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Assessment of suspended solid and particles removal efficiency for hybrid systems connecting a technical BMP device to low impact development technology

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ABSTRACT

The increase in impervious areas caused by urbanization causes the amount of surface rainfall-runoff and nonpoint source (NPS) pollutant discharge to also increase. This issue has sparked a growing interest in low impact development (LID) technology and NPS reduction technology. The objective of this study is to analyze the ability of a hybrid system to achieve both rainfall-runoff and NPS pollutant reduction simultaneously. The results indicate that this system is effective in reducing particulate matter with a relatively small particle size (less than 64 μm), which plays an important role in reducing NPS pollution. It is expected that a LID-based urban water cycle recovery policy could be established through further research on various hybrid system configuration methods and socioeconomic effect analysis.

Keywords: Stormwater runoff; Decentralized rainwater management system; Particle size distribution; Low impact development

1. Introduction

The increase both in the impervious surface due to urbanization and in concentrated rainfall due to climate change has made the management of nonpoint source (NPS) pollution more difficult [1,2]. Over the past decades, NPS pollution has been managed around centralized rainwater management systems (RMSs) such as structural best management practice (BMP) devices [3,4]. Such centralized RMSs have some problems, including increased maintenance costs due to aging and a decreased ability to reduce nonpoint pollution [5]. In addition, centralized RMSs cannot flexibly adapt to changes in rainfall patterns due to climate change and thus cannot effectively cope with urban flood damage [6]. To solve this problem, decentralized RMSs have been recently applied in the rainwater management field [7]. Decentralized RMSs have different names in different countries, such as low impact development (LID) and green infrastructure in the USA, decentralized urban design in Germany, water sensitive urban design in Australia, and sound water cycle on national planning in Japan [8], but the basic concepts are similar. These are to minimize stormwater discharge through natural infiltration at the point of occurrence of rainfall-runoff, restore distorted water circulation, and manage additional nonpoint pollutants. Decentralized RMSs can reduce the load on sewerage during rainfall, which can in turn reduce the occurrence of

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combined sewer overflows and the amount of nonpoint pollution [8,9]. Ultimately, this can help water quality management by reducing the inflow of contaminants that adversely affect river water quality.

When using the concept of a decentralized RMS, techniques such as permeable blocks, infiltration trenches, and so forth can be applied in urbanized areas [10,12]. As rainwater management facilities, these techniques, in addition to centralized facilities, may not improve water circulation and nonpoint pollution as much as intended if proper maintenance is not carried out. In the case of technologies for treating NPS pollution in roads or industrial parks during rainfall events, it is necessary to enhance the pretreatment function of removing large particulate matter, external debris, and non-biodegradable litter such as leaves or cigarette butts contained in influent water in order to extend the life of these technologies [11]. However, unlike a centralized RMS, a decentralized RMS including LID technologies is difficult to install in a large-scale pretreatment unit. Therefore, to improve stormwater quality, it is necessary to consider installing two or more facilities in parallel in accordance with the characteristics of the stormwater runoff. Winston has assessed stormwater quality improvements by combining several LID technologies including vegetative filter trips, wetland swales, and dry swales [12]. In the case of roads and parking lots, rainwater is treated in a permeable block or pervious pavement that is drained through underground penetration or a separate pipe network. If the water drained through a pipe network is additionally treated through a separate penetration trench or the like, an improvement in water quality for stormwater can be expected.

To effectively reduce the level of NPS pollution using a decentralized RMS, it is possible to analyze the characteristics of stormwater and treated water. Particulate matter is an indicator of the characteristics of the stormwater runoff, and the distribution of particulate matter is related to water pollution through various studies. Particulate matter of 64 μm or less is especially related to water pollution items such as heavy metals and nutrients [13–15]. Therefore, the objectives of this study are (1) to identify the pollutant removal capacity of decentralized RMSs through analysis of particle size distribution (PSD) and (2) to evaluate the applicability of technologies through a combination of two types of RMS.

2. Materials and methods

2.1. Manufacturing stormwater; pilot-scale tests

It is very difficult for urban stormwater runoff to mimic actual runoff. To evaluate the technologies for the RMS, it is necessary to reproduce similar concentrations of particulate size distribution and suspended solids (SS) as occur in actual urban stormwater runoff. The Technology Acceptance Reciprocity Partnership [16] and the Technical Guidance Manual for Evaluating Emerging Stormwater Treatment Technologies [17] in the USA presents the distribution and concentration of particle sizes required for manufacturing stormwater. In Korea, manufacturing stormwater is mentioned in the Nonpoint Pollution Reduction Facility Performance Test Manual of the Ministry of the Environment (NPPT manual). This manual states that manufactured stormwater should not exceed 200 μm maximum and particle sizes below 64 μm should be between 60% and 70% of the total volume. Furthermore, SS concentration should be in the range of 150–350 mg/L.

In this study, silica sand was used for SS concentration production. The raw water used for manufacturing was rainwater collected in a reservoir. After being transferred to a pump, it was manufactured in a 5-ton agitator.

2.2. Linking a structural BMP device and LID facilities

For this study, the hybrid system consisted of two types. For each system configuration, a structured BMP device as a form of NPS reduction technology was installed at the front part of the system, while a planted-type facility and porous pavement, as decentralized RMSs, were installed at the rear part of the system. Additionally, the infiltration trench was installed at the end of the porous pavement with fine filters. Detailed descriptions of each facility are as follows:

- *Structural BMP device*: exterior is made of stainless steel and consists of two pretreatment units and one filtration unit. There is a pump for backwash and a diffuser for backwash air transfer. The granular media is 60 cm in depth and the filtration unit and filtration area are 1 m^2.
- *Tree filter box as a planted-type facility*: exterior is made of stainless steel and the inflow water passes through the nonwoven fabric and sand filter layer, and the treated water is discharged through the bottom pipe.
- *Porous pavement*: surface filtration area for the porous pavement is 0.16 m^2 and the pavement depth is 30 cm.
- *Infiltration trench*: horizontal length of the infiltration trench is 1m and a particulate filter of less than 64 μm is filled to a 20 cm depth.

2.3. Analysis of PSD and SS

In this study, SS concentrations and particle size analysis were performed at each stage from the manufacturing of manufactured stormwater to the final treated water. The PSD cannot identify the amount of particulate matter quantitatively, but the range of reduction by each facility can be grasped because the range of maximum and minimum PSDs can be known. Particle size analysis was conducted using a QICPIC particle size analyzer. The instrument can measure from 1 μm up to 2 μm maximum and is suitable for analyzing particulate matter contained in wet samples. The analysis principle of this equipment is laser diffraction, which measures the particle distribution by measuring the angle change of the light scattered when the laser beam passes through the pipe through which the water sample flows. Large particles scatter light at small angles while small particles scatter light at large angles. The PSD measured in this manner is calculated as the volume equivalent diameter of the analysis.

In this method, first, the weight of the glass fiber filter attached to the filter is measured, and a certain amount of the sample is filtered. The material remaining on the filter paper is dried at 105°C–110°C for about 2 h, and its weight is measured. Thereafter, the weight difference between the glass fiber filter before and after filtration is calculated and expressed as mg/L.

2.4. Experimental design

In this study, a hybrid type for RMSs has simulated a hybrid type that treats stormwater runoff by connecting three technologies, more specifically, by introducing water treated first in a structural BMP device into a LID facility. The reason for this was to confirm the possibility of substantial water quality improvement by complementing the advantages and disadvantages of structural BMP device, which is a representative technology of centralized rainwater management, and LID technology, which is a representative technology of decentralized rainwater management. To do this, the structural BMP device was set as the primary treatment facility, and the LID facility was installed in the secondary and tertiary treatment facilities. Two techniques, the tree filter box and porous pavement were applied to the secondary treatment. Penetration trench technology was applied to the tertiary treatment only.

A flow rate of approximately 10 ton/h from the agitator was introduced into the structural BMP device. After 3 h of operation, as indicated by the testing manual, the filter media in the device was backwashed for 5 min due to the desorption of particles from the filter media. The water treated in this process was secondarily introduced into a porous pavement and a tree filter box. The treated water from the structural BMP device was introduced at a flow rate of about 1 ton/h into the two LID techniques, and the rest was bypassed. The water treated by the two LID techniques, which represented the decentralized RMSs, was finally drained through the infiltration trench.

All experiments consisted of three cycles including backwashing. After the backwash of each cycle, the head loss was recovered, and then the next cycle was tested. Samples were collected and head loss was measured every 30 min, and flow rates were measured between each process.

3. Results

3.1. SS removal efficiency at each treatment step

Fig. 2a shows the results of a test for the sequential connection of a structural BMP device, tree filter box, and infiltration trench. The manufactured stormwater, with an SS concentration of around 300 mg/L, flowed into the facility at a rate of about 10 ton/h, and the SS concentration was reduced by about 80% through the structural BMP device. Backwashing was carried out for one cycle of 180 min. After backwashing, the head loss returned to its initial state. The treated water was transferred to the next facility, the tree filter box. At this time, the transfer flow rate was limited to about 1 ton per hour, considering the penetration level, and the remaining water was discharged by the bypass. The mean SS concentration of the water introduced into the tree filter box was 60.2 mg/L (±3.8 mg/L), and the mean concentration of the treated water was 35.1 mg/L (±2.3 mg/L). The water passing through the tree filter box was introduced into the infiltration trench. Infiltration into the infiltration trench was as shown in Fig. 1, and the average concentration of effluent was 10.2 mg/L (±0.6 mg/L).

Fig. 2b shows the results of a test of the sequential connection of the structural BMP device, porous pavement, and infiltration trenches. The process flow and operation flowing into the structural BMP device are displayed in Fig. 2a. The water passing through the structural BMP device was transferred to the next facility, the porous pavement. At this time, the transfer flow rate was limited to about 1 ton/h, considering the penetration level, and the remaining water was discharged by the bypass. The mean SS concentration of the

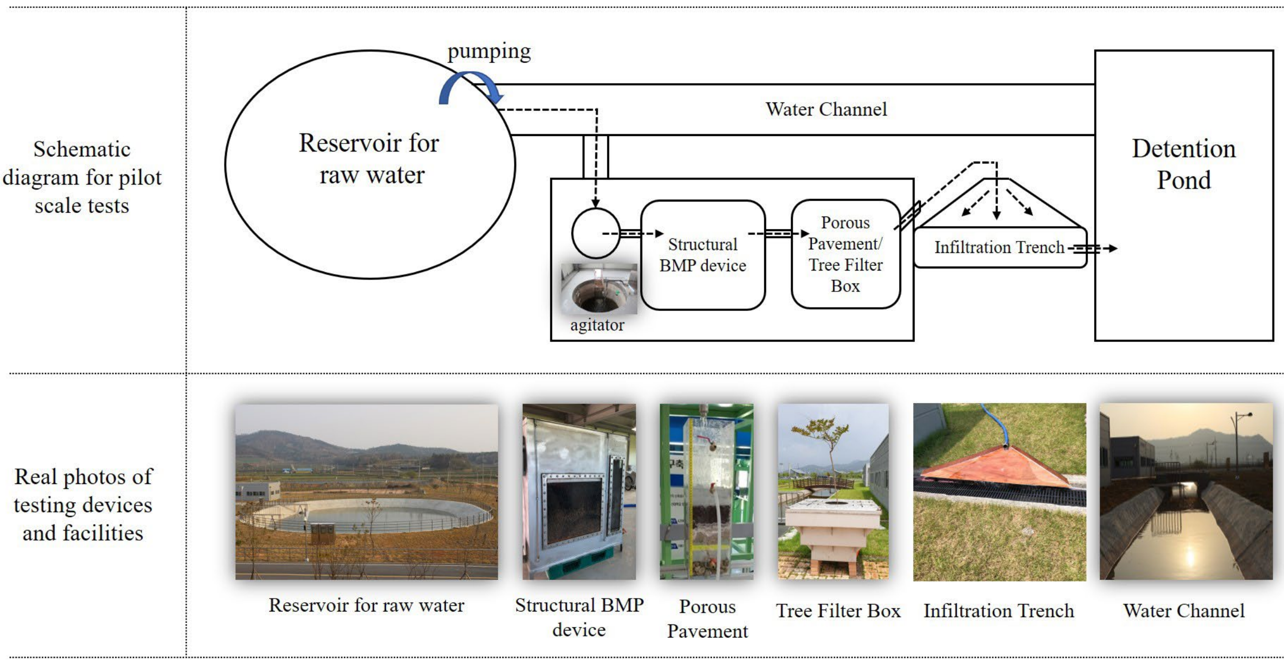

Fig. 1. The schematic diagram for the pilot-scale tests and real photos of testing devices and facilities.

water introduced into the porous pavement was 60.2 mg/L (±3.8 mg/L), and the mean concentration of the treated water was 42.7 mg/L (±2.1 mg/L). The water passing through the porous pavement was infiltrated into the infiltration trench. The mean concentration of the final effluent filtered through the infiltration trench was 10.7 mg/L (±0.6 mg/L). As a result of the experiments on the two-hybrid types, SS mean concentration of effluent was about 60.2 mg/L when only the structural BMP device was operated. However, when the tree filter box or porous pavement was combined with the infiltration trench facility, the SS concentration decreased to 10 mg/L.

3.2. Changes in particle distribution at each step

The maximum particle sizes were decreased through each treatment step. Fig. 3 shows the cumulative distribution of the mean particle sizes from the manufactured stormwater to the final outflow of the infiltration trench. Fig. 3a is a hybrid system with a structural BMP device connected to a tree filter box and infiltration trench. As shown in Fig. 3a, the mean maximum particle size was 157 μm in the manufactured stormwater, but this decreased to 86 μm after treatment by the structural BMP device. The results show that structural BMP devices have the ability to reduce the relatively large size particles that discharge from a drainage area during rainfall, although this can vary depending on site-specific and media characteristics. In the case of the tree filter box, particles larger than 48 μm were found to be filtered. This shows that particulate matter related to substances causing water pollution, such as heavy metals and nutrients, can be sufficiently reduced by combining a structural BMP device with tree box filters. The relative distribution of particulate matter showed a similar trend from the manufactured stormwater to the runoff of the tree filter box but showed a different tendency in the infiltration trench. It is assumed that this is because the filter material in the infiltration trench is composed of fine particles with a size of 64 μm or less, and these are filtered during the penetration of various sizes of particulate matter.

Fig. 3b is a hybrid system connecting a structural BMP device, porous pavement, and infiltration trench. In this system, the average maximum particle size of the particulate matter passing through the porous pavement is 72 μm, which is not much different from the maximum particle size of 86 μm discharged from the structural BMP device. This indicates that the ability of the porous pavement to reduce particulate matter related to SS concentrations is lower than that of the tree filter box.

Fig. 3 shows the maximum particle size and distribution reduced for each treatment step. However, since this

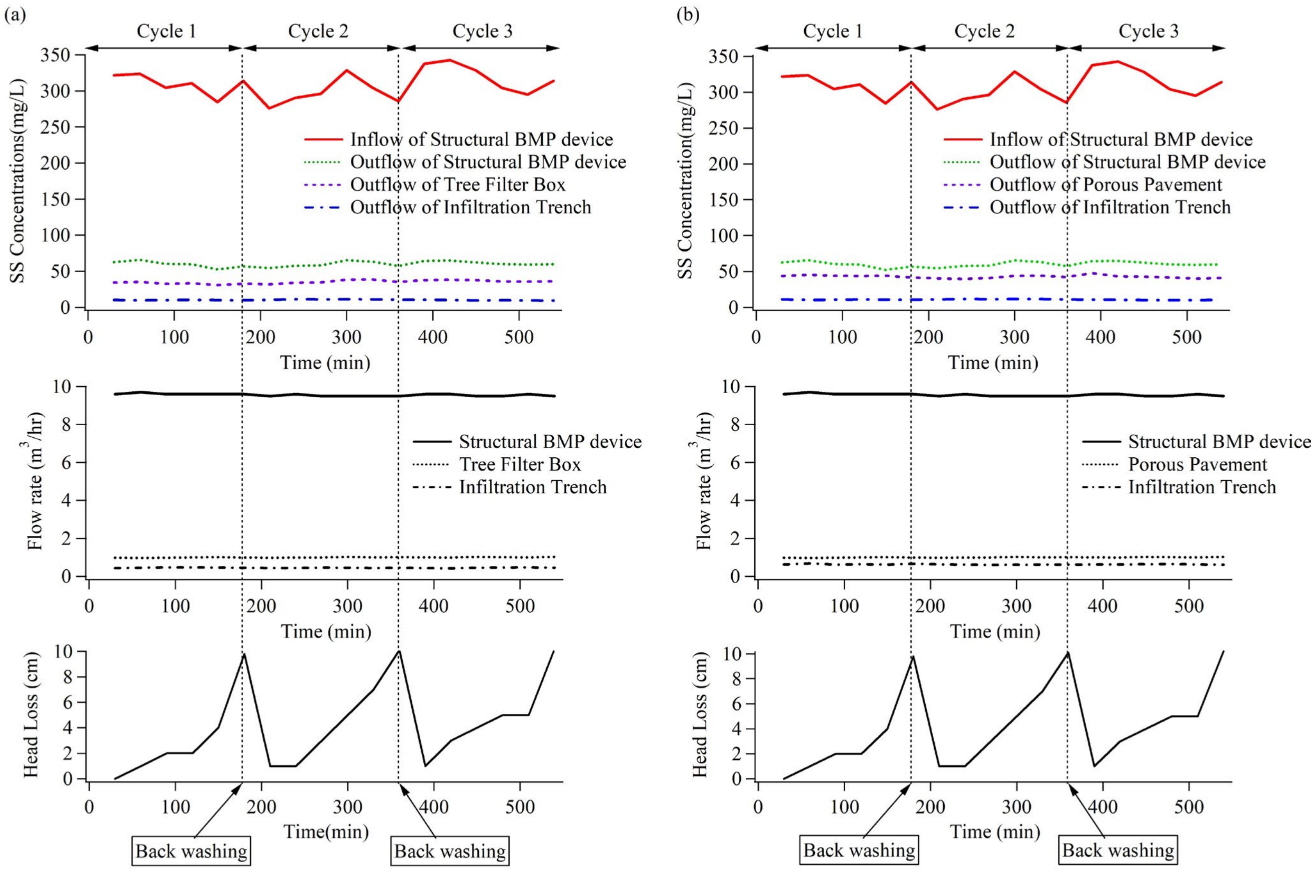

Fig. 2. Variations for SS concentration in two-hybrid system cases during performance test (top panel), flow rate changes (second panel), variations of head loss and timing for backwashing. (a) A hybrid system connecting a structural BMP device with a tree filter box and infiltration trench and (b) hybrid system connecting a structural BMP device with porous pavement and infiltration trench.

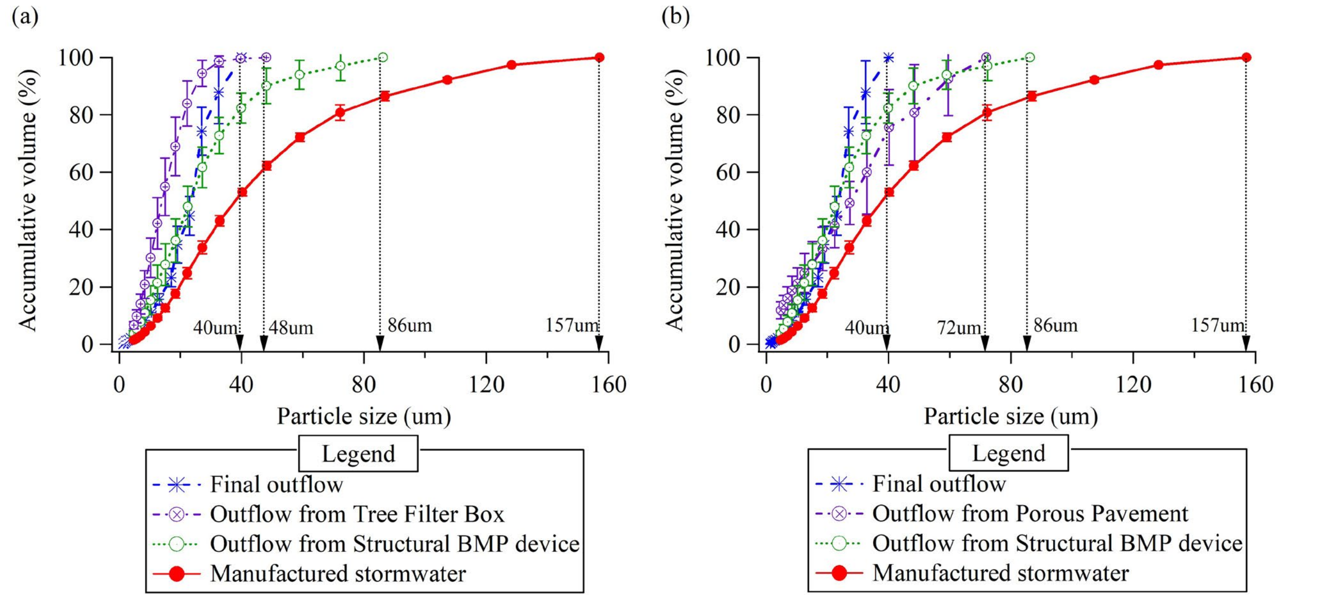

Fig. 3. Particle size distributions for each treatment step from manufactured stormwater to final outflow. The horizontal axis indicates the particle sizes, and the vertical axis indicates the accumulative volume (%).

graph presents relative ratios, it is difficult to determine whether the quantitative reduction is possible. Therefore, it is necessary to understand how the amount of particulate matter has changed in order to determine the reduction of particles.

3.3. Distribution and variation of particle matter count in each treatment step

Reducing the amount of particulate matter means a decrease in SS concentration. The analysis of the amount of particulate matter is important because the distribution

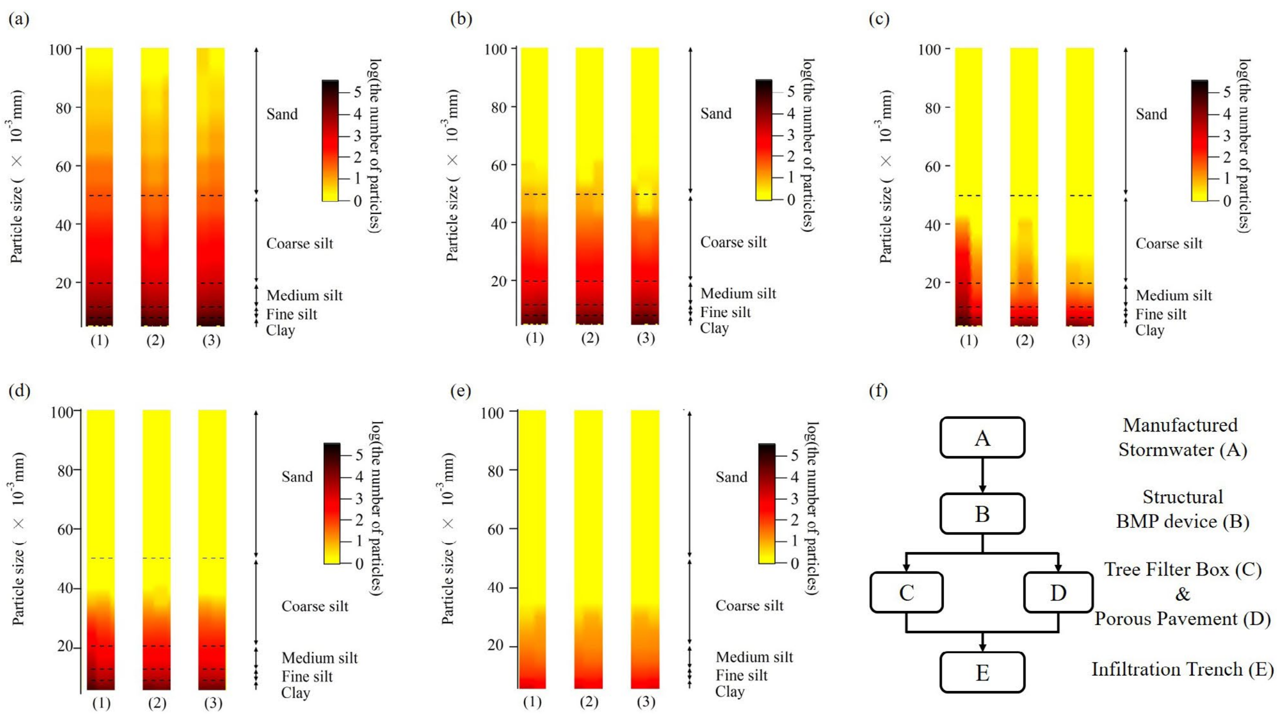

Fig. 4. Spectral graph of log-transformed particle bins. To create these plots, the measured particle bins at each treatment step were transformed and interpolated onto a uniform grid using a Delaunay triangulation algorithm. (a) Inflow to the structural BMP device, (b) outflow from the structural BMP device and the inflow to the tree filter box/porous pavement, (c) outflow from the tree filter box, (d) outflow from the porous pavement, (e) final outflow, and (f) water flow direction for this study.

of particulate size can lead to a wide range of results, even at low concentrations. Fig. 4 shows the distribution of the amount of particulate matter in each treatment step. In Fig. 4, each spectral bar is represented by log-transformed values of the number of particles. When the color of the spectral bar is close to black, it means that the amount of particulate matter is large, whereas when it is close to yellow it means that the amount of particulate matter is small. As shown in Fig. 4 and Table 1, for the number of particles, there were particles larger than 100 μm in the manufactured stormwater. Also, it was confirmed that the particle sizes of the infiltration trench drainage were finally up to 40 μm. Particles smaller than 20 μm are known to account for more than 50% of SS loading [18]. The amount of particulate matter smaller than 20 μm contained in the water treated in the structural BMP device was reduced to 46.9% of the manufactured stormwater. It was then reduced to 1.8% by infiltration trench through a tree filter box or porous pavement. These results indicate that better water quality improvement can be achieved when two or more technologies are connected to each other, depending on site conditions. The reduction rate of particulate matter smaller than 20 μm according to the connected technology is as follows:

- Structural BMP device – tree filter box: 84.0%
- Structural BMP device – porous pavement: 63.6%
- Structural BMP device – tree filter box/porous pavement – infiltration trench: 98.2%

4. Discussion

Combining two or more NPS pollutant removal techniques can lead to better water quality improvement than applying one technique. In this study, combinations of a structural BMP device and LID technique, as a hybrid system, were tested and analyzed for technically reducible NPS levels. When two or more techniques are combined, the frontal structural BMP device can be affected by turbulence, eddies, and circulation currents, depending on the characteristics of the filter media, the linear velocity, and the structural characteristics [11,19]. Nevertheless, this experiment showed that the stormwater runoff can be improved if the structural BMP device is responsible for pretreatment and LID technology is responsible for particulate matter reduction related to nutrients, heavy metals, and SS loading.

Hybrid systems can expect more various effects for the improvement of water quality, and several studies on hybrid systems that combine two technologies suggest the additional potential for water quality improvements. For example, Choi et al. [20] have shown that nutrients, heavy metals, SS loading, and chemical oxygen demand are reduced through the application of hybrid wetlands

Table 1
Mean values and standard deviation of particles in each treatment step and sizes. A to E in each treatment step correspond to in Fig. 4f

	Manufactured stormwater (A)		Outflow of structural BMP device (B)		Outflow of tree filter box (I)		Outflow of porous pavement (D)		Outflow of infiltration trenI(E)	
Size	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
1–5	101,002.9	25,215.3	48,263.1	7,652.5	18,762.9	5,851.0	39,100.6	8,801.0	1,946.0	1,104.6
5–10	12,935.6	2,836.8	5,812.8	1,141.6	314.4	129.4	3,299.9	687.0	140.7	15.8
10–15	3,919.7	908.5	1,462.4	193.5	52.2	31.5	817.4	139.1	43.7	7.4
15–20	1,509.0	364.3	521.9	46.5	16.3	12.4	261.0	17.5	20.3	1.5
20–25	823.3	199.1	270.1	25.8	8.7	6.8	104.6	16.3	13.3	2.1
25–30	409.0	104.3	125.9	18.8	4.1	2.5	33.4	9.1	6.0	2.6
30–35	215.8	60.5	56.6	9.5	2.3	1.1	8.1	3.1	2.0	0.0
35–40	125.7	34.4	28.7	4.6	1.8	1.3	1.6	1.3	1.0	1.0
40–45	57.2	16.0	8.9	3.1	1.0	0.7	0.6	0.5	0.0	0.0
45–50	47.6	13.5	6.9	2.3	0.7	0.7	0.4	0.5	0.0	0.0
50–55	24.7	7.8	2.9	1.1	0.1	0.3	0.3	0.5	0.0	0.0
55–60	22.5	7.1	2.3	0.8	0.1	0.3	0.2	0.4	0.0	0.0
60–65	9.6	3.1	1.3	0.5	0.1	0.3	0.1	0.3	0.0	0.0
65–70	9.6	3.1	1.3	0.5	0.1	0.3	0.1	0.3	0.0	0.0
70–75	6.2	1.5	0.8	0.4	0.0	0.0	0.0	0.0	0.0	0.0
75–80	4.4	1.0	0.3	0.5	0.0	0.0	0.0	0.0	0.0	0.0
80–85	4.4	1.0	0.3	0.5	0.0	0.0	0.0	0.0	0.0	0.0
85–90	2.8	0.6	0.2	0.4	0.0	0.0	0.0	0.0	0.0	0.0
90–95	1.5	1.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
95–100	1.5	1.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
100>	4.3	2.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

that treat stormwater runoff. Jurczak et al. have proposed that a combination of structural technologies and biological measures can reduce total suspended solids and nutrients by 86% and 70%, respectively. Meanwhile, Zurita and White [22] have reported that a two-stage hybrid ecological wastewater treatment system at a sewage treatment plant reduced *E. coli* by 99%.

Although these preliminary studies have shown the possibility of improving water quality, there are additional considerations when applying such hybrid technology to the field. Structural BMP devices generally require additional energy to be transported to the ground because they are typically installed underground. A technical review of the road design method for transferring water from the porous pavement to the infiltration trench is also needed. In the case of structural BMP devices, the difference in removal efficiency for NPS pollutants due to maintenance is significant. Therefore, it is also necessary to develop a regulatory system for actual maintenance.

5. Conclusions

Based on these results and the discussion of the findings, this study presents the following conclusions:

- Hybrid NPS pollutant removal systems are much more effective at reducing particulate matter associated with the discharge of nutrients and heavy metals than single technology solutions.
- Smaller the amount of particulate matter contained in the rainwater runoff between the tree filter box and the porous pavement, the more efficient the tree filter box is at improving water quality.
- Legal and technological complement is needed to improve water quality through the application of hybrid NPS pollutant removal systems.

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