Water Science & Technology | 69.7 | 2014

Particle retention in compact constructed wetlands treating highway stormwater

Yaoping Chen, Kisoo Park and Youngchul Kim

ABSTRACT

Three pilot-scale compact constructed wetland systems were constructed to treat stormwater from a highway. They each comprised a sedimentation tank, and a vertical flow (VF) wetland bed equipped with a recirculation device. The VF wetland beds were filled with woodchip, pumice and volcanic gravel, respectively. According to the analysis of the particle size distributions (0.52–500 μm), the predominant particles in stormwater ranged in size from 0.52–30 μm. In the sedimentation tank, with a 24 h settling time, the settling efficiencies of the particles increased with increasing particle size. In the VF wetland beds, further capture of the particles was achieved; however, the woodchip and volcanic gravel wetlands displayed relatively low trapping of micro-particles, due to the natural properties of the substrates. Recirculation caused a positive effect on the retention of particles in the woodchip wetland. Due to the employment of a pre-treatment tank and the high porosity of materials, the accumulated solids occupied very low proportions of the pore volume in the wetland substrates. The results also showed that the accumulation of copper, zinc and lead do not pose a problem for the disposal of the substrates when the wetlands reach the end of their operational lifetime.

Key words | non-point source pollution, particle retention, stormwater, substrate, vertical flow wetland

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INTRODUCTION

Stormwater runoff from paved areas, such as highways, parking lots, and roofs, has become a major non-point pollution source in many urban areas, due to the high loads of pollutants in the first-flush (Davis *et al.* 2001; Kayhanian *et al.* 2007). Amounts of pollutants carried by stormwater have been documented to be particulate-associated, especially in fine to medium particles, which accounted for most of the total suspended solids (TSS) loads and solid pollutant loads. Researchers stated that 70–80% of the TSS load in stormwater was contributed by particles of less than 50 μm in diameter (Roger *et al.* 1998; Andral *et al.* 1999). In Furumai's *et al.'s* (2002) study, more than 50% of the particulate mass of runoff samples with a TSS concentration of less than 100 mg/L was related to particles of less than 20 μm. The finest particles in highway runoff had the highest concentration for many pollutants, especially metals (Morquecho & Pitt 2003; Yu *et al.* 2010). Most of the particulate phosphorus and nitrogen were attached to particles between 11 and 150 μm in diameter, with 30–60% of particulate total nitrogen (TN), and 30–50% of particulate total phosphorus (TP) associated with particles of less than 20 μm (Vaze & Chiew 2004). These findings suggested that removal of small particles is an important issue for the treatment of stormwater.

Subsurface flow constructed wetlands have been shown to be an attractive and stable alternative for the treatment of stormwater, due to their low costs, energy savings, esthetic values, and easy operation and maintenance (Rousseau *et al.* 2008). In the case of vertical flow (VF) stormwater wetland, suspended particles are detained via the mechanisms of filtration and adsorption. The removal of particles not only affects the wetland's treatment performance, but is also associated with clogging of the bed and the future disposal of the substrate due to the accumulation of heavy metals. In this paper, particle retention in three compact constructed wetlands was investigated, by measuring the particle size distributions in stormwater, settled stormwater, and effluents of the wetlands.

doi: 10.2166/wst.2014.026

MATERIALS AND METHODS

Design of the compact constructed wetlands

Three parallel compact constructed wetland systems were designed to treat stormwater collected from a highway (Figure 1). Each of them had a rectangular configuration, with dimensions of $1.3 \times 0.6 \times 1.1$ m^3 ($L \times W \times H$), and consisted of a sedimentation tank, and a VF wetland bed equipped with a recirculation device. The lengths of the sedimentation tank and the VF wetland bed were 0.5 and 0.8 m, respectively. The dimension of the recycle pump compartment was $0.2 \times 0.2 \times 1.1$ m^3 ($L \times W \times H$).

Woodchip, pumice and volcanic gravel were selected as the main substrate materials, and their physical characteristic are shown in Table 1. For the purpose of distributing the inflow or drainage, quartz stones (diameter: 4.8–5.5 mm), medium pebbles (diameter: 22.3–31.7 mm), and big pebbles (diameter: 24–36 mm) were employed as auxiliary materials. The packing order from top to bottom was quartz stones (5 cm), medium pebbles (5 cm), main substrate (60 cm), medium pebbles (10 cm), and big pebbles (10 cm); the main substrate varied with each wetland.

Before packing, all materials were washed off with clean lake water. *Acorus Calamus* was planted as wetland vegetation, without using soil. These wetland systems were located at the side of an asphalt road near Hanseo University, Seosan city in Korea, and were operated from May 29, 2012 to November 4, 2012.

Experimental operation

These wetlands employed a downward hydraulic regime, and were operated in batch mode. The water level was maintained at the middle of the substrate, to divide each wetland equally into two different strata: an upper unsaturated zone, and a bottom saturated layer. The stormwater used was the first-flush collected from a highway with a catchment area of 500 m^2. Due to the varying substrate porosity, 126, 102, and 120 L of stormwater were fed into woodchip, pumice, and volcanic gravel treatment units as a batch, respectively. For each batch treatment cycle, the stormwater was initially introduced into the sedimentation tank, allowed to settle for 24 h, and subsequently fed into the wetland beds with a flow rate of 23 m^3/day. The effluent from each wetland was completely recycled, to receive multiple filtrations every 6 h, in order to understand the effect of recirculation. The treatment period was designed as 3 days to simulate the short dry days occurring especially in summer due to the frequent rainfall. However, when there was no new stormwater available during long dry days, the treated water was retained in the wetland bed to support biofilm and plant growth until

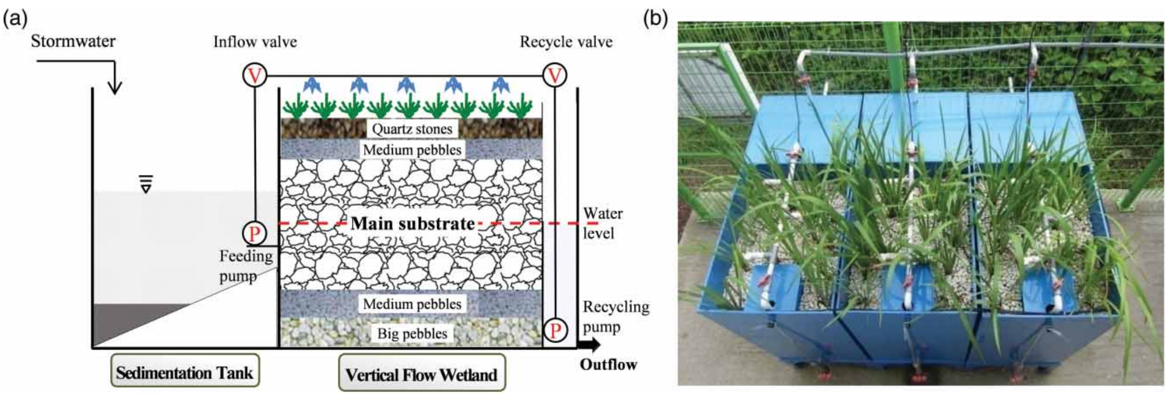

Figure 1 | Schematic diagram (a) and photograph (b) of the compacted wetland systems.

Table 1 | Specific information for the substrate materials

Materials	Range (mm)	*d_{10} (mm)	d_{50} (mm)	d_{60} (mm)	*U	Porosity (%)	Packing density (kg/m^3)
Woodchip	15.0–65.0	20	31	34	1.7	64	305
Pumice	6.0–13.0	7	9	9	1.29	55	390
Volcanic gravel	11.0–20.0	13.5	16	16.5	1.22	65	780

*d, the diameter of an equivalent volume of sphere; *U, uniformity coefficient.

the stormwater from the next rainfall was collected. The hydraulics of the wetlands is summarized in Table 2.

Empty bed contact time (EBCT), effective hydraulic retention time (EHRT), approach velocity (AV) and pore velocity (PV) were calculated by using the following equations:

$$\text{EBCT, day} = \frac{\text{Volume of the main substrate, m}^3}{\text{Stormwater fed as a batch, m}^3/\text{day}} \quad (1)$$

$$\text{EHRT, day} = \frac{\text{Volume of the pores in the main substrate, m}^3}{\text{Stormwater fed as a batch, m}^3/\text{day}} \quad (2)$$

$$\text{AV, m/day} = \frac{\text{Flow rate, m}^3/\text{day}}{\text{Surface area of the wetland bed, m}^2} \quad (3)$$

Table 2 | Hydraulic operation conditions

Wetland type	*NDDs (day)	Recycling	*EBCT (day)	*EHRT (day)	*AV (m/day)	*PV (m/day)
Woodchip	1	3	3.49	2.23	52	82
	2	7	3.49	2.23	52	82
	3	11	3.49	2.23	52	82
Pumice	1	3	4.31	2.37	52	95
	2	7	4.31	2.37	52	95
	3	11	4.31	2.37	52	95
Volcanic gravel	1	3	3.67	2.38	52	80
	2	7	3.67	2.38	52	80
	3	11	3.67	2.38	52	80

*NDDs – Number of dry days; *EBCT – Empty bed contact time; *EHRT – Effective hydraulic retention time; *AV – Approach velocity; *PV – Pore velocity.

$$\text{PV, m/day} = \frac{\text{Flow rate, m}^3/\text{day}}{(\text{Surface area of the wetland bed, m}^2) \times (\text{Main substrate porosity, \%})} \quad (4)$$

Sampling and measurements

Eighteen rainfall events were monitored during the operational period. Samples of stormwater ($n = 18$), settled stormwater ($n = 18$), and daily effluents from each wetland ($n = 162$) were taken for all of the rainfall events. Particle size distributions were measured within 6 h after sampling, by means of an AccuSizerTM 780A particle analyzer, which quantifies the number of particles in 255 intervals, over the range of 0.52–500 μm. Heavy metals (copper, zinc and lead) were determined by using an ICPS-7510 sequential plasma spectrometer.

RESULTS AND DISCUSSION

Particle size distributions in stormwater

Figure 2 shows the distribution of the particles in stormwater for all of the investigated rain events. The horizontal axis indicates the individual particle diameter range. The box plots, which correspond to the left vertical axis, display the number or volume percentages of the particles in each size range. The continuous lines corresponding to the right vertical axis show the cumulative number or volume

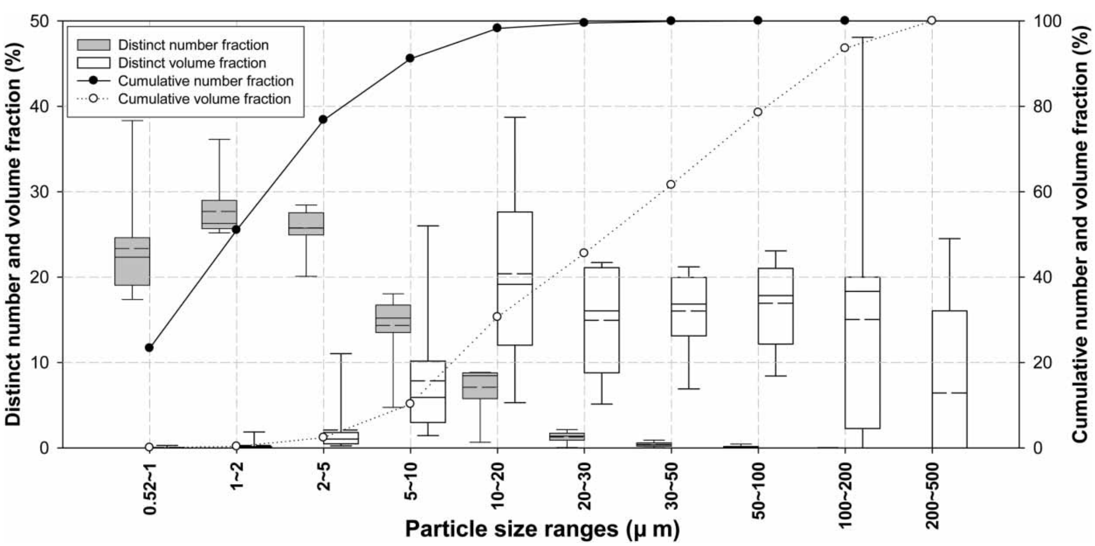

Figure 2 | Particle size distributions in stormwater.

percentages of the particles. According to this figure, the content of the particles fluctuated largely among the varied size ranges. Smaller particles contributed a larger proportion in number, but a relatively smaller fraction in volume. Overall, particles in the size range of 0.52–30 μm were predominant in the stormwater, which accounted for nearly 99% in number, and about 45% in volume.

Particle removal in sedimentation tank

Figure 3 displays the removal efficiencies of particles with respect to particle size range in the sedimentation tank (particles larger than 30 μm are not included, because of their very small contribution in number). As can be seen, the retention efficiency of particles increased with the increasing size range. More than 80% of the particles in the size range of 10–30 μm was detained, whereas only an approximate 40% reduction was observed for particles smaller than 1 μm. This is consistent with the study of Li *et al.* (2005), wherein larger particles in stormwater showed higher removal efficiency than smaller particles, due to the greater settling velocity. For micro-particles of less than 1 μm, the removal mechanism would not be the sedimentation, but diffusion, which is largely affected by coagulation and flocculation, due to the electrostatic interactions between the particles; thus, the removal efficiency was low (Symons 1990). This is exemplified by Stokes' Law: the coarsest clay particle with a density of 2.65 g/cm^3 needs a minimum of 88 h for settling, in a 1 m column at a temperature of 15 °C (Braskerud 2003). Thus, the settling time of 24 h in the present study was insufficient for the settling of micro-particles.

Particle retention in the VF wetland beds

Figure 4 shows the average retention efficiencies of the particles by number, in the different size ranges in the VF wetlands. In general, the pumice wetland displayed the highest particle capture, of more than 90% in all the size ranges, due to the smaller void spaces resulting from smaller grain size and higher adsorption capacity (Chen *et al.* 2013). However, lower efficiencies were observed in the woodchip and volcanic gravel wetlands, especially for the micro-particles smaller than 1 μm. With the exception of the larger grain size and lower adsorption capacity, the release of particles from biodegradable woodchip and fragile volcanic gravel might be other reasons.

To easily explain the effect of recirculation on particle retention, the term number of dry days (NDDs) is used instead of the term recirculation in this paper. Figure 5 represents the effects of recirculation on particle removal efficiency in different wetlands. For the woodchip wetland, enhanced particle retention efficiency was found with increasing NDDs, especially during the first two treatment days. However, only a slight impact was observed in the subsequent treatment day, which means that longer NDDs may be unnecessary in removing particles. In the pumice wetland, the removal efficiencies of the particles between different NDDs were similar. This is because more than 90% of the particles in all the size ranges were trapped during the first treatment day. Therefore, it was difficult to further remove particles by increasing NDDs. A similar observation was made in volcanic gravel wetland, except for the micro-particles. For the particles in the size range of 0.51–2 μm, the volcanic gravel wetland showed worse capture than the pumice wetland. This was probably due to the leaching out of debris from the

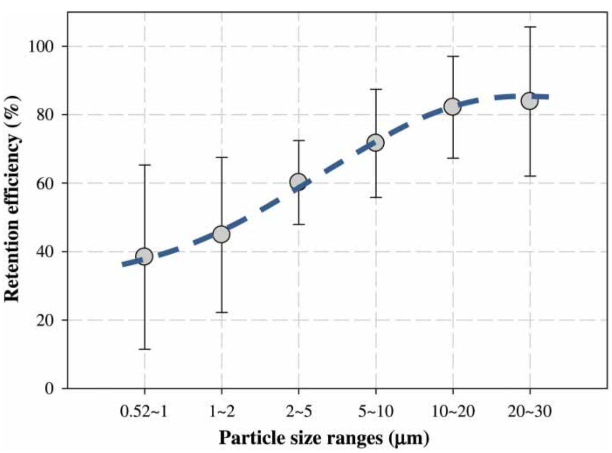

Figure 3 | Particles retention efficiency in sedimentation tank by number.

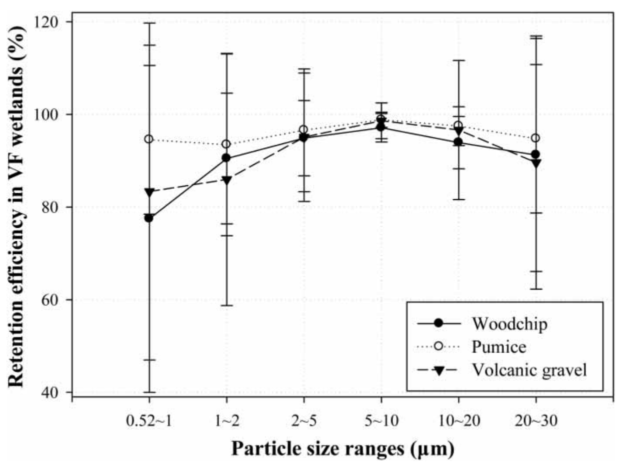

Figure 4 | Particle trapping efficiency in VF wetlands by number.

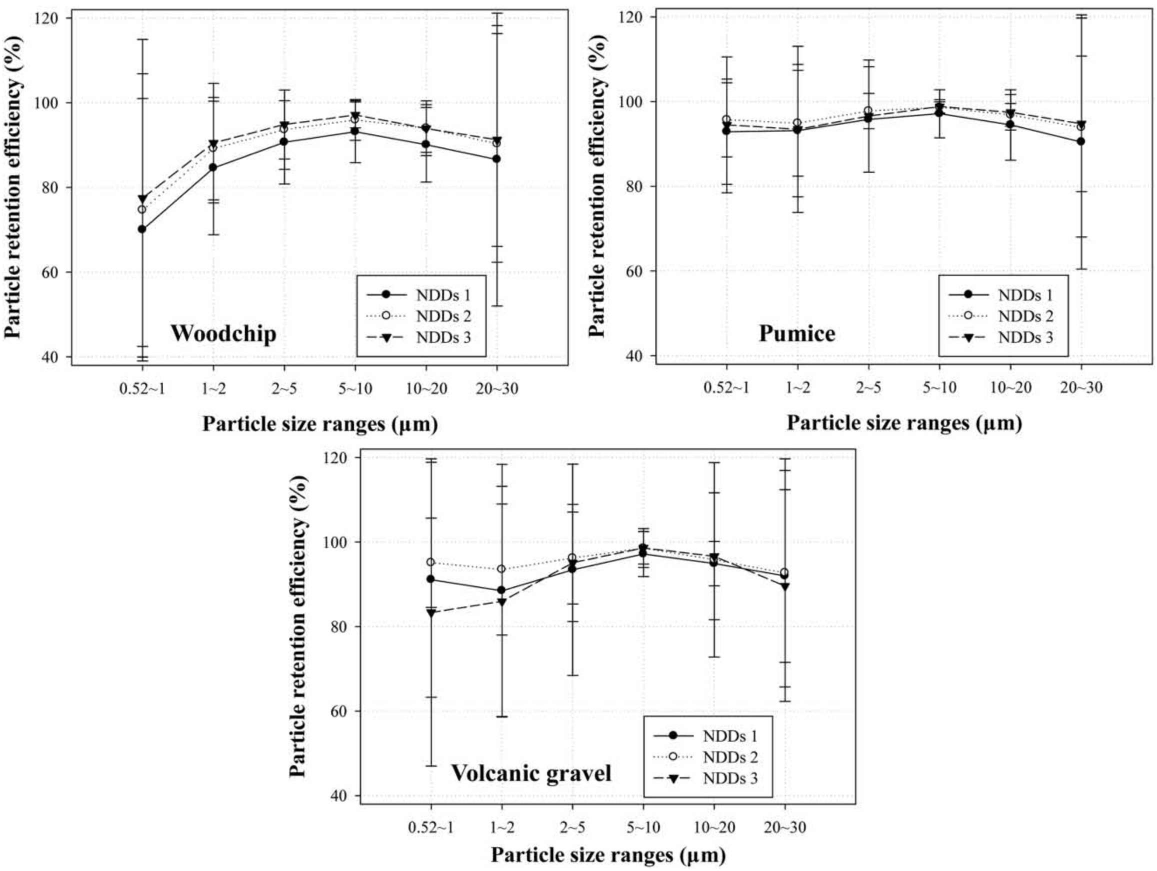

Figure 5 | Effects of recirculation on particle retention efficiency by number.

broken volcanic gravel during the wetland installation, because the volcanic gravel was angular and brittle.

Particle accumulation in the wetland beds

Assuming the individual particles to be of spherical geometry, the total volume of the trapped particles in the VF wetlands was estimated by summing up the volumes of the individual particles. Table 3 shows the accumulation of the particles by volume through the operation period. The greatest accumulation was found in the pumice wetland with 1.57 L, followed by the woodchip wetland with 1.18 L, and the volcanic gravel wetland with 0.51 L, which contributed low proportions of 1.15, 0.74, and 0.32% of the pore volume in the wetland substrate, respectively, due to the utilization of a pre-treatment tank and the high porosity of substrates. Regarding substrate clogging, however, more operational data are required for further evaluation, since clogging develops as time passes. Furthermore, the accumulation of the suspended solids, the biofilm growth, and the development of plant root as well as the debris coming from broken media also affect the clogging process (Knowles *et al.* 2011; Pedescoll *et al.* 2011).

Table 3 | Accumulation of particles in the wetland beds

Wetland type	$V_{substrate}$ (L)	V_{pores} (L)	$V_{particles}$ (L)	$P_{particle}$ (%)
Woodchip	247	158.4	1.18	0.74
Pumice	247	136.1	1.57	1.15
Volcanic gravel	247	160.8	0.51	0.32

$V_{substrate}$ – volume of the substrate; V_{pores} – volume of the pores in the substrate; $V_{particles}$ – volume of the trapped particles; $P_{particle}$–$V_{particles}/V_{pores} \times 100$.

Heavy metals accumulation in the wetland beds

Heavy metals from leaded gasoline, tire wear, brake linings, oil, and grease are the main contributors of highway stormwater pollution. An analysis on the retention of three heavy metals (copper, zinc and lead) were made, to evaluate the risk of the substrate becoming a contaminated site, according to the 1 year of operational data and the strictest legal limits of the threshold concentrations in soil from the Korean Ministry of Environment (KME 2013). The total accumulation (M, mg/year), the accumulation rate in the substrates (R, mg/kg · year), and the working time of the substrates before becoming contaminated sites (T, year) were calculated by using the following equations.

$$M\text{, mg/year} = (C_{\text{in}} - C_{\text{out}}) \times Q \times N \quad (5)$$

$$R\text{, mg/kg} \cdot \text{year} = \frac{M\text{, mg/year}}{\text{Substrate mass, kg}} \quad (6)$$

$$T\text{, year} = \frac{\text{Legal threshold in soil in Korea, mg/kg}}{R\text{, mg/kg} \cdot \text{year}} \quad (7)$$

where C_{in} and C_{out} are the average influent and effluent concentrations of the metals of the beds, Q is the stormwater volume fed to each bed as a match, and N is the number of the rainfall events. As shown in Table 4, the accumulation of the investigated heavy metals in the substrate takes at least 75 years before reaching contaminated site concentration thresholds. This does not cause a problem, because this period is longer than the expected wetland lifetime (around 15 years). The worst situation is related to the accumulation of zinc in the woodchip wetland.

CONCLUSIONS

The results show that the compact constructed wetlands were capable of accomplishing good treatment of particles carried by urban stormwater. The particles ranging in size 0.52–30 μm were predominant in the stormwater used as the influents. The sedimentation tank as a pretreatment facility was a necessary element, especially for the removal of large particles, in which most of the particles larger than 10 μm were detained at a 24 h settling time. Through filtration, further particle capture was achieved in all the VF wetlands. The substrate type had a significant effect on the retention of the micro-particles, due to the biodegradability, physical strength and grain size of the substrate materials. The employment of organic and fragile materials showed a relatively low capacity in capturing the micro-particles. Recirculation of the effluents was able to elevate particle retention in the woodchip. Owing to the utilization of a pre-treatment tank and the high porosity of the substrate materials, very low occupancy of the substrate pores was observed in the VF wetland beds. The results also showed

Table 4 | Risk evaluation of the accumulated heavy metals in the wetland beds

Heavy metal	Cu			Zn			Pb		
Wetland bed	***W**	***P**	***V**	**W**	**P**	**V**	**W**	**P**	**V**
Influent to bed, μg/L	*114.2 (22.8)			300.2 (279.2)			60.9 (17.8)		
Effluent from bed, μg/L	97.8 (13.5)	89.4 (7.2)	98.4 (14.3)	143.1 (72.4)	75.7 (6.3)	79.1 (8.7)	52.6 (10.1)	53.4 (9.9)	54.4 (9.9)
Total accumulation, mg/year	37.2	45.5	34.1	356.3	412.2	477.6	18.8	13.8	14.0
Substrate mass, kg	80.5	103.0	205.9	80.5	103.0	205.9	80.5	103.0	205.9
Accumulated rate, mg/kg · year	0.46	0.44	0.17	4.43	4.00	2.32	0.23	0.13	0.07
Legal threshold in soil in Korea, mg/kg	150			300			200		
Working time, year	326	340	882	68	75	129	870	1538	2857

**W* – woodchip; **P* – pumice; **V* – volcanic gravel; *114.2 (22.8) – Average (STDEV).

that the accumulation of copper, zinc, and lead do not lead to an environmental problem for the disposal of the substrate material when the wetlands reach the end of their operational lifetime.

ACKNOWLEDGEMENT

This research was supported by the Korean Ministry of Environment, as 'The Eco-innovation Project (Non-point Pollution Management Research Center)'.

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First received 4 November 2013; accepted in revised form 6 January 2014. Available online 24 January 2014