Performance of a half-saturated vertical flow wetland packed with volcanic gravel in stormwater treatment

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ABSTRACT

A half-saturated pilot-scale wetland planted with *Acorus calamus* was built to treat urban stormwater. The design comprises a sedimentation tank for pretreatment, and a vertical flow volcanic gravel wetland bed equipped with a recirculation device. Eighteen rainfall events were monitored in 2012. The treatment system achieved total removal efficiencies of 99.4, 81, 50, and 86% for suspended solids, organic matter, nitrogen and phosphorus, respectively, and 29, 68, and 25% for copper, zinc, and lead, respectively, at a 3-day hydraulic residence time. In the wetland bed, the removal of ammonia, total nitrogen, and zinc were improved by recirculation. Plant uptake provided 18% of nitrogen removal and 39% of phosphorus removal. During the experimental stage, only 1.4% of the pore volume in substrate was reduced due to clogging, implying that the wetland can operate without clogging for a relatively long period.

Key words | non-point source pollution, stormwater, vertical flow wetland, volcanic gravel

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INTRODUCTION

Stormwater runoff from urban areas has been identified as a major contributor of non-point source pollution to receiving waters. Various facilities have been developed to prevent the spread of pollutants, such as infiltration basins, grass swales, porous pavements, wet detention basins, sand filters, and constructed wetlands (Tsihrintzis & Hamid 1997).

As an important type of wetlands, vertical flow (VF) wetlands have been widely used as on-site treatment, especially in an area with limited land available. In a VF wetland, the pollutants are removed or transformed via microbial degradation, plant uptake, sorption, sedimentation, and filtration (Brix & Arias 2005). Suspended solids as well as biochemical oxygen demand (BOD) and ammonia can be efficiently removed in VF wetlands (Cooper 2005; Vymazal 2007; Kadlec & Wallace 2009). In order to further improve treatment efficiency, some methods are implemented in VF wetlands, such as supplementary aeration, intermittent feeding, recirculation, and half-saturated zone (Zhu *et al.* 2013; Chen *et al.* 2013).

Based on previous studies, the most important factors towards VF wetlands design include a good bed matrix, which allows the passage of water and provides adequate contact time between pollutants and bacteria, and a sufficient surface area that allows oxygen transfer to occur and sufficient bacteria to grow (Cooper 2005). Several available materials, such as sand, gravel, blast furnace slag, woodchips, zeolite and bauxite (Korkusuz *et al.* 2007; Zhang *et al.* 2009; Stefanakis & Tsihrintzis 2012a; Niu *et al.* 2013), have been employed. Moreover, it is suggested to select high porosity media and to pretreat the inflow in sedimentation basins to reduce clogging risk (Brix & Arias 2005).

In this study, a VF stormwater wetland packed with volcanic gravels was built to treat rainfall runoff from paved roads. The objectives of this study were to evaluate the removal capacities of this treatment system in terms of suspended solids, organic matter, nutrients, and heavy metals carried by urban runoff, as well as the cumulative effect and distribution of clogging matter.

MATERIALS AND METHODS

Site description

The study site was located in Seosan, Korea (36.7°N, 126.6°E), with an altitude of 100 m. The average annual temperature is 11.7 °C, with the lowest and highest average monthly temperature of −1.9 °C in January and 25.0 °C in August, respectively. The average annual rainfall is 1,232.1 mm, with summer average rainfall of 654 mm. This stormwater wetland was developed as a test towards a future field application for the treatment of the first-flush collected from a highway runoff, corresponding to a catchment area of 500 m^2 (wetland

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area to catchment ratio is 1.5%). In Korea, the initial 5 mm of runoff is generally considered for treatment because of the higher pollutant content; the ratio of wetland area to the watershed area should be less than 3%.

Prior to the field application, a proportionally minified pilot-scale stormwater wetland was constructed to test the pollutant removal capacity (Figure 1). It had dimensions of $1.3 \times 0.6 \times 1.1$ m, and was vertically divided into a settling tank and a VF wetland bed with respective lengths of 0.5 and 0.8 m. A recirculation device was installed on the wetland bed to provide multi-filtration. In a future full-scale design, the settling tank will also work as a stormwater capture device. The required volume of stormwater can be collected, and excess runoff would be bypassed automatically. Table 1 summarizes the physical properties of the materials used. Volcanic gravel was employed as the main substrate, and the packing order and depths are shown in Figure 1. *Acorus calamus* was transplanted in late April at a density of 38 plants/m^2. This wetland was built in April 2012, and operated from May to November 2012.

Operation

According to our laboratory test, at least 18 h were necessary for the effective settling of suspended solids. For an easy operation, the specific settling time varied from 18 to 42 h depending on the time when the stormwater was collected. Batch operation rather than continuous was implemented because of the intermittent rainfall runoff. During the operational period, 120 L of stormwater, which corresponds to the pore volume of the substrate submerged under the saturated zone, was initially introduced into the settling tank as a batch. After settling, the settled stormwater (ST) (outflow of settling tank) was fed into the wetland bed with an approach velocity of 55 m/day, corresponding to the rainfall event that has a return period of approximately 5 years.

The treatment cycle in the wetland bed was set at 3 days to simulate the short dry period occurring in the summer due to frequent rainfall. The effluent was regularly recycled to the top of the wetland bed to receive multi-filtration and support plant growth before it was finally discharged through the outlet in the bottom. The daily recycle frequency was set at three times in the first day and four times in the following 2 days, to achieve four times of filtration with an interval of 6 h. During the operational period, 18 rainfall events were monitored (Table 2). To get more operational data, stormwater from previous rainfall events was stored, and reintroduced and tested for two or three times when no new stormwater was available during long dry periods. The data obtained from duplicate

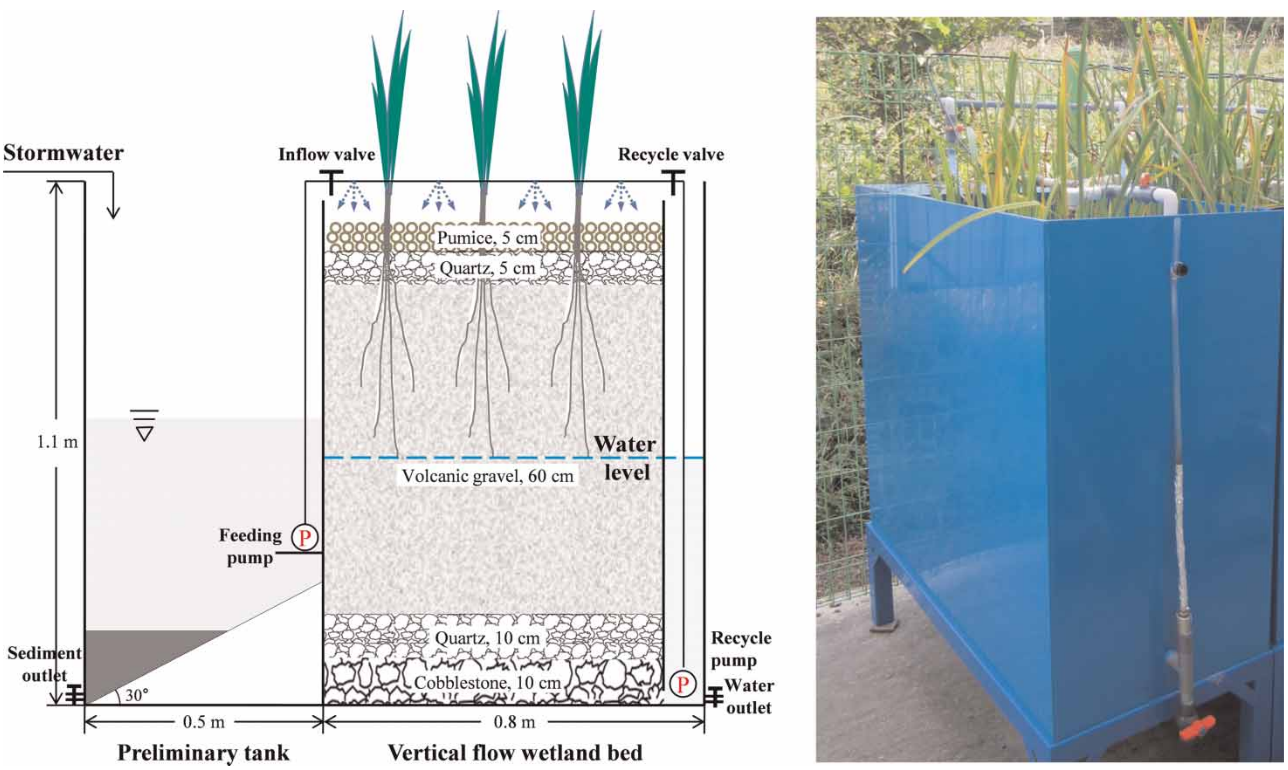

Figure 1 | Schematic diagram and photo of the half-saturated vertical flow stormwater wetland.

Table 1 | Physical properties of materials used as wetland substrate

Materials	Diameter (cm)	d_{10} (cm)	d_{50} (cm)	d_{60} (cm)	*U*	Porosity (%)	BD (kg m^{-3})	SA (m^2 g^{-1})
Volcanic gravel	1.1–2.0	1.35	1.60	1.65	1.22	65	780	4.56
Pumice	0.48–0.55	–	–	–	–	55	482	–
Quartz stone	2.2–3.2	2.28	2.51	2.60	1.13	40	1706	–
Cobblestone	2.4–3.6	2.70	2.95	3.00	1.11	37	1690	–

U, uniformity coefficient; BD, bulk density; SA, surface area; –, not measured.

tests was only used for the analyses of the nutrient removal pathway and clogging matter in the wetland bed.

Analysis and calculation

Water quality parameters were determined according to *Standard Methods* (APHA *et al.* 1998). Mass balance analysis was performed based on the following equation

$$M = \sum_{i=1}^{n} C_i \times Q_i \tag{1}$$

where M is the mass of pollutants in each treatment component (mg), C_i is the corresponding pollutant concentration (mg/L), Q_i is the fed stormwater volume as a batch, and n is the number of monitored rainfall events.

Plant monitoring was on a monthly basis to evaluate the accumulation of biomass and nutrients. In early November, the plant was harvested with a dry biomass of 0.82 kg/m^2. The removal of nitrogen and phosphorus by plant uptake was calculated by using the equation below

$$\text{Mass}_{N,P}, g = C_{N,P} \times M \tag{2}$$

where $\text{Mass}_{N,P}$ is the removed nitrogen or phosphorus; $C_{N,P}$ is the concentration of nitrogen or phosphorus in plant tissue, 8.09 and 0.57 g/kg, respectively; and M is the harvested dry biomass.

At the end of operation, the clogging matter accumulated in volcanic gravels was carefully washed out by using a banister brush, taking a depth of 10 cm as one layer. The mass and volume of the clogging matter, as well as the

Table 2 | Information about the monitored rainfall events

No.	Date	Rainfall depth (mm)	Rainfall duration (h)	Rainfall intensity (mm/h)	ADDs[a] (day)	Test number
1	2012–06–08	2.9	2.17	1.34	24.0	T1, T2
2	2012–06–29	6.4	4.25	1.51	20.0	T3, T4
3	2012–07–05	14.1	17.17	0.82	4.0	T5
4	2012–07–10	12.2	8.67	1.41	3.0	T6
5	2012–07–13	6.2	0.83	7.47	1.0	T7
6	2012–07–18	5.5	6.17	0.89	2.0	T8, T9
7	2012–08–10	11.0	8.58	1.28	9.0	T10
8	2012–08–12	161.3	15.83	10.19	1.0	T11
9	2012–08–20	138.1	23.22	5.95	4.0	T12, T13
10	2012–08–28	29.2	16.5	1.77	3.0	T14
11	2012–09–04	44.7	15.83	2.82	4.0	T15
12	2012–09–07	22.9	2.92	7.84	2.0	T16
13	2012–09–13	12.5	13.67	0.91	5.0	T17
14	2012–09–17	106.5	22.5	4.73	3.0	T18, T19, T20
15	2012–09–28	5.3	1.83	2.90	10.0	T21, T22, T23
16	2012–10–10	10.6	1.5	7.07	11.0	T24, T25, T26
17	2012–10–22	54.4	11.33	4.80	11.0	T27
18	2012–10–27	31.5	16.58	1.90	4.0	T28

[a]Antecedent dry days.

contents of chemical oxygen demand (COD), total nitrogen (TN), and total phosphorus (TP) at various depths, were measured. The accumulation degree of the clogging matter was calculated by using the equation below

$$\text{Accum.} = \frac{V_{CM}}{V_S \times P_s} \times 100 \quad (3)$$

where Accum. is the ratio of accumulated clogging matter to the pore volume in the main substrate (%), V_{CM} is the volume of accumulated clogging matter (2.25 L), V_S is the volume of main substrate (247 L), and P_s is the porosity of the volcanic gravel.

RESULTS AND DISCUSSION

Water quality parameter variation

As shown in Table 3, the temperature varied depending on the season, and was slightly low in the wetland effluents. The mean pH values were in the neutral area for all three sampling points, ranging from 7.02 to 7.65. Mean dissolved oxygen (DO) concentrations increased after filtration, indicating that the oxygenation was enhanced by the recirculation. The mean electrical conductivity (EC) values increased along the facilities probably due to the interaction between filter media and stormwater. The large variations of pollutants in the stormwater were influenced mostly by the antecedent dry days (ADDs). Usually, longer ADDs led to high pollutant content due to more accumulation during dry days followed by more wash-out during wet days.

Pollutant removal in sedimentation tank

Figure 2 shows the concentration variations of the pollutants along the various parts of the treatment unit and varying number of treatment days (NTDs). In the settling tank, total suspended solids (TSS) in stormwater greatly decreased by 92%, on average. The contents of COD, TN, and TP were reduced with an average removal efficiency of 67, 24, and 66%, respectively. It was observed that the removals of COD, TN, and TP were more or less increased with increasing TSS removal efficiency, with a correlation coefficient of 0.61, 0.30, and 0.48, respectively. The results indicate that most of the pollutants could be efficiently removed through settling, except for TN due to the amounts of dissolved forms of nitrogen. As for the dissolved heavy metals, copper, zinc, and lead were reduced by 18, 23, and 17%, respectively, on average.

Performance of the VF wetland bed

The VF wetland bed achieved excellent efficiency in TSS removal by 93%, on average (Figure 2). Smaller particles that escaped the sedimentation tank were captured in the pore space within the substrate. COD and soluble COD in the ST were reduced by 44 and 45%, respectively, percentages that are significantly low compared to the study of Stefanakis & Tsihrintzis (2012b), where 78% removal of COD was achieved in the VF wetland fed with synthetic wastewater with a high BOD/COD value of 0.84. The relatively low removal efficiency in this study is due to two reasons: one is that the inflow COD was predominantly in soluble form (accounting for 76%, calculated according to Table 3) that is difficult to be retained by filtration; and the other one is that a large proportion of COD was probably contributed by non-biodegradable compounds that were unavailable to the biofilm. This had been verified by a previous study (Langeveld *et al*. 2012) where the value of BOD_5/COD in stormwater ranged from 11.0 to 29.1% with a mean of 17.8%.

In this wetland, 95% of NH_4-N on average was transformed. This was mainly attributed to nitrification that was enhanced by recirculation by supplying more oxygen. However, the accumulation of NO_3-N was observed, implying that denitrification was not active because of insufficient available organic carbon, even though an anoxic zone locally existed. As a consequence, a TN reduction was achieved of 34% on average. Conversely, TP was removed by 60%. The reason for this is that particle-associated phosphorus was predominant and was removed with the solid particle at the time of filtration. In addition, zinc achieved the highest removal among the three metals – 59%. Copper and lead were removed by 13 and 11%, respectively.

The recirculation was found to elevate the treatment performance. The removals of NH_4-N and TN were respectively improved from 88 and 26% at NTDs = 1 to 95 and 34% at NTDs = 3. Zinc removal was enhanced from 52 to 59%. For the others, the removals were mostly achieved during the first day of treatment.

Material balance analysis

As shown in Figure 3(a), during the operational period, the total mass of TSS, COD, TN, and TP carried by the stormwater was 575, 366, 12.7, and 0.983 g, respectively; these were finally reduced in the settling unit and VF wetland to 3.3, 67.6, 6.4, and 0.135 g, respectively. The high retentions of particles and particulate-associated pollutants in the pretreatment tank were important for avoiding substrate

Table 3 | Variations of the water quality parameters and removal efficiencies

Parameters	Units	Stormwater		ST		Effluent at day 3		Removal (%)
		Range	Mean ± SD	Range	Mean ± SD	Range	Mean ± SD	
Temp.	°C	15.0–33.0	24.16 ± 5.4	13.5–30.0	23.6 ± 4.6	9.8–26.7	21.5 ± 4.8	–
pH	–	6.70–7.66	7.16 ± 0.28	6.58–7.34	7.02 ± 0.19	7.22–8.45	7.65 ± 0.26	–
DO	mg/L	4.51–11.46	7.44 ± 1.54	4.80–9.72	7.35 ± 1.19	6.60–10.70	8.91 ± 1.04	–
EC	μs/cm	55–1541	312 ± 342	114–1539	317 ± 338	180–1360	356 ± 295	–
Alkalinity	mg/L	19.6–74.5	41.0 ± 15.8	21.6–82.3	44.6 ± 19.7	54.9–88.2	71.6 ± 11.5	–
Turbidity	NTU	22.2–199.0	90.2 ± 55.4	5.0–150.0	25.4 ± 33.5	0.2–1.3	0.6 ± 0.4	99
TSS	mg/L	48.0–645.0	266.1 ± 166.9	4.5–95.0	21.0 ± 22.5	0–6.4	1.5 ± 1.9	99
COD	mg/L	49.7–331.4	169.5 ± 85.8	17.6–257.6	55.6 ± 58.4	7.9–84.1	31.3 ± 18.2	81
SCOD[a]	mg/L	10.5–217.4	49.6 ± 48.5	10.1–193.8	42.2 ± 43.6	8.3–50.0	23.2 ± 11.3	53
TN	mg/L	2.90–12.25	5.88 ± 2.55	2.01–12.63	4.51 ± 2.97	1.28–10.32	2.97 ± 2.02	50
NH_4-N	mg/L	0.16–4.21	0.87 ± 0.94	0.07–3.58	0.88 ± 0.85	0–0.10	0.05 ± 0.03	94
NO_3-N	mg/L	0.24–4.30	0.77 ± 0.90	0.22–2.19	0.63 ± 0.43	0.41–7.87	1.28 ± 1.70	– 66
TP	mg/L	0.12–0.85	0.46 ± 0.24	0.04–0.36	0.16 ± 0.09	0.01–0.25	0.06 ± 0.06	86
PO_4-P	mg/L	0–0.22	0.03 ± 0.05	0–0.06	0.03 ± 0.02	0–0.16	0.04 ± 0.05	7
Cu	μg/L	87.6–263.0	120.9 ± 50.5	93.6–167.4	114.2 ± 22.8	80.5–125.3	98.4 ± 14.3	29
Zn	μg/L	95.3–1279.8	327.4 ± 378.1	93.9–892.4	300.2 ± 279.2	67.5–97.2	79.1 ± 8.7	68
Pb	μg/L	35.5–142.1	64.7 ± 32.0	43.0–92.6	60.9 ± 17.8	35.1–63.4	54.4 ± 9.9	25

[a]Soluble chemical oxygen demand.

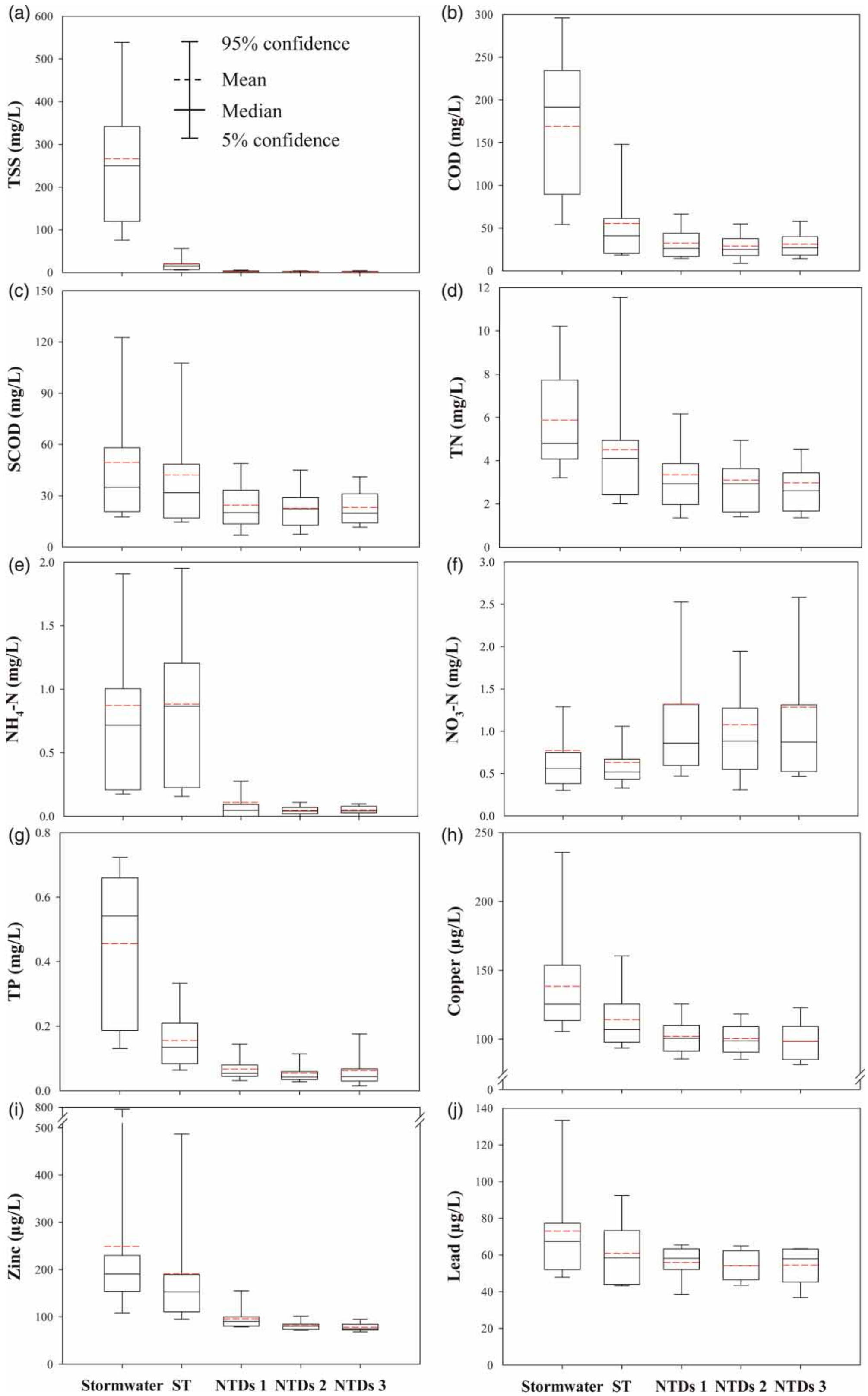

Figure 2 | Comparison of the pollutant concentrations in stormwater, ST, and wetland effluents at days 1, 2, and 3.

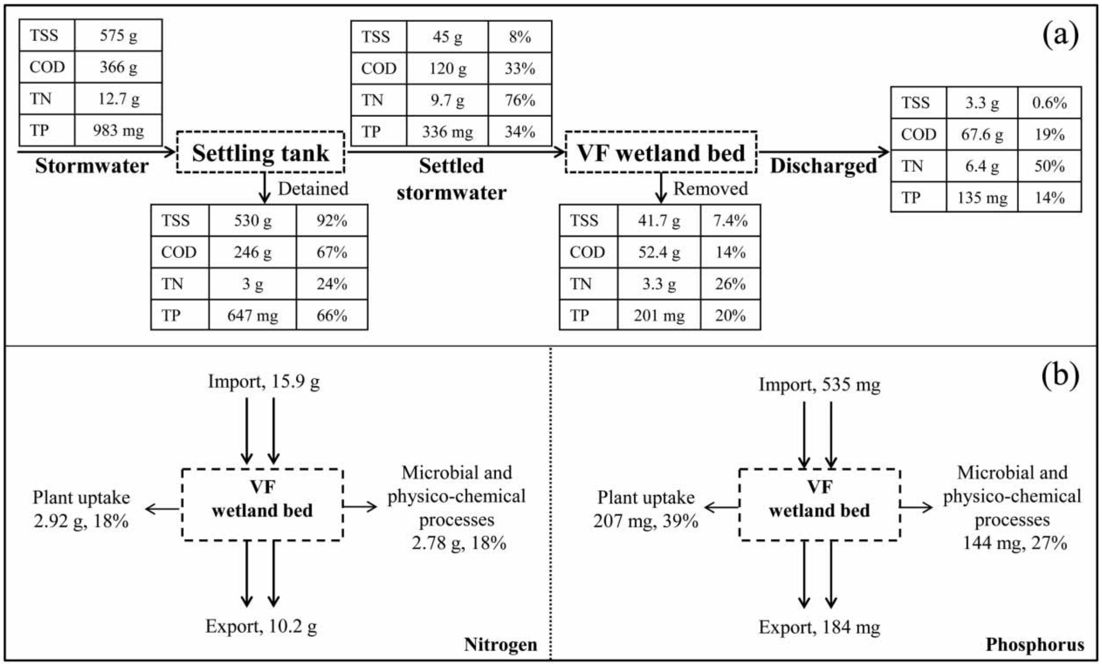

Figure 3 | (a) Mass balance analysis; (b) pathways of nitrogen and phosphorus removal.

clogging, and therefore potentially lengthening the operational lifetime of the wetland bed. Nitrogen removal was slightly greater in the wetland bed (26%) than that in the settling tank (24%).

Pathway of the nutrient retention in the wetland bed

Figure 3(b) shows that the removal of nutrients via plant uptake and retention by microbial and physico-chemical processes were respectively 18 and 18% for nitrogen, and 39 and 27% for phosphorus. It is clear that plant uptake plays an important role in the nutrient removal, which was probably due to the high biomass growth and lower inflow loading of the wetland. Research by Vymazal (2007) stated that the amount of nutrient via plant uptake is low under a high inflow loading but could be important in wetlands that have low inflow loading.

Clogging matter analysis

A relatively small accumulation of 1.4% was observed due to the great removal of solids by the pretreatment tank and the

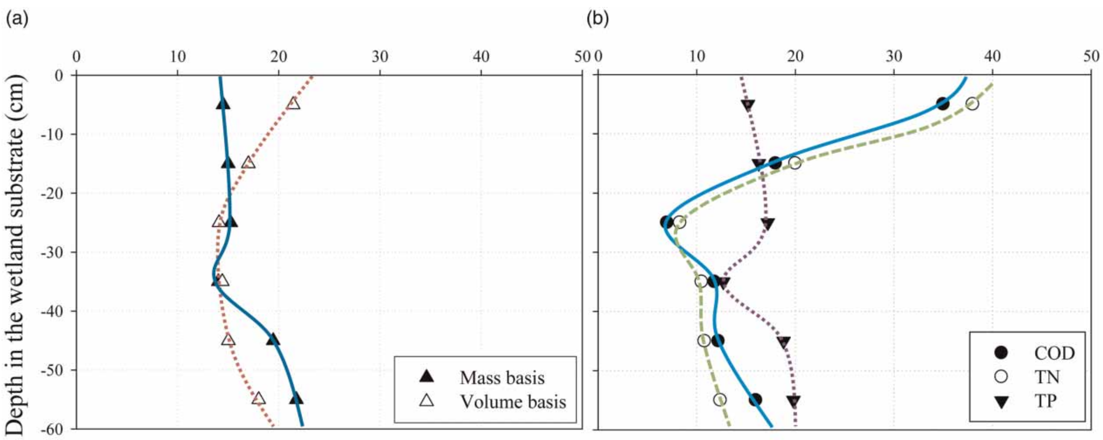

Figure 4 | Profiles of the accumulated clogging matter (a) and COD and nutrients (b) with respect to the substrate depth.

further biological reduction inside the wetland bed. Assuming that the wetland can be used until the accumulated solid reaches 30% of the void substrate volume, an operational lifespan of 20 years can be achieved. However, this originally predicted lifespan could be shortened according to a previous study by Knowles *et al.* (2011), where the longevity of subsurface wetlands had been greatly reduced to 15 years, and even to 8 years, from original prediction of more than 50 years, due to the effect of meteorological factors and maintenance as well as the change of treatment performance.

The clogging matter in mass displayed a slight increase in the bottom layer, which is related to the broken debris of the materials during the process of packing or discharge, while the volume fraction was greater in the upper layer due to the higher content of organic matter coming from trapped solids and attached biofilm (Figure 4(a)). The contents of COD and TN in the accumulated matter displayed a similar trend to the volume fraction. However, the distribution of TP showed a similar trend to the mass distribution, in which higher content was observed in the bottom layer. This is probably related to the background concentration of the substrate material (Chen *et al.* 2013).

CONCLUSIONS

This study showed that the VF stormwater wetland is efficient in removing solids, organic matter, phosphorus, and zinc, while it was moderate in removing nitrogen, and showed a lower removal of copper and lead. Plant uptake was an important pathway for nutrient reduction because of the vigorous growth of plants and the relatively low inflow concentrations of the pollutants. The wetland bed is expected to have a long lifespan due to the very low accumulation of the clogging matter during the 1 year operation. However, it is necessary to collect substantial operational data over a long period to further evaluate the treatment performance and lifespan. Further study should focus on the improvement of nitrogen removal and the risk evaluation of heavy metals as well as substrate clogging.

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REFERENCES

APHA, AWWA, and WEF 1998 *Standard Methods for the Examination of Water and Wastewater*. 20th edn, American Public Health Association/American Water Works Association/Water Environment Federation, Washington, DC, USA.

Brix, H. & Arias, C. A. 2005 The use of vertical flow constructed wetlands for on-site treatment of domestic wastewater: New Danish guidelines. *Ecological Engineering* **25**, 491–500.

Chen, Y., Cheng, J., Niu, S. & Kim, Y. 2013 Evaluation of the different filter media in vertical flow stormwater wetland. *Desalination and Water Treatment* **51** (19–21), 4097–4106.

Cooper, P. 2005 The performance of vertical flow constructed wetland systems with special reference to the significance of oxygen transfer and hydraulic loading rates. *Water Science and Technology* **51** (9), 81–90.

Kadlec, R. H. & Wallace, S. D. 2009 *Treatment Wetlands*. CRC Press, Boca Raton, Florida, USA.

Knowles, P., Dotro, G., Nivala, J. & Garcia, J. 2011 Clogging in subsurface-flow treatment wetlands: occurrence and contributing factors. *Ecological Engineering* **37**, 90–112.

Korkusuz, E. A., Beklioglu, M. & Demirer, G. N. 2007 Use of blast furnace granulated slag as a substrate in vertical flow reed beds: field application. *Bioresource Technology* **98**, 2089–2101.

Langeveld, J. G., Liefting, H. J. & Boogaard, F. C. 2012 Uncertainties of stormwater characteristics and removal rates of stormwater treatment facilities: implications for stormwater handling. *Water Research* **46**, 6868–6880.

Niu, S., Guerra, H. B., Chen, Y., Park, K. & Kim, Y. 2013 Performance of a vertical subsurface flow (VSF) wetland treatment system using woodchips to treat livestock stormwater. *Environmental Science: Processes & Impacts* **15**, 1553–1561.

Stefanakis, A. I. & Tsihrintzis, V. A. 2012a Use of zeolite and bauxite as filter media treating the effluent of vertical flow constructed wetlands. *Microporous and Mesoporous Materials* **155**, 106–116.

Stefanakis, A. I. & Tsihrintzis, V. A. 2012b Effects of loading, resting period, temperature, porous media, vegetation and aeration on performance of pilot-scale vertical flow constructed wetlands. *Chemical Engineering Journal* **181–182**, 416–430.

Tsihrintzis, V. A. & Hamid, R. 1997 Modeling and management of urban stormwater runoff quality: a review. *Water Resources Management* **11**, 137–164.

Vymazal, J. 2007 Removal of nutrients in various types of constructed wetlands. *Science of the Total Environment* **380**, 48–65.

Zhang, D., Gersberg, R. M. & Keat, T. S. 2009 Constructed wetlands in China. *Ecological Engineering* **35** (10), 1367–1378.

Zhu, L., Takala, J., Hiltunen, E., Li, Z. & Kristianto, Y. 2013 Comparison of vertical-flow constructed wetlands with and without supplementary aeration treating decentralized domestic wastewater. *Environmental Technology* **34**, 53–60.

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