Treatment of suspended solids and heavy metals from urban stormwater runoff by a tree box filter

F. K. F. Geronimo, M. C. Maniquiz-Redillas, J. A. S. Tobio and L. H. Kim

ABSTRACT

Particulates, inorganic and toxic constituents are the most common pollutants associated with urban stormwater runoff. Heavy metals such as chromium, nickel, copper, zinc, cadmium and lead are found to be in high concentration on paved roads or parking lots due to vehicle emissions. In order to control the rapid increase of pollutant loads in stormwater runoff, the Korean Ministry of Environment proposed the utilization of low impact developments. One of these was the application of tree box filters that act as a bioretention treatment system which executes filtration and sorption processes. In this study, a tree box filter located adjacent to an impervious parking lot was developed to treat suspended solids and heavy metal concentrations from urban stormwater runoff. In total, 11 storm events were monitored from July 2010 to August 2012. The results showed that the tree box filter was highly effective in removing particulates (up to 95%) and heavy metals (at least 70%) from the urban stormwater runoff. Furthermore, the tree box filter was capable of reducing the volume runoff by 40% at a hydraulic loading rate of 1 m/day and below.

Key words | bioretention, heavy metals, tree box filter, urban runoff

F. K. F. Geronimo
M. C. Maniquiz-Redillas
J. A. S. Tobio
L. H. Kim (corresponding author)
Department of Civil and Environmental Engineering,
Kongju National University,
275 Budaedong, Seobukgu,
Cheonan City,
Chungnamdo, 331-717,
Korea
E-mail: *leehyung@kongju.ac.kr*

INTRODUCTION

Abundant impervious surfaces in Korea mainly cause the inundation of the low lying or flat surfaced areas during a storm event, which contributes to the intolerable pollutant load in the receiving waters. Stormwater runoff from urban areas contains significant loads of metal elements, particularly heavy metals (Revitt *et al.* 1990; Pitt *et al.* 1995; Sansalone & Buchberger 1997a). Heavy metals are of concern because of their potential toxicity and their ability not to be degraded in the environment (Maniquiz 2012). The Korean Ministry of Environment proposed various measures in controlling the urban runoff quality and quantity. One of the countermeasures was the implementation of low impact development (LID).

A number of stormwater management technologies were developed for urban runoff management, one of which was bioretention (Sansalone 1996; Shutes *et al.* 1997). Bioretention systems are generally composed of different layers of media (e.g. sand, gravel, woodchip), a variety of plants, and a mulch having the capability of treating stormwater runoff by assimilating or transforming the organic, inorganic and toxic pollutants through infiltration, filtration and sorption processes (Davis *et al.* 2001). One of the bioretention treatment systems that could be potentially utilized in Korea is the tree box filters which are commonly situated alongside paved roads or adjacent to parking lots. This LID integrates common street trees with stormwater runoff collection and pollutant reduction through physical, chemical and biological processes.

In order to evaluate further the pollutant removal performance of LIDs, particularly the tree box filters, the removal capacity and capabilities of this LID should be identified. This study assessed the efficiency of a tree box filter in reducing total suspended solids (TSS) and heavy metal constituents generated from a highly impervious parking lot. Furthermore, the capacity of the tree box filter in reducing the amount of stormwater runoff and its corresponding pollutant reduction were investigated.

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MATERIALS AND METHOD

Site description

The catchment area of the studied tree box filter was a 312 m^2 rough asphalt parking lot located inside a university campus, having a 0.33% slope and 100% imperviousness. The schematic diagram of the tree box filter and the arrangement of media are shown in Figure 1. The aspect ratio of the length, width, and height of the system was 1:0.67:0.87. There were three layers of media present in the system, namely, top layer woodchip, middle layer sand and bottom layer gravel with corresponding depths of 400, 400 and 500 mm respectively.

Sampling and data handling

The monitoring of storm events was conducted from July 2010 to August 2012 with a total of 11 storm events. In accordance with the typical sampling scheme in Korea, six grab samples were collected during the first hour of the stormwater runoff (Jung *et al.* 2008). The grab samples were two litres in volume and were collected both from the inflow and outflow of the facility. The first grab sample was collected as soon as the runoff entered the inflow of the tree box filter. Then it was followed by another five grab sample collections with a time interval of 5, 10, 15, 30 and 60 minutes respectively. After the first hour of runoff, one grab sample was collected for each succeeding hour or until the runoff ended. A maximum of 12 samples were collected in each rainfall event. This sampling scheme was practised as well in collection of outflow grab samples. Continuous measurement of flow rates was manually performed on both inflow and outflow of the facility and recorded in a 5 minute interval. The flow monitoring was started as soon as the runoff entered the facility and until the outflow ended. After each monitoring event, the water samples were immediately transferred to the university laboratory and stored at 4 °C until further processing and analysis. Water quality parameters such as TSS; soluble heavy metals, specifically chromium (Cr), nickel (Ni), copper (Cu), zinc (Zn), cadmium (Cd) and lead (Pb); and their corresponding total heavy metals, namely, total chromium (TCr), total nickel (TNi), total copper (TCu), total zinc (TZn), total cadmium (TCd), and total lead (TPb) were analysed based on the *Standard Methods for the Examination of Water and Wastewater* (1992).

Event mean concentration (EMC) (in mg/L) was calculated in order to evaluate the effects of the stormwater runoff in the study. EMC represents a flow-weighted average concentration and was calculated as the total pollutant mass divided by the total runoff volume during a storm duration (Sansalone & Buchberger 1997b; Charbeneau & Barretti 1998). The load ratios were also calculated to determine specific relationships between the studied water quality parameters. The water quality results were statistically analysed using SYSTAT 12 (http://www.systat.com/) which includes correlation analysis. The Pearson

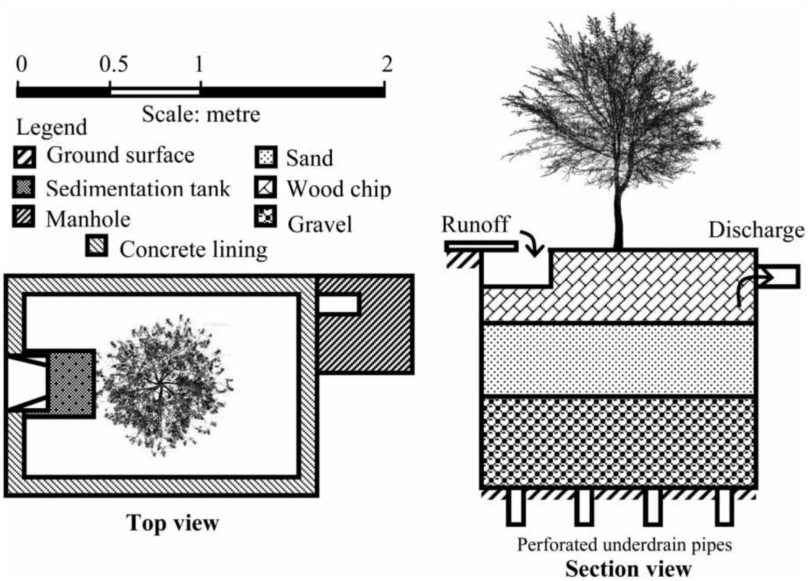

Figure 1 | Schematic diagram of the tree box filter.

correlation coefficient (r) was used to determine the dependence between each water quality parameter wherein the significant correlations were accepted at 95% confidence level, signifying that the probability (p) value was less than 0.05.

RESULTS AND DISCUSSION

Characteristics of monitored events and parking lot runoff EMC

The statistical summary of monitored events is shown in Table 1. The average total rainfall in this study was <5 mm which represents about 70 to 80% of the total number of storm events per year in Korea (Maniquiz *et al.* 2010). The LID was designed to treat the 'first flush' runoff or the initial 5 to 10 mm rainfall of a storm event. The first flush generated from 5 and 7.5 mm rainfalls were 36 and 22% greater than the average EMC (Lee *et al.* 2010). If a heavy rainfall event occurred, the treatment system would only treat the portion of first flush runoff and bypass the remaining runoff volume. Among the 11 storm events, only six were able to produce outflow wherein either of or both the total rainfall and rainfall duration were above the obtained mean values. Using statistical analyses of the monitored events, the capability of the system to produce a discharge was dependent on total rainfall and rainfall duration (total rainfall: $r = 0.700$; rainfall duration: $r = 0.541$; both have $p < 0.05$). The LID could achieve 100% volume reduction if the total rainfall was below 5 mm and/or the rainfall duration was less than 2.2 hrs.

Table 1 | Statistical summary of the monitored rainfall events (July 2010–August 2012)

Parameter	Unit	Minimum	Maximum	Mean	STD
Antecedent dry days	day	0.20	9.90	3.01	3.33
Total rainfall	mm	1.50	22.5	4.91	5.98
Rainfall duration	hr	0.50	4.45	2.18	2.04
Average rainfall intensity	mm/hr	0.77	5.87	2.88	3.23
Average flow rate	m^3/hr	0.01	2.74	0.52	0.82
Runoff volume	m^3	0.04	5.07	0.78	1.49

STD: standard deviation.

Based on Figure 2, the water quality pollutants except TSS, Cd and TCd have higher median EMC than the mean EMC, which implies that the influent concentration was generally high during storm events. The opposite statistical trend for TSS and both forms of cadmium was caused by low traffic intensity in parking lots compared to paved roads (Wiesner *et al.* 1998). Since the main contributor of cadmium forms is gasoline emission of moving vehicles, it is apparent that it would have the smallest or most varying concentration. In contrast, forms of zinc and lead have the most consistent concentration wherein the minimum and maximum values of these metals have few differences compared to the other metal constituents. Due to several sources, like vehicle combustion emissions, material abrasions and pavement components (e.g. motor oil and grease, brake linings, asphalt, rubber, gasoline), the concentrations of zinc and lead in urban runoff were approximately maintained.

Among the total heavy metals, 60 to 75% of chromium, nickel, copper and cadmium was in the dissolved forms while zinc and lead had 60 to 90% in the particulate form. As shown in Table 2, total and soluble heavy metals have high correlations with the particulates with

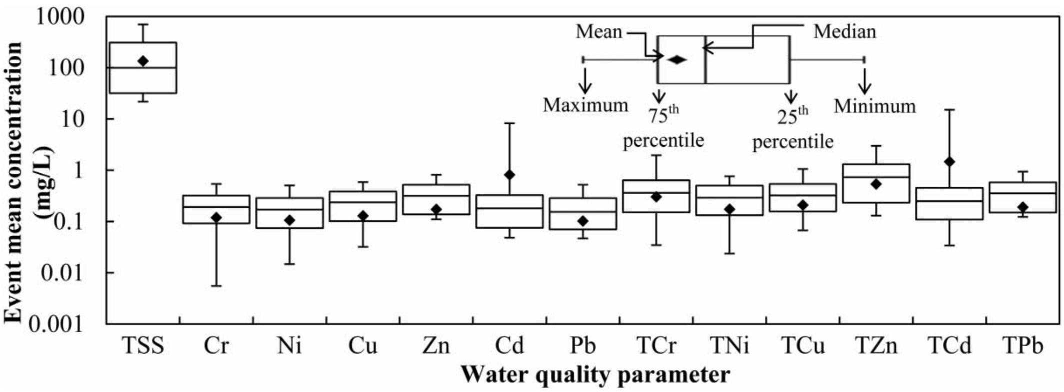

Figure 2 | Statistical EMCs of the influent particulates and heavy metal constituents.

Table 2 | Pearson correlation matrix of TSS, and total and soluble heavy metals from the influent load

	TSS	Cr	Ni	Cu	Zn	Cd	Pb	TCr	TNi	TCu	TZn	TCd	TPb
TSS	1												
Cr	0.846	1											
Ni	0.852	**0.998**	1										
Cu	0.849	**0.998**	**0.999**	1									
Zn	0.677	**0.948**	**0.944**	**0.949**	1								
Cd	0.855	**0.999**	**0.998**	**0.999**	**0.942**	1							
Pb	0.777	**0.990**	**0.988**	**0.990**	**0.983**	**0.987**	1						
TCr	0.871	**0.992**	**0.992**	**0.994**	**0.950**	**0.992**	**0.985**	1					
TNi	0.860	**0.999**	**0.999**	**0.938**	**0.946**	**0.999**	**0.988**	**0.996**	1				
TCu	0.883	**0.997**	**0.998**	**0.998**	**0.932**	**0.998**	**0.980**	**0.996**	**0.999**	1			
TZn	**0.994**[a]	0.861	0.866	0.865	0.721	0.870	0.805	0.895	0.876	0.898	1		
TCd	0.859	**0.995**	**0.996**	**0.986**	**0.940**	**0.958**	**0.986**	**0.992**	**0.999**	**0.998**	0.873	1	
TPb	**0.910**	**0.990**	**0.991**	**0.991**	**0.910**	**0.992**	**0.966**	**0.993**	**0.993**	**0.997**	**0.922**	**0.993**	1

[a]Bold values were considered highly correlated for *r* greater than 0.900 and *p* value less than 0.05.

r values ranging from 0.68 to 0.99 and $p < 0.05$. These results suggested that the metal transport and behaviour was closely related to the partitioning of the pollutant between soluble and particulate phases, wherein TSS played an important role in the whole transport process (Yuan *et al.* 2001). In addition, the degree of association of heavy metals to the suspended materials was highly affected by the size and shape of the particles present in the stormwater runoff (Maniquiz *et al.* 2009). The dissolved and particulate phases of the heavy metal were highly correlated with other metal constituents because of the same source such as the chemical emissions of parked vehicles.

Pollutant mass and flow volume reduction

The change of pollutant and volume reduction at varying hydraulic loading rate is shown in Figure 3. Based on the results, approximately 40% of the runoff volume was reduced by the system at a hydraulic loading rate of 1 m/day. The results also showed that the increase of hydraulic loading rate from 2 to 8 m/day would yield a decrease in volume reduction performance of the system by almost 30%. Hydraulic loading rate was dependent on the total runoff volume received by the system: it was highly correlated with total rainfall ($r = 0.970$, $p < 0.01$) and rainfall duration ($r = 0.541$, $p < 0.05$).

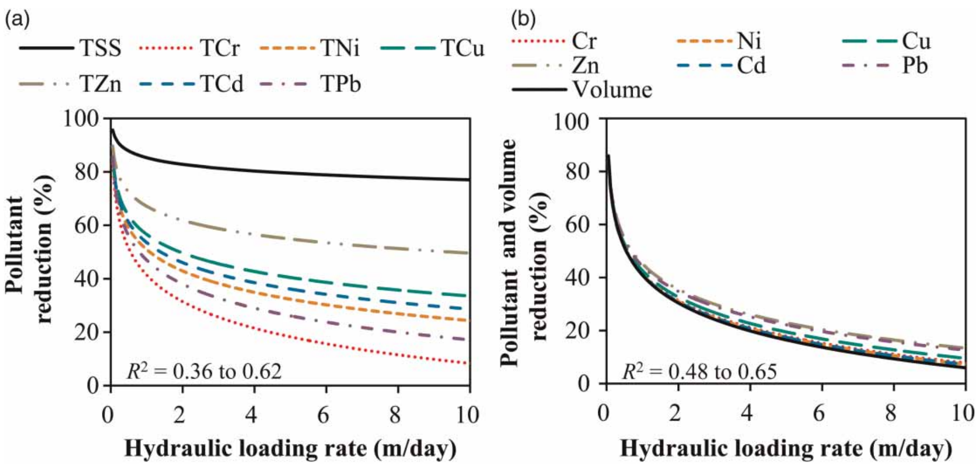

Figure 3 | (a) Pollutant reduction of particulates and total heavy metals, (b) pollutant reduction of soluble heavy metals and volume reduction, as a function of hydraulic loading rate.

The TSS showed the highest removal efficiency for having an 80 to 98% reduction at varying hydraulic loading rate. These results suggested that the filtration capacity of the system was the main removal mechanism for the particulates. Among the total heavy metal constituents, the system showed a high variation in removing TCr and corresponded to the lowest removal efficiency. For a hydraulic loading rate of approximately 2 m/day, TCr was reduced by up to 30%. The same trend of removal efficiency was observed with the soluble heavy metals. Most chromium compounds associated with urban runoff were commonly transported by suspended adsorbing particles (Bielicka *et al*. 2005). Based on the recent findings, chromium metal was highly present in dissolved form that could easily be discharged in the runoff. However, the corresponding removal efficiency of the system for the mentioned heavy metal was obtained from both the adsorption capability of the wood chip media and the infiltration capacity of the tree box filter. Due to these removal mechanisms the system could reduce other total heavy metals by approximately 50 to 70% for a hydraulic loading rate of 1 m/day.

Based on Figure 4(a), the pollutant removal efficiency was significantly associated with the volume reduction capacity of the system. The TSS mean concentration was reduced by approximately 95% for a 0.2 ratio of outflow and inflow volume. Consequently, the total heavy metals, specifically TZn, TCu, TCd and TNi, were reduced by almost 80 to 90% for the same volume ratio. The volume reduction through infiltration and retention capabilities of the facility also represents an important role in reducing pollutant loads since they could be infiltrated to the drain pipes going through the native soil, and retained or stored within the system (Jang *et al*. 2005; Geronimo *et al*. 2013).

Based on Figure 4(b), for a 0.5 volume ratio the load ratio of the soluble heavy metals ranged from 0.4 to 0.5. The results showed that dissolved forms were able to pass the filter media layer, and the treatment mechanisms that caused the diminutive reduction would be infiltration and adsorption processes. The filtration treatment mechanism was incorporated in the facility to primarily treat the particulates. It was presumed that the pollutants adsorbed by these particulates, including the particulate and soluble form of heavy metals, were captured within the filter media. Indirectly, the filtration capability of the system could also have an effect on the treatment of dissolved heavy metal constituents.

Relationship between load ratio of TSS and heavy metal

Figure 5(a) shows the removal of total heavy metal constituents in relation to TSS removal. At least 70% removal of total heavy metals may be attained by achieving about 0.10 of TSS fraction or approximately 90% removal of TSS. A TSS fraction corresponds to the relationship of outflow load with the inflow. Among the total heavy metals, TZn and Cu forms have the most significant correlation with TSS load ratio with $p < 0.01$ and $p < 0.05$ respectively. Approximately 30 to 80% of total heavy metal reduction was also observed for TSS load ratio of less than 30%. These findings proved that the main removal mechanism of the tree box filter was filtration using different media.

Moreover, heavy metals, once emitted in the environment, could occur in different forms: adsorbed by the particulates or as ions in water. The relationship of soluble heavy metals with their equivalent total heavy metal forms is shown in Figure 5(b). At least 50 to 55% reduction of soluble heavy metals corresponds to the 50% removal of the

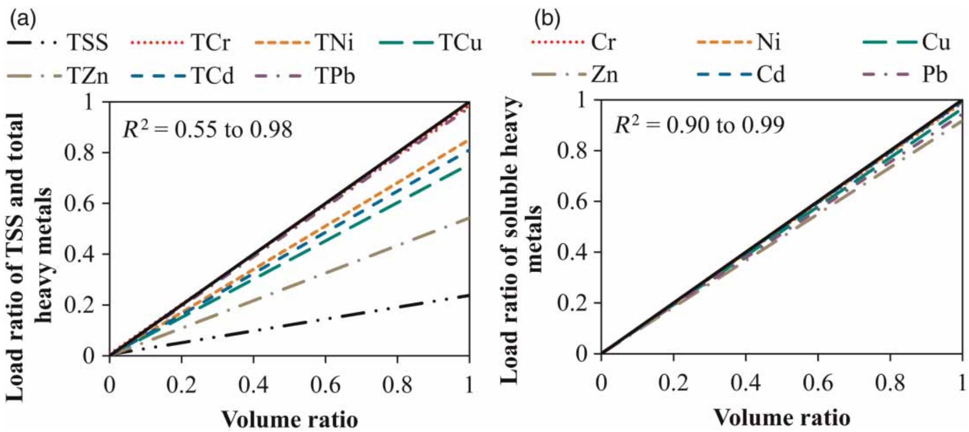

Figure 4 | Load ratio of (a) TSS and total heavy metals and (b) soluble heavy metals as a function of volume ratio.

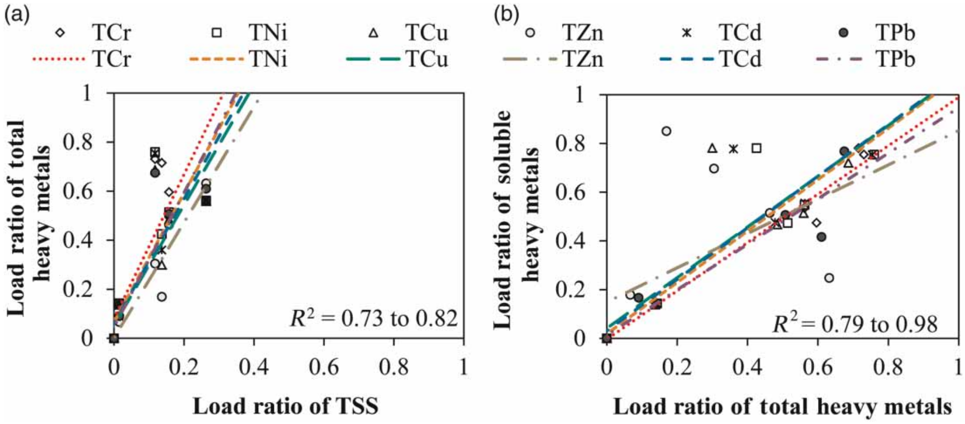

Figure 5 | Load ratio of (a) total heavy metals as a function of particulate load ratio and (b) soluble heavy metals as a function of total heavy metals.

total heavy metals except for the Zn forms. The TZn was more highly correlated with TSS than the other heavy metal. Approximately 70% of TZn was in particulate form leaving at least 30% in soluble form. In addition, the scattered TZn plots were caused by the low correlation ($r = 0.72$ to 0.90 with $p < 0.10$) with the soluble forms. Thus, the removal of soluble zinc was not primarily dependent on the treatment of particulate zinc compared to other heavy metal constituents.

Operation and maintenance activities

Several maintenance guidelines regarding LID were published by the United States Environmental Protection Agency; however, the frequency of maintenance and schedule of maintenance in each facility usually varies (Geronimo 2013). Most of the maintenance performed in the tree box filter have been focused on the cleaning of the sedimentation chamber. This included the removal of leaves, litter and sediments accumulated in the sedimentation tank caused by several storm events. Based on the monitoring and removal performance, the maintenance should be more frequent due to the relatively small size of the sedimentation chamber of the LID. Thus, the maintenance activities were performed at the end of every season with rainfall occurrences (i.e. spring, summer and autumn) to ensure the effectiveness of the treatment mechanisms incorporated in the system.

However, the maintenance activities performed in the sedimentation tank would only result in temporary restoration of the treatment mechanisms. The common visual indications that show a need for immediate intensive maintenance or renovation would be the ponding at the surface area, unusual delay of the discharge and the 'release' of pollutants at the outflow. According to Le Coustumer et al. (2012), the mentioned indications were results of the occurrence of 'clogging' in the filter media. Alleviation of the clogging would sustain the effectiveness of the treatment mechanisms and eventually prolong the service life of the LID. A renovation was performed during the spring season in order to prepare the facility before the successive rainfall events occur. The intensive maintenance included the cleaning of all the filter media inside the treatment system and the removal of accumulated sediment. Based on the removal performance results, the maintenance scheme performed in the research was recommended.

CONCLUSION AND RECOMMENDATION

A tree box filter with a catchment area of an impervious parking lot was investigated in order to assess the current TSS and heavy metal removal capabilities. The efficacy of the system to produce a discharge was found to be dependent on total rainfall and rainfall duration (total rainfall: $r = 0.700$; rainfall duration: $r = 0.541$; both have $p < 0.05$). The LID could achieve 100% volume reduction if either of or both the total rainfall and rainfall duration were less than the obtained mean values. The results showed that the influent concentration was significantly contaminated by heavy metals except for TCr, which arose from the by-products of vehicle combustion emission rather than the accumulation of particulates in the runoff. Nonetheless, the total and soluble heavy metals have a high correlation with the particulates, in which the r value ranges from

0.68 to 0.99 and $p < 0.05$. These results suggested that the metal transport and partitioning of heavy metals were correlated with the suspended solids.

The system also showed an approximate 40% runoff volume reduction for a hydraulic loading rate of 1 m/day. It was found out that the hydraulic loading rate was dependent on the total runoff volume received by the system, with corresponding Pearson correlations of $r = 0.970$ ($p < 0.01$) and $r = 0.541$ ($p < 0.05$) for total rainfall and rainfall duration respectively. Moreover, the TSS showed the highest removal efficiency, having an 80 to 98% reduction at varying hydraulic loading rate, which indicates the effectiveness of the filtration capacity of the system. Heavy metals could also be reduced by 40 to 70% for a hydraulic loading rate of 1 m/day.

Furthermore, at least 70% removal of total heavy metals was attained by achieving about 0.10 of TSS fraction. Among all of the total heavy metals, TZn and Cu forms have the most significant correlation with TSS load ratio with $p < 0.01$ and $p < 0.05$ respectively. Since particulate and dissolved forms of heavy metals were presumed to be adsorbed by the suspended solids, the filtration capacity of the tree box filter was identified as the main removal mechanism of pollutants. Lastly, there was 50 to 55% reduction of soluble heavy metals, which corresponds to the 50% removal of the total heavy metals, except for TZn forms. Based on the results, the TZn was dominantly particulate-bound. Thus, the removal of soluble zinc was not mainly dependent on the treatment of particulate zinc compared to the other heavy metal constituents.

In order to sustain the satisfactory removal performance of an LID, the research suggested a maintenance scheme based on the obtained results. An intensive maintenance or renovation should be performed before the successive rainfall events occur. The renovation includes the cleaning of all filter media and removal of accumulated sediment. After the renovation, a periodic maintenance activity should be practised. It was recommended that at the end of every season a maintenance activity focused on cleaning the sedimentation tank of the system should be performed. The maintenance scheme suggested in the research would ensure the effectiveness of the treatment capabilities of the LID.

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