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Evaluation on the suspended solids and heavy metals removal mechanisms in bioretention systems

Franz Kevin F. Geronimo[1], Marla C. Maniquiz-Redillas[2], Jungsun Hong[1] and Lee-Hyung Kim*[1]

[1]Department of Civil and Environment Engineering, Kongju National University, 1223-24 Cheonan-daero, Seobukgu, Cheonan city, Chungnam province, South Korea, 31080
[2]Civil Engineering Department., 2401 Taft Avenue, De La Salle University-Manila, Malate Manila, Philippines

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Abstract. Application of bioretention systems in Korea is highly considered due to its minimal space requirements, appropriateness as small landscape areas and good pollutant removal and peak hydraulic flow reduction efficiency. In this study, the efficiency of two lab-scale bioretention types having different physical properties, media configuration and planted with different shrubs and perennials was investigated in reducing heavy metal pollutants in stormwater runoff. Type A bioretention systems were planted with shrubs whereas type B were planted with perennials. Chrysanthemum zawadskii var. latilobum (A-CL) and Aquilegia flabellata var. pumila (A-AP) respectively were planted in each type A bioretention reactors while Rhododendron indicum linnaeus (B-RL) and Spiraea japonica (B-SJ), respectively were planted in each type B bioretention reactors. Results revealed that the four lab-scale bioretention reactors significantly reduced the influent total suspended load by about 89 to 94% ($p<0.01$). Type B-RL and B-SJ reactors reduced soluble Cr, Cu, Zn, and Pb by 28 to 45% that were 15 to 35% greater than the soluble metal reduction of type A-CL and A-AP reactors, respectively. Among the pollutants, total Cr attained the greatest discharged fraction of 0.52-0.81. Excluding the effect of soil media, total Pb attained the greatest retention fraction in the bioretention systems amounting to 0.15-0.34. Considering the least discharge fraction of heavy metal in the bioretention system, it was observed that the bioretention systems achieved effectual reduction in terms of total Cu, Zn and Pb. These findings were associated with the poor adsorption capacity of the soil used in each bioretention system. The results of this study may be used for estimating the maintenance requirements of bioretention systems.

Keywords: bioretention; heavy metal; low impact development; nature-based solution; stormwater management

1. Introduction

Exposure to heavy metals was proven to have caused severe consequences to human health and retard plant growth (Qu *et al*. 2018, ur Rehman *et al*. 2018). Since heavy metals cannot be degraded or destroyed, these heavy metals pose high risk to human health when ingested through food and drinks and inhalation (Majid *et al*. 2018). Some of the causes of heavy metals production in the environment include natural phenomenon such as atmospheric deposition and local erosion and anthropogenic activities such as automobile activities resulting to mechanical and tire wear, construction, mining and other industrial activities (Ghosh *et al*. 2018, Milik and Pasela 2018). In urban environment, heavy metals are mostly attached to sediments and particulates implying that the partitioning of heavy metals between soluble and particulate and its transport process are greatly affected by sediments and particulates (Geronimo *et al*. 2014).

Effective methods and processes of treating of heavy metals in water, stormwater and wastewater include chemical precipitation, ion exchange, adsorption, membrane filtration, coagulation and flocculation, flotation and electrochemical treatment (Fu and Wang 2011). However, these methods and processes either require high capital cost and/or operation and maintenance cost. An innovative and cost-effective way of treating heavy metals in stormwater runoff is through nature-based solutions (NBS). NBS utilizes natural processes through conserving or rehabilitating natural ecosystems and/or enhancement or creation of modified or artificial ecosystem to contribute to a water management outcome (UN WWAP/UN-Water, 2018). Good examples of NBS for stormwater were called low impact development (LID) technologies or green infrastructures (GI) which both aims to mimic the pre-development state of an area. Typical stormwater LID technologies and GI include bioretention systems, infiltration trenches, constructed wetlands, infiltration planters, vegetated strips and many others.

Among these NBS for stormwater, bioretention systems have received global attention due to its applicability in developed areas and transportation land uses that are identified as one of the great contributors of non-point source pollution in stormwater runoff. Application of bioretention is highly considered in Korea due to its minimal space requirements, appropriateness as small

*Corresponding author, Ph.D., Professor
E-mail: leehyung@kongju.ac.kr
[a] Ph.D. Student
[b] Ph.D., Associate Professor
[c] Ph.D., Research Fellow

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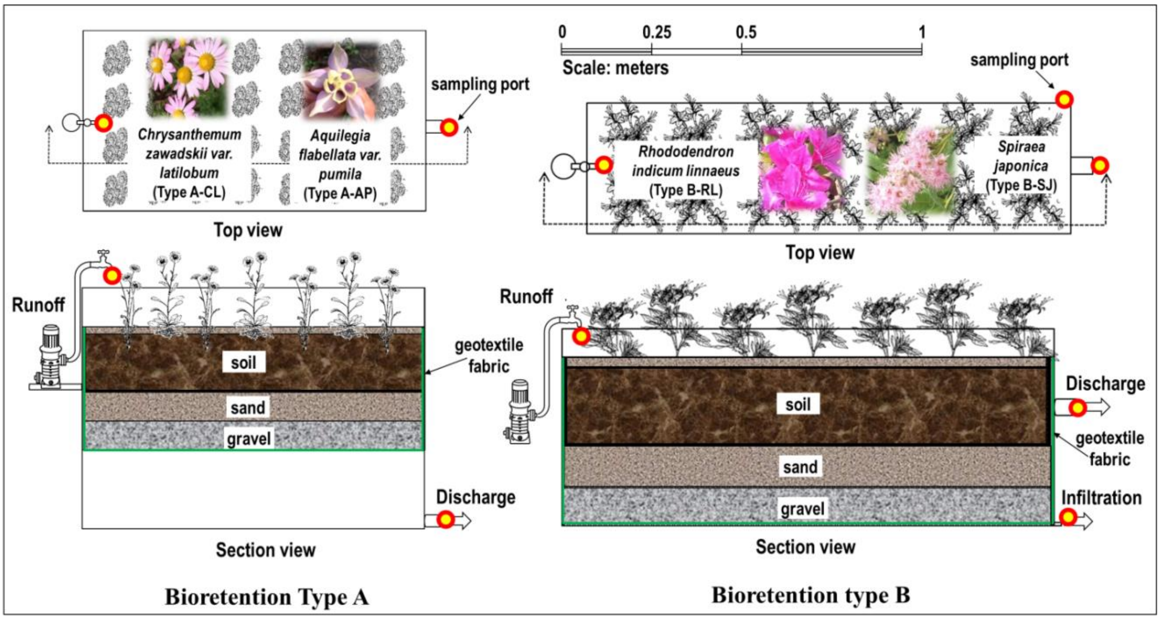

Fig. 1 Schematic diagram of each type of lab-scale bioretention system

landscape areas and good pollutant removal and peak hydraulic flow reduction efficiency. In this study, the efficiency of two lab-scale bioretention types having different physical properties, media configuration and planted with different shrubs and perennials was investigated in reducing heavy metal pollutants in stormwater runoff. Particularly, the behavior of heavy metals after entering the bioretention systems were analyzed and used to estimate bioretention life span until it reaches the standard limit allowed for soil contamination.

2. Material and methods

2.1 Lab-scale bioretention design

Two reactors were designed for each lab-scale bioretention types. Type A reactors were planted with shrubs whereas type B reactors were planted with perennials as shown in Fig. 1. Chrysanthemum zawadskii var. latilobum (A-CL) and Aquilegia flabellata var. pumila (A-AP) respectively were planted in each type A bioretention reactors while Rhododendron indicum linnaeus (B-RL) and Spiraea japonica (B-SJ), respectively were planted in each type B bioretention reactors. Both types of lab-scale bioretention were rectangular box shaped with the length, width and height aspect ratio of 2.1:1.1:1 and 3.75:1:1.5 for type A and B, respectively. Woodchip, soil, sand, gravel, coconut mat and geotextile were used as filter media for the bioretention.

2.2 Experimental scenarios and monitoring

One to two kg of sediments collected from a 520 m^2 impervious road was diluted in 2 m^3 of tap water and used as synthetic stormwater runoff for each experimental run. Each experimental run was conducted during 120 min. The synthetic stormwater runoff was applied to the system with initial inflow rate of 2, 3, 4, 5 and 6 L/min. These flow rates were selected based on 10 years' 55%, 60%, 65%, 70%, 75% occurrence frequency of rainfall depth occurring in Cheonan city, South Korea. The samples were collected after the initial application of synthetic stormwater runoff and every 30 minutes until 120 minutes test run time was reached in the inflow, infiltration and discharge ports. Consequently, manual flow checking was conducted every 10 minutes to ensure that there will be no changes in flow rate. Soil samples from the bioretention systems were collected before the test runs, once every season and after all the test runs. Analyses of water samples for parameters including total suspended solids, dissolved heavy metals and total heavy metals were conducted based on the Standard Methods for the Examination of Water and Wastewater (APHA *et al*. 1992). Meanwhile, analysis of soil samples for metal contents including chromium (Cr), copper (Cu), zinc (Zn), cadmium (Cd) and lead (Pb) were conducted based on the soil sampling and methods of analysis (Carter and Gregorich 2007).

2.3 Calculations and analyses

Event mean concentration (EMC) is used to quantify concentrations in various studies as a measure of a treatment facilities' efficiency (Maniquiz *et al*. 2010b, Geronimo *et al*. 2013). EMC is calculated by dividing the total pollutant mass by the total runoff volume for event duration. The overall efficiency of the system was evaluated through the summation of loads method calculated by dividing the difference of the summation of influent and summation of effluent loading with the summation of influent loading. Fractional distribution of heavy metals through each removal mechanisms was analyzed by considering retention in the soil, retention in the system other than the bioretention soil, infiltration to the ground

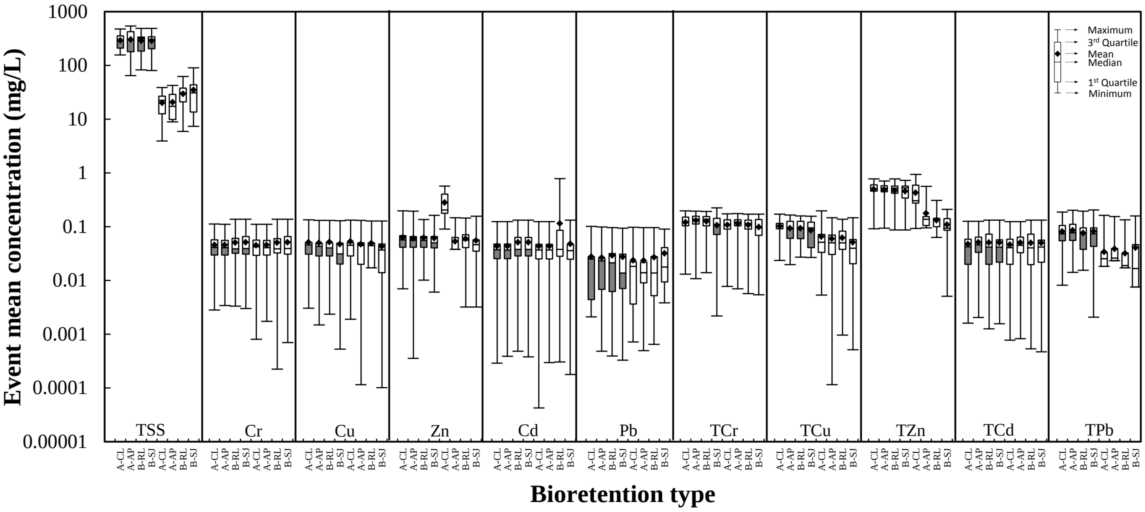

Fig. 2 Boxplot of inflow and outflow event mean concentrations in each bioretention system

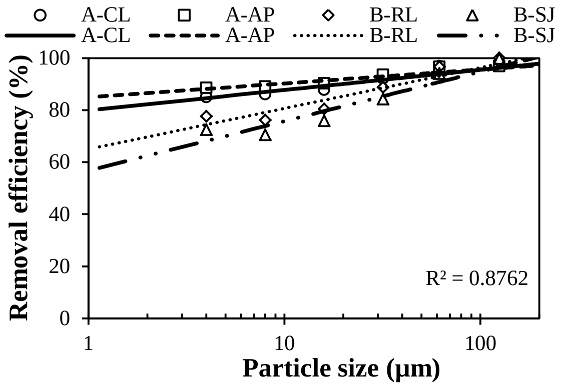

Fig. 3 Logarithmic regression plot of mean removal efficiency for different TSS particle size in each bioretention

and discharging to the sewer systems. Results were statistically analyzed using SYSTAT 12 and Origin Pro 8 package software. Statistical analyses include one way analysis of variance (ANOVA) and Pearson correlation analysis to determine the difference between the variance of the each water quality parameters and the dependence between each water quality parameter, respectively. Significant differences between parameters were accepted at 95% confidence level, signifying that probability (p) value was less than 0.05.

3. Results and Discussion

3.1 Characteristics and behavior of TSS and heavy metals in bioretention systems

The ranges of inflow and outflow EMC in A-CL, A-AP, B-RL and B-SJ are shown in Fig. 2. Inflow TSS mean EMC (EMCin) in A-CL, A-AP, B-RL and B-SJ which were 292 ± 101, 304.4 ± 150, 287 ± 117 and 290 ± 122 mg/L, respectively were significantly reduced to outflow TSS mean EMC (EMCout) of 20.1 ± 10.6, 20.5 ± 11, 29.5 ± 15.5 and 35 ± 24 mg/L ($p < 0.001$). Among the heavy metals constituents analyzed, only total Pb (TPb) EMCin was significantly lower from 0.08 ± 0.05 mg/L compared to EMCout of 0.04 ± 0.04 mg/L in A-CL (TPb: $p = 0.04$; other soluble metal except TPb: $p > 0.05$). For A-AP, only total Zn (TZn) and TPb were significantly reduced from EMCin 0.49 ± 0.17 and 0.09 ± 0.05 mg/L compared to EMCout which were 0.18 ± 0.13 and 0.04 ± 0.04 mg/L, respectively (TZn: $p < 0.001$; TPb: $p = 0.02$; other soluble metal except TZn and TPb: $p > 0.05$). On the other hand, among the total heavy metal constituents, B-RL and B-SJ significantly reduced total Cu (TCu), TZn and TPb EMCin by about 0.03 to 0.04, 0.28 ± 0.31 and 0.04 ± 0.05 compared to EMCout ($p < 0.05$). The minimum and maximum values of EMCout of all the constituents in A-CL, A-AP, B-RL and B-SJ were less than the minimum and maximum values of EMCout except, Zn and TZn in A-CL, in A-AP and Cd in B-RL implying that the systems developed showed efficiency in reduction pollutant EMC in the synthetic stormwater runoff applied in the system.

The foundation of filtration capacities of bioretention systems resulting to high particulate removal efficiency is most commonly associated with filtration theory for rapid and slow sand filtration (Li and Davis 2008a). Although, the study conducted by Li and Davis also enumerated several factors that made the filtration mechanism of bioretention systems differs from rapid and slow sand filters including the variability of runoff behaviors in bioretention systems and employing significantly different filter medium between the two systems. 80% of the inflow TSS load in each bioretention system was categorized as silt and sand. A-CL and A-AP yielded less difference in TSS inflow and outflow particle sizes compared to B-RL and B-SJ ranging from 0.5% to 15%. As shown in Fig. 3, the removal of smaller TSS particles was greater in A-CL and A-AP compared to B-RL and B-SJ. These finding was associated with the ponding capacity employed in the design of B-RL and B-SJ. Ponding mechanism employed in B-RL and B-SJ caused smaller particles to be dragged by the water in the system making it difficult to undergo the process of sedimentation and filtration. Retaining the larger particles in

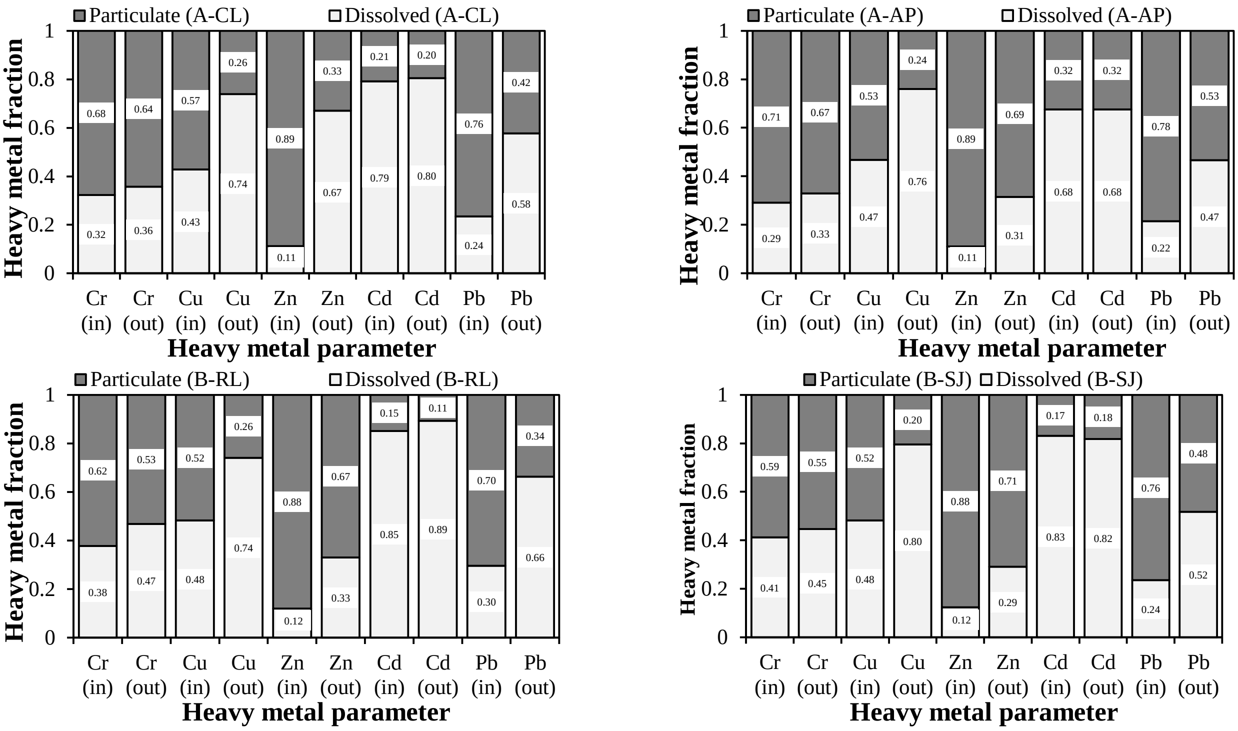

Fig. 4 Normalized fractional distribution of inflow and outflow heavy metal loads in each bioretention system

the system enabled the bioretention system to have cake formation at the top sand layer. The cake formation or sediment particle accumulation in the top sand layer both had an advantage and disadvantage. Sediment that accumulated in the surface of bioretention was usually coarse TSS particles which can help in TSS capture for the succeeding inflow TSS loads. However, Li and Davis found that clay-sized TSS particles are usually the cause of clogging in media (Li and Davis 2008b).

Maniquiz *et al*. identified that transportation land uses highly contributed to NPS pollution including heavy metals (Maniquiz 2010c). However, in the study conducted by Brown and Peake, it was identified that heavy metal concentrations from suspended solids in urban (road) and rural catchment has almost similar concentration (Brown and Peake 2006). Controlling the heavy metal constituents in stormwater runoff is necessary since high metal concentration discharge to surface water may be detrimental to the living organisms in the surface water bodies. Similarly, identifying the forms of heavy metals in runoff is important to determine the most appropriate treatment approach should be employed to the treatment system.

The fractional distribution of heavy metal loads is displayed in Fig. 4. Apparently, the heavy metals in the synthetic runoff applied to A-CL, A-AP, B-RL and B-SJ were particulate bound in nature except for Cd. Similar results in terms of heavy metal constituents predominantly the particulate-bound reduction were yielded by A-CL, A-AP, B-RL and B-SJ. These results implied that the filtration mechanism employed in each bioretention was an effective way to reduce the particulate bound heavy metal in runoff. Teng and Sansalone identified that relative size ratio of the filter media and the infiltrating particle size account for the removal of particles in the stormwater runoff (Teng and Sansalone 2004). Therefore, in order to increase the removal efficiency of the particulate and soluble heavy metal, smaller particle of soil must be employed in bioretention considering the infiltration rate required in the design. Sansalone *et al*. 1996 also identified that the most appropriate treatment mechanism for dissolved heavy metals is adsorption through media with large surface area.

3.2 Heavy metal mass balance in bioretention systems

In Fig. 5, the mass balance of each heavy metal constituent in the bioretention system was illustrated. It is evident that the infiltration mechanism employed in the design of B-RL and B-SJ accounted for the decrease in heavy metal discharge of the bioretention systems compared to A-CL and A-AP. Among the pollutants, TCr and TCd attained the greatest discharged fraction of 0.52 to 0.81 and 0.65 to 0.87, respectively. On the other hand, excluding the effect of soil media, TPb attained the greatest retention fraction in the bioretention systems developed amounting to 0.15 to 0.34. Considering the least discharge fraction of heavy metal in the bioretention system, it can be concluded that the bioretention systems developed achieved effectual reduction in terms of TCu, TZn and TPb. However, compared to the bioretention systems developed by Davis *et al*. the system developed in this study achieved less heavy metal removal efficiency associated with the difference in soil media configuration employed in this study. For designs considering greater heavy metal removal, it is suggested that pH of the soil mixture must be engineered to upper or lower ranges of pH scale (Davis *et al*. 2001). In order to achieve good pollutant removal efficiency, the soil configuration that will be used in the

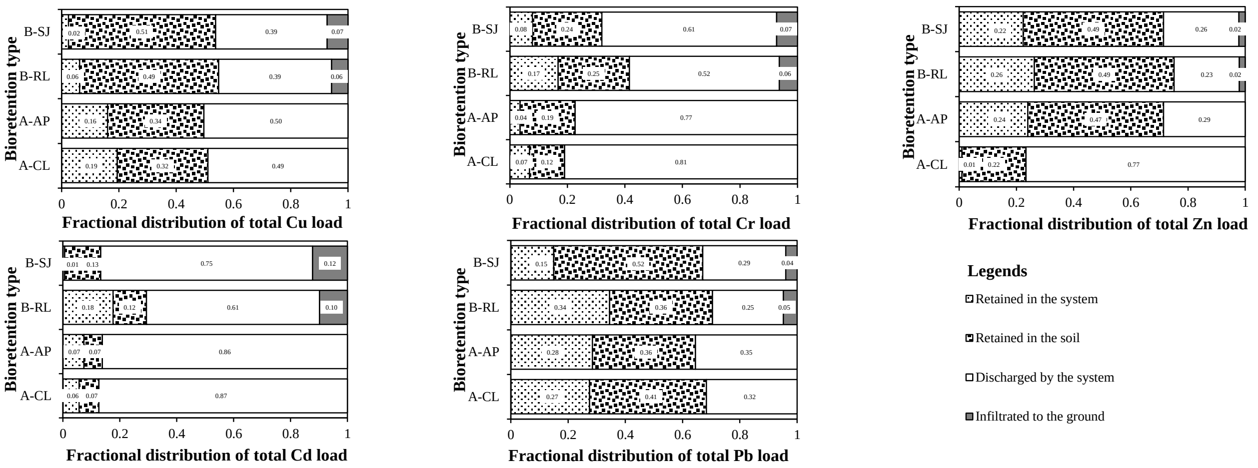

Fig. 5 Multiple plots of fractional heavy metal mass balance in each bioretention systems

Table 1 Heavy metal accumulation factor (g/g) in bioretention soil

Parameter	unit	Bioretention type			
		A-CL	A-AP	B-RL	B-SJ
Cr	g/g*	0.12	0.19	0.25	0.24
Cu	g/g	0.32	0.34	0.49	0.51
Zn	g/g	0.22	0.47	0.49	0.49
Cd	g/g	0.07	0.07	0.12	0.13
Pb	g/g	0.41	0.36	0.36	0.52

* implies gram of heavy metal per gram of soil

Table 2 Average concentration of heavy metal constituents in Korea (Adapted from Mercado *et al*. 2012)

Land use		Parking lots	Road
Parameter	units	Mean concentrations	
Cu	μg/L	1224.5	132.4
Zn	μg/L	213.3	145.9
Pb	μg/L	116.4	77.0

bioretention systems is important. Sandy soil that was used in this study exhibited poor soluble metal removal but satisfactory total heavy metal removal. These findings were associated with the poor adsorption capacity of the soil used in each bioretention system.

3.3 Estimation of heavy metal accumulation and bioretention soil life span

The heavy metal accumulation factor in soil is presented in Table 1. The heavy metal accumulation factor was calculated by dividing the heavy metal load accumulated in soil with the total inflow heavy metal load. It was observed that among the three parameters included in soil contamination standard of Korea, only TCu accumulation factor was not highly variable with respect to bioretention type compared to TPb and TZn. Therefore, TCu can be used as a factor in designing similar bioretention system.

All stormwater management facilities have service life. Upon reaching the service life of these LID or GSI, the facilities were rendered useless in terms of its designated stormwater management goal. Several maintenance guidelines regarding BMP were published by U.S. EPA. However, the frequency of maintenance and schedule of maintenance in each facility usually varies. In bioretention systems, one of the most important factors that should be considered is the accumulation of heavy metal in the planting soil. Davis *et al*. 2003, estimated the lifetime accumulation of heavy metal levels in infiltration BMPs. Parameters such as runoff volume, runoff coefficient; BMP surface area, catchment area and typical metal concentration in urban runoff were used. The limiting factor used was the soil heavy metal limits set by U.S. government. Similarly, the lifetime of bioretention developed in this study was estimated using Eq. 1. Unlike the estimation used by Davis *et al*. the estimation used in this study included the metal accumulation factor calculated by dividing the heavy metal load accumulated in soil with the total inflow heavy metal load. The factors calculated in this study were explained in part 3 section 3 of the results of this study. The typical heavy metal concentration in road and parking lot runoff was based on the study of Mercado *et al*. 2012 exhibited in Table 2. Parameters such as Cu, Zn and Pb were selected as focus of this part since the government of Korea provided soil contamination standard considering these heavy metals (MOE 2011). The runoff coefficient was assumed to be 0.9. Summarized in Table 2 were the estimated life span of the bioretention systems developed considering its application to roads and parking lots.

$$N = ((SS-SLin)*1000)/(R*RC*CA*C*MF) \quad (1)$$

where: N = number of years; SS = Soil standard limit (g); $SLin$ = Initial metal load in soil (g); R = Average annual rainfall depth (m); RC = Runoff coefficient; CA = Catchment area (m^2); C = Typical metal concentration in runoff (g/m^3); MF = Metal accumulation factor in soil;

Using Eq. 1 and the water quality volume equation, the regression plots of bioretention system life span with respect to the ratio of facility surface area (SA) and CA was developed as shown in Fig. 6. Among the three heavy metals of concern, Cu was used in developing design criteria since the Cu retention is type A and type B were highly varaiable considering A-CL, A-AP, B-RL and B-SJ.

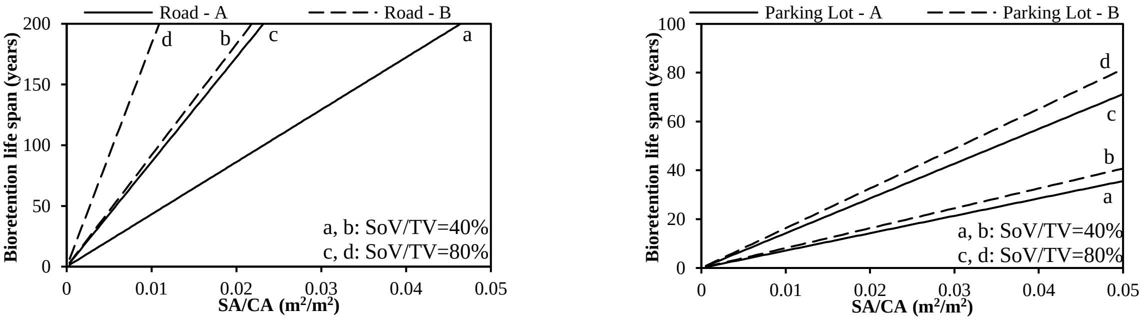

Fig. 6 Regression plots of facility surface area to catchment area ratio with respect to bioretention life span applied to roads (a) and parking lots (b)

Table 3 Estimation of bioretention life span based on soil concern standards of South Korea

Para-meter		Time before exceeding concern limit				Time before exceeding concern limit			
	Bioretention type	A				B			
	Load concern limit	Parking lots		Roads		Parking lots		Roads	
	mg/kg	CL yr	AP yr	CL yr	AP yr	RL yr	SJ yr	RL yr	SJ yr
Cu	2000	6	5	35	34	8	8	95	88
Zn	2000	2	23	22	56	48	48	149	122
Pb	700	13	19	32	29	41	29	91	73

For a bioretention to be applied on a 200 m^2 road catchment that considers a life span of 20 years, the corresponding SA should be 1.4% and 1.2% of the CA for bioretention type A and B, respectively. On the other hand, for a similar bioretention design requirement to be applied on a 200 m^2 parking lot catchment, the corresponding SA should be 0.2% and 0.1% of the CA for bioretention type A and B, respectively.

5. Conclusions

The four lab-scale bioretention systems were effectual in heavy metal reduction that was attributed to the soil medium used in each reactor. Several treatment mechanisms including sedimentation, filtration, infiltration, sorption, biological uptake, evapotranspiration, bioremediation and phytoremediation were incorporated in the system which made it an advance stormwater management technology compared to other systems. Particularly, the following conclusions were drawn from the results:

• The bioretention systems developed achieved highest TSS removal efficiency ranging from 89% to 94% followed by nutrients total heavy metals and soluble heavy metals, respectively. Meanwhile, only 0.3 to 15% and 0.24 to 13% of the influent load infiltrated in B-RL and B-SJ, respectively.

• Greater removal efficiency for TSS particle size ranging from 4 to 32 µm was exhibited by A-CL and A-AP were associated with the ponding capacity employed in B-RL and B-SJ that caused smaller particles to be dragged by runoff in the systems.

• The soil medium was able to adsorbed 7% to 52% of the total influent heavy metal loads signifying that adsorption and filtration were the main mechanisms for the removal of heavy metal constituents in bioretention.

• Heavy metal accumulation rate in bioretention soil of A-CL and A-AP were less compared with B-RL and B-SJ except for TPb signifying that greater fraction of inflow heavy metal load were retained in the planting soil of B-RL and B-SJ. The results of this study may be used for estimating the maintenance requirements of bioretention systems.

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