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Treatment of parking lot runoff by a tree box filter

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ABSTRACT

Nonpoint source pollutants were usually transported by stormwater runoff, especially in highly urbanized areas. For this reason, studies on stormwater management have been one of the major focuses of the Ministry of Environment of Korea at present. Application of tree box filter, an example of stormwater best management practice, is highly considered in Korea due to its minimal space requirements, applicability in landscaping and good pollutant-removal efficiency. This study investigated the efficiency of a tree box filter in reducing both the pollutant and volume of stormwater runoff generated from a parking lot. This study also identified the relationship between pollutant and volume reduction and the effects of varying amount of rainfall to the overall volume reduction efficiency of the system. The study proved the capability of the tree box filter in improving stormwater runoff quality that was more efficient in total suspended solids (TSS) and soluble heavy metals discharging only 9 and 30% of the inflow load, respectively. In addition, high pollutant reduction of the system was associated with volume reduction of the system especially for TSS in which 20% volume reduction corresponds to at least 80% TSS reduction. The system also exhibited good volume reduction capability, especially for rainfall less than 10 mm. The tree box filter has proved to be an option for a cost-effective stormwater management, since it only requires a minimal space (surface area less than 5% of catchment area) and is applicable at small landscape areas in any urban land uses.

Keywords: Best management practices; Event mean concentration; Stormwater; Tree box filter

1. Introduction

Urban development greatly affects the deterioration of surface water bodies through transporting nonpoint sources (NPS) of pollutants conveyed by the stormwater runoff [1–6]. Mostly, highly urbanized areas comprising transportation, commercial, residential and industrial land uses were 100% impervious, thus preventing the stormwater to naturally infiltrate into the ground. NPS pollutants, such as particulates, organics, nutrients and heavy metals, were transported by weathering and vehicular activities from these areas. In response to the increasing risk posted

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by the effects of NPS to the surface water bodies in Korea, "Comprehensive measures for Nonpoint Source pollution Management" was established in March 2004 [7]. Several studies and reports were made concerning the application of best management practices (BMPs) such as constructed wetlands, permeable pavements and filtration and infiltration systems in Korea. However, investigation about the application of biological retention such as tree box filter is highly considered due to its minimal space requirements, applicability in landscaping and good pollutant removal efficiency. These BMP technologies can reduce both the pollutant loads and storm peak flows.

Tree box filters, a combination of both infiltration and biological retention practice, were usually used to manage stormwater runoff from paved areas, including highways, roads, bridges, and parking lots. Tree box filters have large planting pit for additional storage, a storm flow inlet from the side walk and an under drain system [8]. Tree box filters were considered to be an example of infiltration practices due to their capacity to remove particulate pollutants, organics, and heavy metals by 90%, whereas it can reduce nutrients by 60% [9]. Similarly, tree box filters were considered to be an example of biological retention practices because of their ability to remove water pollutants through biological processes and reduce peak hydraulic flows of up to 96% [10–12]. Tree box filters are generally small, occupying only 5–15% of the drainage area, esthetically pleasing and are reported to achieve a number of more sustainable stormwater management objectives [11,13].

This study investigated the efficiency of a tree box filter in improving the quality of stormwater runoff generated from parking lot through assessing the event mean concentration (EMC) and pollutant loads. In addition, this study also evaluated the capacity of the tree box filter in reducing the quantity of stormwater runoff. Lastly, this study identified the relationship between pollutant and volume reduction and the effects of varying amount of rainfall to the overall volume reduction efficiency of the system.

2. Materials and methods

2.1. Site description and tree-box filter design

The tree box filter test bed was constructed at Kongju National University in Cheonan city, Chungcheong Province, South Korea. The simple schematic of media arrangement in tree box filter and its location is illustrated in Fig. 1. The aspect ratio of the length, width, and height of the tree box filter was 1:1:0.87. The tree box filter has a storage capacity of $1.76\,m^3$ designed to store the runoff produced by 5 mm rainfall. On an average, the city receives a mean annual rainfall amounting to 1,236 mm [14]. The tree box filter was developed mainly to treat stormwater runoff generated from a 100% impervious parking lot with an area of $450\,m^2$ by combining the infiltration and biological retention of stormwater BMPs. This study employed the application of tree box filters to parking lots that were considered to be one of the largest contributors to impervious surface coverage in most of the land uses [8].

2.2. Monitoring, data collection, and analyses

Monitoring of storm events were conducted from July 2010 to November 2011 in the tree box filter test bed. Both water quality and quantity data were gathered from a total of nine storm events. Following the typical sampling scheme in Korea, six grab samples were collected during the first hour of the storm event [7,15]. The first grab sample was collected as soon as the runoff entered the tree box filter, followed by the grab sample collection after 5, 10, 15, 30, and 60 min, respectively. After the first hour, one grab sample was collected for each succeeding hour. In addition to the grab samples collected for chemical analyses, continuous flow measurements were also performed and recorded using a 5-min interval.

The stormwater runoff quality was evaluated with the use of EMC and pollutant loads. The EMC represents a flow-weighted average concentration, computed by dividing the total pollutant mass by the total runoff volume for event duration [16]. In addition, the summations of the runoff and discharge volume were calculated for each storm event to determine the volume reduction capacity of the system. Volume reduced by the system was calculated by subtracting the discharged volume from the runoff volume. Lastly, the pollutant mass reduction of the system was calculated by dividing the difference of the summation of influent and summation of effluent loading with the summation of influent loading, also known as summation of loads method [17]. The results of water quality were statistically analyzed using SYSTAT 12 and OriginPro 8 package software including normality test and analysis of variance. Shapiro–wilk normality test was used to determine the distribution of data, while one-way ANOVA was performed to investigate the significant differences between parameters. The differences were tested at 95% confidence level, which signifies that probability (p) value was less than 0.05.

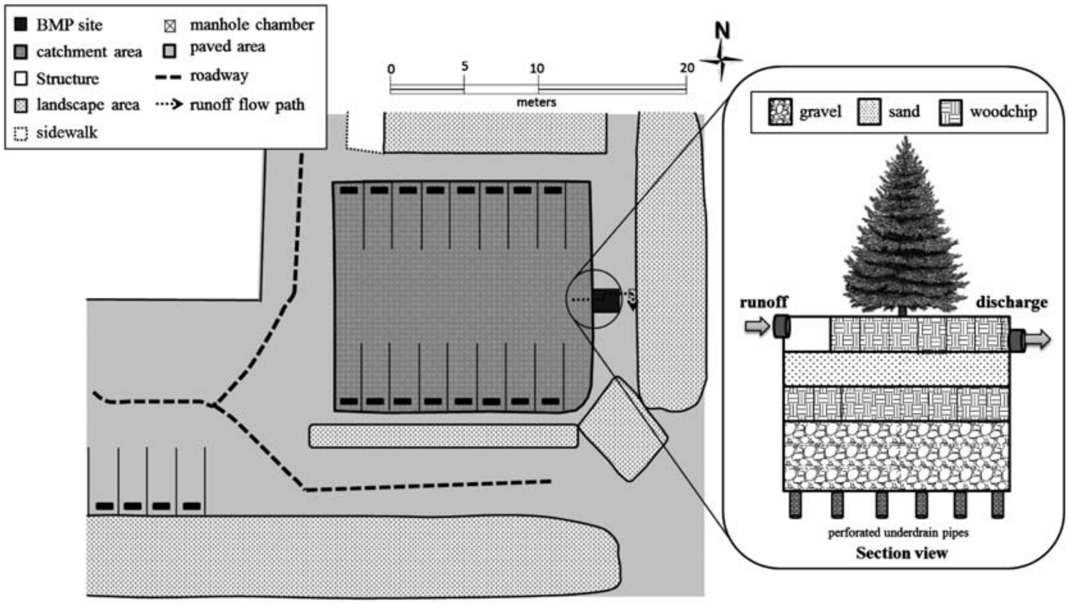

Fig. 1. Schematic diagram of tree box filter and its location.

3. Results and discussion

3.1. Monitored rainfall events

South Korea has four seasons among which summer is the hottest and wettest season. Almost 56% of the monitored rainfall events were between June and August. Table 1 shows the statistical summary of the monitored rainfall events. The highest value for antecedent dry days (ADD) was associated with the winter season, while relatively short ADD was observed during summer season. About 89% of the monitored rainfall events were below 10 mm which occurred in average rainfall duration of 2.2 ± 1.4 h. Among the nine storm events monitored, only five were able to produce outflow for the tree box filter caused by rainfall depth and runoff volume. The system can achieve 100% volume reduction below 4.5 mm rainfall depth and 0.06 m^3 runoff volume, based on the storm events monitored. Using polynomial regression analysis of the monitored events with outflow, the hydraulic retention time (HRT) in the facility was determined to be dependent on rainfall duration and average rainfall intensity (rainfall duration: $R^2 = 0.84$; average rainfall intensity: $R^2 = 0.61$). These results suggested that an increase in rainfall duration corresponds to increase in HRT, while, as the average rainfall intensity decreases, a corresponding increase in HRT was observed. The findings were apparent during the observation of highest HRT of 2.63 h caused by the lowest average rainfall intensity of 0.9 mm/h and longest rainfall duration of 4.45 h observed.

3.2. Event mean concentrations

Fig. 2 shows the box plot of the inflow and outflow EMCs of the nine storm events monitored. The median

Table 1
Statistical summary of monitored rainfall events

	Units	N*	Minimum	Maximum	Mean	Median	SD**
ADD	day	9	0.2	34.2	7.1	3.7	10.5
Total rainfall	mm	9	1.5	22.5	5.5	3.5	6.6
Rainfall duration	h	9	0.5	4.5	2.2	1.9	1.4
Runoff duration	h	9	0.3	3	1.4	1.2	1
Time before runoff	h	9	0	2.4	0.9	0.5	0.9
HRT	h	5	0.1	2.6	1.1	0.9	1.1
Runoff volume	m^3	9	0.01	5.07	0.94	0.21	1.62

*Number of data used.
**Standard deviation.

inflow EMC (EMC_{in}) is less than the mean EMC_{in}, signifying that the samples have low concentration for all the constituents. The mean total suspended solids (TSS) EMC_{in} was significantly decreased from 156.54 ± 150.95 mg/L to an outflow TSS mean EMC (EMC_{out}) of 9.3 ± 12.96 mg/L ($p = 0.01$). Similarly, the average total nitrogen (TN) EMC_{in} of 8.97 ± 5.13 mg/L was significantly reduced to EMC_{out} of 3.71 ± 4.20 mg/L in the discharge ($p = 0.03$). On the other hand, the average EMC_{out} discharged by the system in terms of biological oxygen demand (BOD), chemical oxygen demand (COD), and total phosphorus (TP) were 5.39 ± 7.15, 29.82 ± 40.31, and 0.14 ± 0.14 mg/L, respectively, were not significantly lower compared with the average EMC_{in} of 12.12 ± 9.67, 131.95 ± 137.07, and 0.54 ± 0.46 mg/L, respectively ($p > 0.05$). Lastly, there was no significant difference between the inflow and outflow concentrations of all the soluble heavy metals analyzed including copper (Cu) and lead (Pb) except zinc (Zn) which was reduced from mean EMC_{in} of 0.2 ± 0.05 to mean EMC_{in} of 0.2 ± 0.05 to mean EMC_{out} of 0.1 ± 0.1 mg/L (Zn: $p = 0.02$; other soluble metal except Zn: $p > 0.05$). The EMC_{in} has greater variations compared with EMC_{out} which was evident through the existing outliers except for TSS, BOD, and Zn wherein the coefficient of variation (CV) of EMC_{out} is greater than EMC_{in} (TSS CV: $EMC_{in} = 0.96$, $EMC_{out} = 1.03$; BOD CV: $EMC_{in} = 0.80$, $EMC_{out} = 0.86$; Zn CV: $EMC_{in} = 0.27$, $EMC_{out} = 0.28$). Lastly, the minimum and maximum values of EMC_{out} were less than the minimum and maximum values of EMC_{in}. These findings signify that the system showed efficiency in reducing the amount of pollutant contained in the stormwater runoff.

3.3. Pollutant load ratio

Tree box filter is a BMP which falls under the category of combined bioretention and infiltration trench or basin. Infiltration trenches or basins and bioretention facilities demonstrated good removal efficiency of organics, metals, and nutrients [9,10]. The ratio of runoff and discharged pollutant loads is demonstrated in Fig. 3. Among the constituents analyzed, the system attained lowest load ratio ($Load_{out}/Load_{in}$) for TSS of almost 0.09 signifying that 91% of the TSS inflow load was reduced by the system. The system also exhibited good soluble metal reduction evident in load ratios ranging from 0.1 to 0.3. On the other hand, the system demonstrated higher load ratio ranging from 0.35 to 0.6 for both organics and nutrients. The TSS and Pb load ratio of the system studied is almost in the same range with system reported by Maniquiz et al., while the organics and nutrients load ratio of the system in this study was greater. The infiltration system studied by Maniquiz et al. treated road runoff from a 0.5 ha drainage area and has a design rainfall of 10 mm [15]. These findings showed that the system can satisfactorily reduce soluble heavy metals and high reduction with respect to the TSS concentration can be expected from the system. On the other hand, compared with the particulate and soluble heavy metals, the system showed lower removal efficiency for organics and nutrients. Significant pollutant reduction showed by the system was associated with the volume reduction capacity of the system, since the treatment system did not produce discharge in most of the storm events monitored.

3.4. Relationship between pollutant mass and volume reduction

Fig. 4 exhibits the relationship between the pollutant removal efficiency and volume reduction of the facility. Compared with other constituents, the system exhibited at least 80% TSS by reducing approximately 20% runoff volume. On the other hand, at least 50% reduction of organics, nutrients, and soluble heavy metals may be attained by reducing 25–65% of runoff volume.

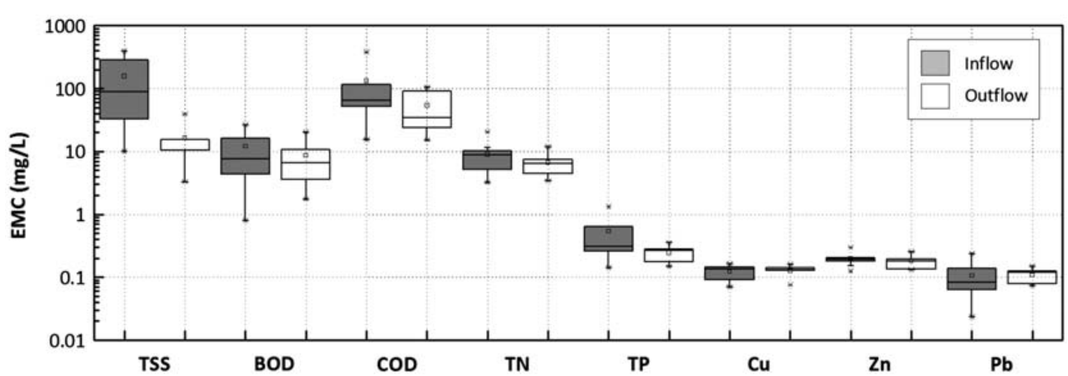

Fig. 2. Box plot of the inflow and outflow EMCs of typical stormwater constituents.

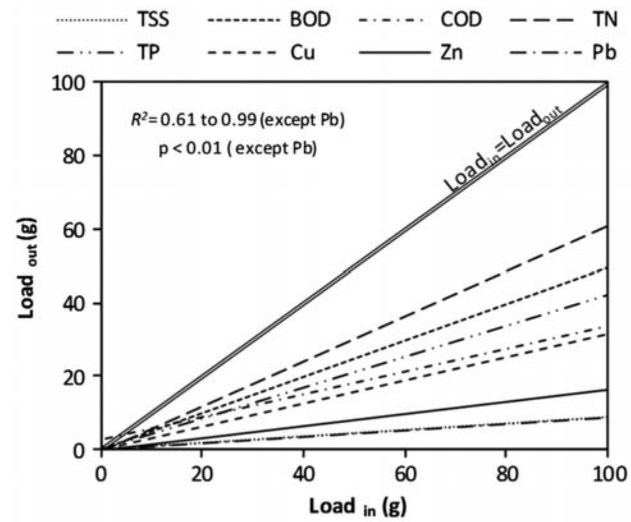

Fig. 3. Ratio of inflow and outflow load for particulate, organics, nutrients and soluble heavy metals.

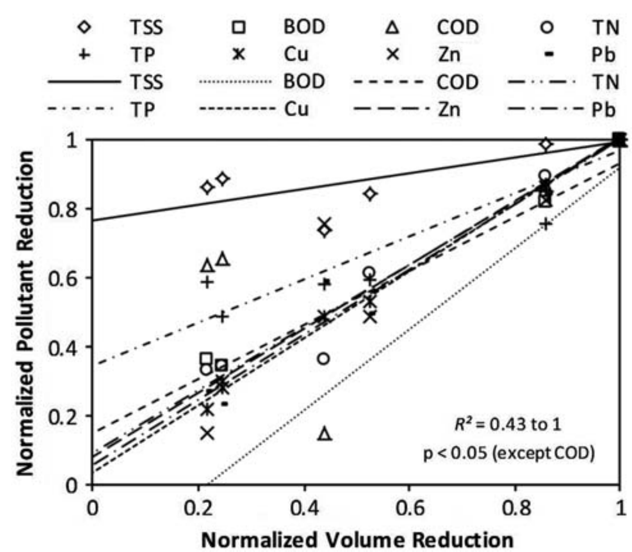

Fig. 4. Linear fitting of normalized pollutant reduction with normalized volume reduction.

This finding suggested that volume reduction through infiltration and retention in the facility plays an important role in reducing the pollutant loads from parking lot runoff. The linear regression plot displaying the relationship between the discharged and reduced volume with rainfall is presented in Fig. 5. The runoff volume reduced by the system was assumed to have infiltrated the ground through the drain pipes, evaporated through the plants, and retained and stored in the system. The amount of volume reduced by the system was higher compared with the volume discharged by the system up to approximately 12 mm rainfall wherein beyond this value, the percentage of volume discharged

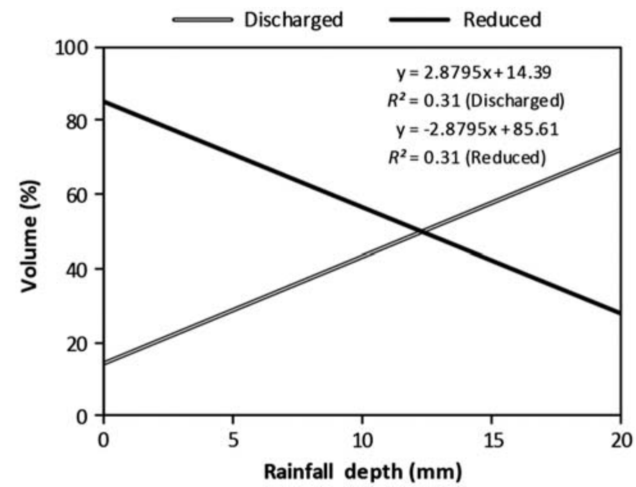

Fig. 5. Linear regression plot displaying the relationship of the discharged and reduced volume with rainfall.

by the system increased with a corresponding decrement in volume reduced by the system. Based on the storm events monitored, for rainfall of less than 5 mm, the system reduced 73% of the total runoff volume which entered the system. Meanwhile, for rainfall between 5 and 10 mm, the mean percentage of runoff volume that was reduced by the system was decreased to 52%. Beyond 10 mm, the average volume which was reduced by the system was further decreased to 22%. Since 70–80% of the total numbers of storm events per year in Korea were mostly below 10–20 mm, this system is appropriate to be applied in Korea [17].

4. Conclusion

The tree box filter, a combination of infiltration and bioretention type of LID technology, was investigated by assessing its capabilities in pollutant load and flow volume reduction. This study showed that the tree box filter was effective in reducing the NPS pollutants present in the stormwater runoff. In particular, the TSS, TN, and Zn EMC_{in} were significantly reduced ($p < 0.05$). Also, the EMC_{in} has greater variations compared with EMC_{out} which was evident through the existing outliers except for TSS, BOD, and Zn. In addition, the system exhibited low pollutant load ratio for TSS and soluble heavy metals of less than 0.09 and 0.3, respectively. Compared with TSS, the system discharged greater organics and nutrients load ranging from 35 to 60% of the inflow load. The TSS, BOD, COD, TP, and Zn removal by the system was coincidental in terms of EMC and pollutant load assessment. Moreover, this study also demonstrated that the tree box filter can efficiently reduce the runoff volume. At least 80% TSS reduction may be achieved by attaining at least 20% of runoff volume reduction suggesting that volume reduction through infiltration and retention in the facility plays an important role in reducing the pollutant loads from the catchment. The system was most efficient for rainfall less than 12 mm wherein beyond this value, the percentage of volume discharged by the system increases with a corresponding decrease in volume reduced by the system. Overall, the system showed good reduction of pollutant mass and flow volume. Continuous monitoring will be conducted to more effectively assess the limitations of the system and determine the design considerations for this type of LID technology in the future.

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