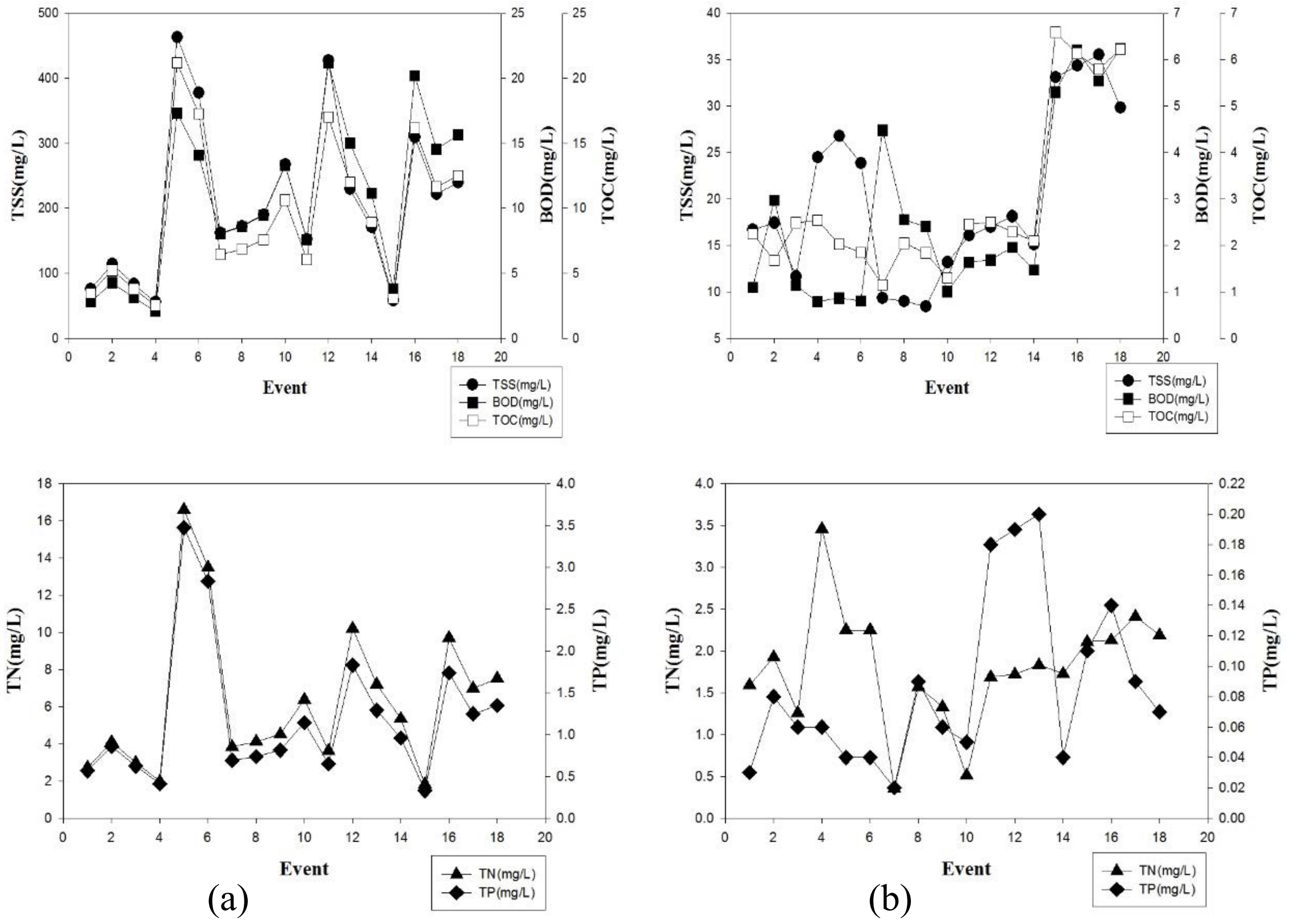


Fig. 4. Inflow/outflow EMC of crevice-type permeable pavement: (a) inflow and (b) outflow.

are TSS 8.4–35.5 mg/L (Avg.: 20.0 mg/L), BOD 0.8–6.2 mg/L (Avg.: 2.7 mg/L), TOC 1.2–6.6 mg/L (Avg.: 3.0 mg/L), TN 0.4–3.5 mg/L (Avg.: 1.8 mg/L), TP 0.02–0.20 mg/L (Avg.: 0.09 mg/L). In the case of crevice-type permeable pavement, the reductions were all lower than the filter-type permeable pavement. As a result of the inflow/outflow EMC analysis of the crevice-type permeable pavement, the TOC showed the smallest difference.

Fig. 5 depicts the pollutant removal efficiency by using the SOL method for TSS, BOD, TOC, TN, and TP of filter-type permeable and crevice-type permeable pavements. The pollutant removal efficiency of filter-type permeable pavement is TSS 68.6%~100.0% (Avg.: 90.0%), BOD 65.0%~100.0% (Avg.: 86.9%), TOC 88.1%~100.0% (Avg.: 97.9%), TN 72.0%~100.0% (Avg.: 89.0%), TP 94.8%~100% (Avg.: 98.1%), and the efficiency of pollutant removal in crevice-type permeable pavement is TSS 82.2%~100.0% (Avg.: 93.6%), BOD 72.2%~100.0% (Avg.: 90.4%), TOC 81.4%~100.0% (Avg.: 96.5%),TN 69.4%~100.0% (Avg.: 90.4%), TP 92.3%~100.0% (Avg.: 98.0%). Analysis of pollutant removal efficiency using SOL method showed that the crevice-type permeable pavement showed higher efficiency with TSS and BOD values. The TOC value showed higher efficiency with the filter-type permeable pavement. TN and TP values showed similar reduction efficiencies.

3.3. Annual removal efficiency analysis

Analysis of the rainfall runoff reduction efficiency shows that, in the case of crevice-type pavements, the average value rises to 60.7%, 84.7%, and 88.1%. In the case of the filter-type, 60.3%, 55.0%, and 68.3% did not show a clear tendency, but the reduction efficiency was lower than that of the crevice-type. The pollutant removal efficiency of organic matter (BOD, TOC) in crevice-type permeable pavement was 93.8% and 90.9% in 2016–2018, and 91.2% and 98.0% for nutrients (TN, TP), SS was 96.9%. The pollutant removal efficiency of organic matters (BOD, TOC) in filter-type permeable pavement was 88.9% and 85.9% in 2016–2018, and 88.5% and 97.9% in nutrients (TN, TP), SS was 97.8%. Also, in Fig. 6, in the case of crevice-type permeable pavement, the removal efficiency shows a tendency to increase based on the 2016–2018 average value. In the case of organic matters (BOD, TOC) and SS, the filter-type permeable pavement tends to decrease by the average value. In addition, it can be seen that the filter-type permeable pavement has a lower overall average removal efficiency overall in BOD, TOC, TN, and TP, except for SS, compared to the crevice-type permeable pavement. In the case of the permeable pavement, both existing studies and published manuals are designed as WQ_V. However, this is

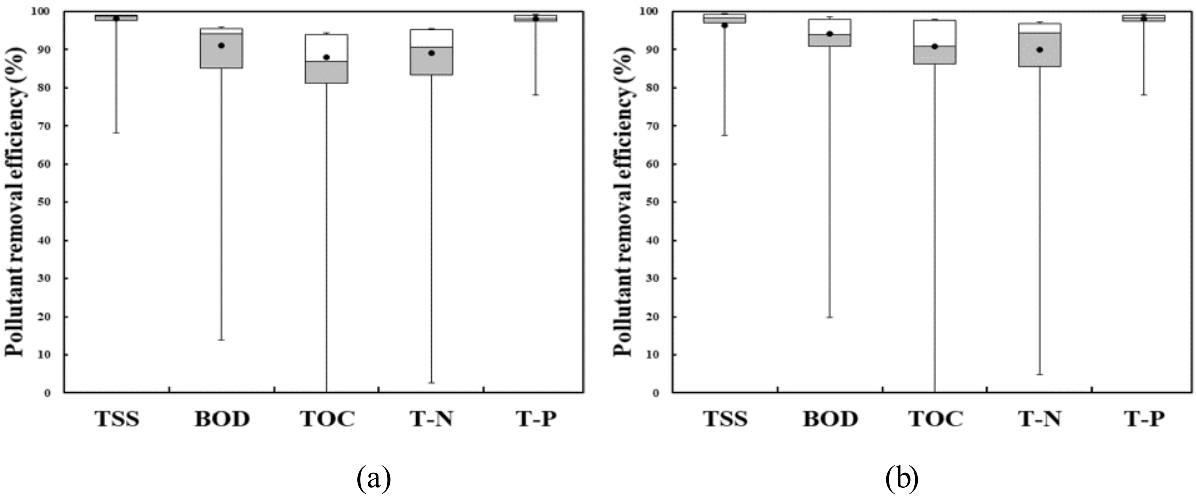


Fig. 5. Pollutant removal efficiency analysis: (a) permeable pavement – filter and (b) permeable pavement – crevice.

a method of estimating the design volume that does not consider the detailed structure and processing of each type of permeable pavement. In the case of crevice-type permeable pavements, there is a storage space in which rainfall runoff can be initially stored. Therefore, it can be seen that the WQ_V was designed properly when calculating the design volume. Filter-type permeable pavement is a device-type facility, which has no separate storage space and must be designed with WQ_F as a facility for continuous filtration of rainfall runoff. However, it was classified as a permeable pavement and designed as a WQ_V. As a result, the design volume was under-estimated and the efficiency of the filter-type permeable pavement, such as blockage of the air gap during filtration, tended to decrease every year. On the other hand, in the case of a crevice-type permeable pavement, it can be seen that the efficiency is maintained. The following results indicate that pavements should be based on their types and characteristics when calculating the design volume of LID facilities.

4. Conclusions

In this study, the inflow/outflow EMC and pollutant removal efficiencies were analyzed. Based on the results of the analysis, a study was conducted on the necessity of estimating the appropriate design volume according to the characteristics of the permeable pavement. The results are as follows.

- The criteria for calculating the design volume of an LID facility are classified into WQ_V and WQ_F in consideration of the basic structure of the LID facility. However, in Korea, all of the permeable pavements in LID facilities are designed as WQ_V regardless of the characteristics of the permeable pavement. Therefore, a study on the necessity of calculating the appropriate design volume according to the characteristics of the permeable pavement was conducted.
- This study presents data values based on the results of 3 y of monitoring. The study was conducted based on 19 events for the filter-type permeable pavement and 20 events for the crevice-type permeable pavement. Rainfall monitoring was carried out using artificial rainfall and real rainfall in order to monitor various rainfall conditions.
- The inflow/outflow EMC of the filter-type permeable and crevice-type permeable pavements showed that the inflow EMC concentrations of the filter-type permeable pavement were TSS 422.1 mg/L, BOD 11.6 mg/L, and TOC 10.2 mg/L, TN 6.6 mg/L, and TP 1.2 mg/L outflow EMC concentrations were TSS 19.3 mg/L, BOD 2.6 mg/L, TOC 3.0 mg/L, TN 1.4 mg/L, and TP 0.05 mg/L, inflow EMC concentration of crevice-type permeable pavement is TSS 209.4 mg/L, BOD 10.7 mg/L, TOC 9.6 mg/L, TN 6.3 mg/L, and TP 1.2 mg/L outflow EMC concentration is TSS 20.0 mg/L, BOD 2.7 mg/L, TOC 3.0 mg/L, TN 1.8 mg/L, and TP 0.09 mg/L.
- Analysis of pollutant removal efficiency and runoff reduction efficiency of filter-type permeable and crevice-type permeable pavements showed that BOD, TOC, and TSS values increased from 2016 to 2018 for crevice-type permeable pavement. On the other hand, the filter-type permeable pavement was found to reduce the efficiency. In the case of crevice-type permeable pavement, the proper design was based on the storage, and the reduction efficiency increased due to this, while the filter-type permeable pavement is a facility that treats non-point pollutants by continual filtering. Therefore, it should be designed as WQ_F, instead of erroneously designing it as WQ_V. The obtained results are considered to be an important derivation factor when calculating the design capacity according to the type and characteristics of LID facilities.

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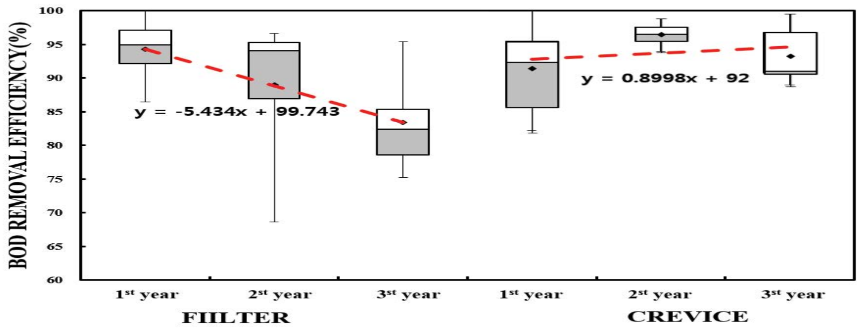
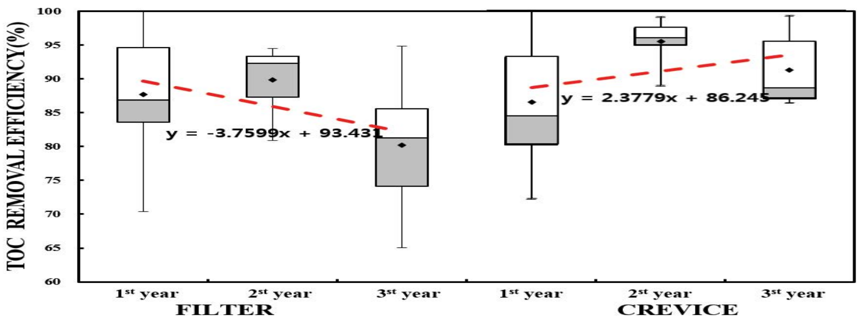
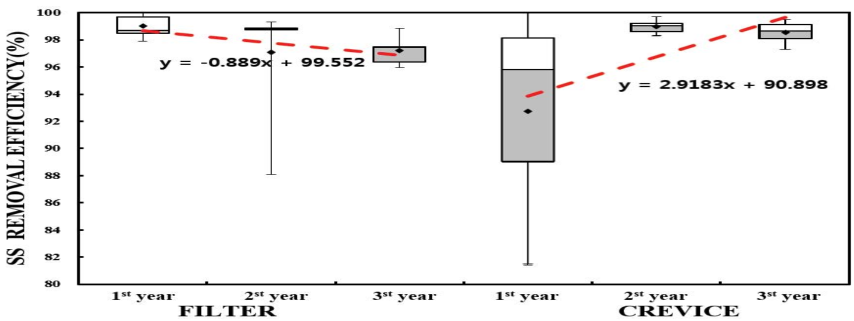


(a)



(b)



(c)

Fig. 6. Runoff and pollutants removal efficiency of monitored permeable pavement: (a) BOD removal efficiency, (b) TOC removal efficiency, and (c) SS removal efficiency.

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