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Operation of the vertical subsurface flow and partly submersed stormwater wetland with an intermittent recycle

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ABSTRACT

In this study, a vertical subsurface flow (VSF) stormwater wetland having a partially submersed zone in the bottom was operated for 90 d. This wetland is designed to recycle the effluent on the basis of designated antecedent dry days (ADDs). A total of four groups of bench-scale VSF wetlands filled with different media such as woodchip, pot gravel, synthetic fiber and volcanic stone were made. Each group of wetlands having the same media was operated with different recycle scheme. Operational results show that at the beginning of the wetland operation for about 30 d, there was a maturation or acclimation phase as usually observed in a filter and biofilm process. After the acclimation phase, the wetland displayed stable functions. Regardless of the media and operational mode employed, all groups of wetland were found to be able to reduce 70% of TSS in the stormwater. For nutrients removal, different medium showed different performances. Woodchip was most effective for TN removal (more than 25%), while it is the poorest in the removal of organic matters due to the release from the medium by itself. Pot gravel, synthetic fiber and volcanic stone showed similar performances in organics removal (more than 72% for Total COD). Synthetic fiber was poor in ammonia removal in the beginning of operation because it was probably dissolved from the fiber (Nylon and Amine synthetics). Pot gravel and synthetic fiber showed a better performance on the removal of TP (more than 64%) than woodchip and volcanic stone. Volcanic stone released a significant amount of phosphorus during the operation. The effect of recycling on the pollutants removal was also analyzed. Generally, the recycling frequency turned out to have no significant effect on the biodegradation of organic matters and biological nitrogen removal, which is considered to be due to the fact that the stormwater contains some toxic substances that inhibit microbial growth.

Keywords: Dry days; Recycle; Stormwater runoff; Vertical subsurface flow; Wetland; Media

1. Introduction

Stormwater runoff from urban areas has been considered a major pollution source. Runoff from roads and highways has received much attention due to the abundance of heavy metals, hydrocarbons, and fuel additives [1,2]. In recent years, many government and community organizations have placed increasing emphasis on developing and implementing strategies to reduce urban stormwater pollution [3,4]. Many kinds of best management practices (BMPs) have been designed and conducted in the treatment of stormwater runoff

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such as swales, infiltration systems hydraulic separators, and constructed wetlands [5].

Constructed wetlands are nature-based systems for treating wastewater, stormwater and agricultural runoff. Due to its nutrient capturing capacity, simplicity, low operation cost and low energy demand, this technology has been more widespread in industrialized countries [6].

VSF wetlands are constructed wetlands that have been designed as vegetated recirculating gravel filters. They have been used for wastewater treatment in Europe and the United States. VSF wetlands typically employ a downward hydraulic regime, which is effective for removing ammonia from polluted water at the laboratory and field scale [7].

The typical design parameters of vertical flow wetland filters are the required area, filter depth, type of medium and retention time. The most important factor in the design and operation of this system is the characteristics of the filtering media. Selection of the proper media involves the specification of grain size, media porosity, media depth and cost [8]. Generally, it should have a high porosity to reduce clogging and should also indicate a low adsorption capacity to prevent the accumulation of pollutants. In addition, it should be cost-effective.

In VSF wetland systems, the flow is usually intermittent. This provides a "resting period" for biosolids formation. Also, it allows oxygen inside the filter media to promote the decomposition of accumulated biosolids. Due to this, there is less risk of media clogging in VSF wetlands as compared to other kinds of constructed wetlands.

In terms of flow pattern, stormwater BMPs are different from a conventional wastewater treatment plant. The flow rate and pollutant load of a wastewater treatment plant is relatively continuous with a little fluctuation while that of stormwater BMPs are event-driven and has large fluctuation only during rainfall events (Fig. 1). This behavior can also be assumed for a VSF wetland. Moreover, VSF wetland systems can be an appropriate space-saving facility for urbanized areas where space is limited.

Different types of vertical flow wetlands (downflow, upflow and in-series) may be employed usually depending on the nitrogen characteristics of the target water. For treated water high in ammonia and low in nitrate where only nitrification is of interest, unsaturated downflow wetland filters are the best choice. For the nitrified water where denitrification is needed, saturated upflow wetland systems may be the best option [9].

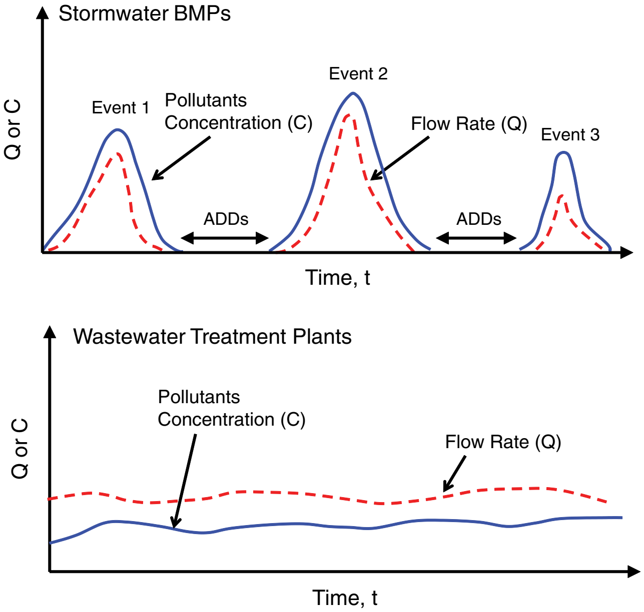
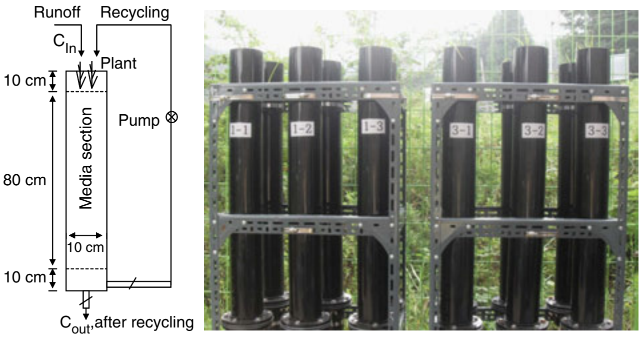


Fig. 1. Diagram on flow rate and pollutants concentration in stormwater BMPs and wastewater plants.



(a) (b)

Fig. 2. The schematic diagram and photo of the wetland system used in this study, (a) schematic diagram; (b) photo.

Considering the flow patterns and the characteristics of urban areas, a modified vertical flow wetland filter system with recycling during dry days was developed in this study. The modified system provides many advantages. First, the recycling process can make a full use of the BMP during ADDs (*see* Fig. 2). Increasing the recycling frequency may also improve the treatment efficiency of the system. Second, the recycling activity can provide water and nutrients for plant growth which can improve pollutant removal and gives an aesthetic function. Finally, since we make use of the period of ADDs, the time required for treatment is increased and the size can be reduced which makes it a space-saving facility.

This study aims to investigate the VSF wetland characteristics during dry days. This was accomplished by: (1) evaluating the performance of the VSF wetlands for the treatment of stormwater runoff; (2) comparing and analyzing the characteristics of different medium; (3) determining the effects of recycling frequency on the pollutants removal.

2. Materials and methods

2.1. Structure and dimension

A modified VSF column wetland with a recycling device was used in this study (Fig. 2). The column is made of opaque acryl which provides a dark environment inside. This condition prevents sunlight which gives stress on the roots and also prevents the growth of autotrophic organisms. The column has a total length of 1 m and a diameter of 0.1 m. The length in this bench-scale system is the same as the one in the planned full-scale system in the future.

A total of four groups filled with different media were implemented. Three columns with different recycling frequencies were set for each group. A recycling device was installed to pump the effluent to the wetland for further treatment (*see* Fig. 2). All columns were placed vertically on the support.

A type of vegetation called *Acorus Calamus* was planted in the top layer to provide landscape and improve treatment efficiency in terms of filtration. It was planted directly in the media without making use of top soil to prevent clogging.

2.2. Media components

The components of the media in the columns are shown in Table 1. Each column contains small pot gravel, main media, medium stone, and big stone, from top to bottom. The main media varies with each group and includes woodchip, pot gravel, synthetic fiber and volcanic stone. This is done to be able to compare the treatment efficiency of the different media.

The top layer which is small pot gravel is 0.05 m in depth. It is mainly used to weaken the scouring effect by the incoming water and to distribute the inflow uniformly over the wetland. The main media for the second layer has a depth of 0.55 m. This is considered the most critical part of the wetland system since this is where physical and biochemical processes in the wetland takes place. To encourage proper drainage, 0.1 m of medium stone as well as big stone were used in the third layer and bottom layer, respectively. The porosity of the column wetland ranges from 48% to 72% depending on the media type.

2.3. Operation

The inflow used for the VSF wetland system is the stormwater collected from a bridge. At the first day, 2.1 l of runoff was fed to each column within 1.5 min. The approach velocity was estimated to be around 243 m/d which is significantly higher than rapid sand filtration rate. The hydraulics of the system is summarized in Table 2.

In order to make a full use of the VSF wetland system during dry days and to determine the effect of ADDs, the fed stormwater was recycled after 24 h of retention in the columns. The recycling frequencies were set as 1, 3 and 7 respectively for the three columns in each group.

Table 1
Specific information of the media

Group	Porosity (%)	Media components (from top to bottom)
Woodchip	57	Small pot gravel, size: 0.48–0.55 cm, depth: 5 cm
		Woodchips, size: 2.6–11.5 cm, depth: 55 cm
		Medium stone, size: 1.7–3.6 cm, depth: 10 cm
		Big stone, size: 2–5 cm, depth: 10 cm
Pot gravel	48	Small pot gravel, size: 0.48–0.55 cm, depth: 5 cm
		Pot gravel, size: 1–2.3 cm, depth: 55 cm
		Medium stone, size: 1.7–3.6 cm, depth: 10 cm
		Big stone, size: 2–5 cm, depth: 10 cm
Synthetic fiber	72	Small pot gravel, size: 0.48–0.55 cm, depth: 5 cm
		Synthetic Fiber, depth: 55 cm
		Medium stone, size: 1.7–3.6 cm, depth: 10 cm
		Big stone, size: 2–5 cm, depth: 10 cm
Volcanic stone	49	Small pot gravel, size: 0.48–0.55 cm, depth: 5 cm
		Volcanic stone, size: 0.9–4.5 cm, depth: 55 cm
		Medium stone, size: 1.7–3.6 cm, depth: 10 cm
		Big stone, size: 2–5 cm, depth: 10 cm

Table 2
Hydraulic operation conditions

Group	No.	Recycling	*EBCT (d)	*EHRT (d)	*AV (m/d)	*PV (m/d)
Woodchip	1–1	1	2.99	1.7	243	426
	1–2	3	2.99	1.7	243	426
	1–3	7	2.99	1.7	243	426
Pot gravel	2–1	1	2.99	1.44	243	506
	2–2	3	2.99	1.44	243	506
	2–3	7	2.99	1.44	243	506
Synthetic fiber	3–1	1	2.99	2.15	243	338
	3–2	3	2.99	2.15	243	338
	3–3	7	2.99	2.15	243	338
Volcanic stone	4–1	1	2.99	1.47	243	496
	4–2	3	2.99	1.47	243	496
	4–3	7	2.99	1.47	243	496

*EBCT – Empty bed contact time; EHRT – Effective hydraulic retention time; AV – Approach velocity; and PV – Pore velocity.

These frequencies correspond to ADDs equal to 2, 4 and 8. After the specified recycling frequency for each wetland, the treated stormwater will be collected for laboratory testing and another batch of stormwater will be fed again to the columns.

2.4. Water quality of influent and effluent

The influent used in this study was the runoff from the first flush phenomenon collected from an asphalt-paved bridge. The water quality parameters were determined and shown in Table 3. The total suspended solids (TSS) concentration was 43–350 mg/l while the total nitrogen (TN) and total phosphorus (TP) content were 1.87–8.38 mg/l and 0.096–0.778 mg/l, respectively.

The parameters used to determine water quality were temperature, pH, conductivity, turbidity, TSS, and chemical oxygen demand (COD) including total COD (TCOD) and soluble COD (SCOD). Nutrients such as total and dissolved nitrogen and phosphorus (TN, DTN, TP, and DTP), ammonia (NH_3–N), and nitrate (NO_3–N) were also determined. Temperature, pH and conductivity were measured using YSI 556 portable water quality monitor while turbidity was measured using 2100N Turbidimeter. The others were determined based on the Standard Methods for the Examination of Water and Wastewater (AWWA, 1995).

Table 3
Quality of stormwater used as inflow to the bench-scale wetlands

Test items	Units	Range	Mean	Standard deviation
Temperature	ºC	15.02–27.50	22.89	3.70
pH	–	6.08–7.53	6.85	0.35
EC	µs/cm	31–278	149	60
Turbidity	NTU	26.0–132.0	77.0	24.1
TSS	mg/l	43.0–350.0	208.0	85.2
TCOD	mg/l	24.9–129.1	87.7	29.4
SCOD	mg/l	1.2–79.5	25.8	17.9
TN	mg/l	1.865–8.380	4.758	1.600
DTN	mg/l	0.922–5.815	2.966	1.226
NH_3–N	mg/l	0.020–1.955	0.363	0.489
NO_3–N	mg/l	0.098–2.718	1.111	0.818
TP	mg/l	0.096–0.778	0.318	0.159
DTP	mg/l	0.008–0.201	0.049	0.044

3. Results and discussions

3.1. Acclimation

The wetland system had been operated and monitored over a period of 90 d from July 15 to October 12, 2011. Forty-four samples were collected from each column with ADDs equal to 2. The total inflow volume was around 92.4 l.

Fig. 3 shows the concentration ratio of outflow to inflow with respect to the cumulative inflow volume for TSS, TCOD, TN, and TP. This figure corresponds to the values obtained for ADDs equal to 2. It was observed that an acclimation occurred at the beginning of operation then the treatment became stable as the total influent volume reached to around 25 l, 18 l, and 9 l for the columns with 2, 4 and 8 ADDs, respectively. During this acclimation phase, formation of biosolids took place as well as the balancing of biochemical processes such as the growth of bacteria and biofilm formation in the media. Acclimation phenomenon has been reported in previous studies. It was found out that there is a selection and multiplication of specialized microorganisms during this stage [10].

The concentration ratio was higher than 1 and varied in a large range at the acclimation stage. This is due to the fact that some substances contained in the media were washed out at the beginning. Moreover, the wetland system needed a period to reach a stable stage. Therefore, the results during the acclimation phase were neglected in the analysis of treatment efficiency in this study.

3.2. Effects of the medium type

In order to establish a better representation of the performance of the wetland columns, the values obtained during the acclimation phase was not included in the analysis. Take the data collected from the columns with ADDs equal to 2 for example, wherein the pollutants concentration in the influent and effluents of the wetlands with different media were shown in Fig. 4.

3.2.1. Woodchip

Generally, woodchip showed a positive efficiency for TSS (more than 71%), as well as turbidity, nitrogen and

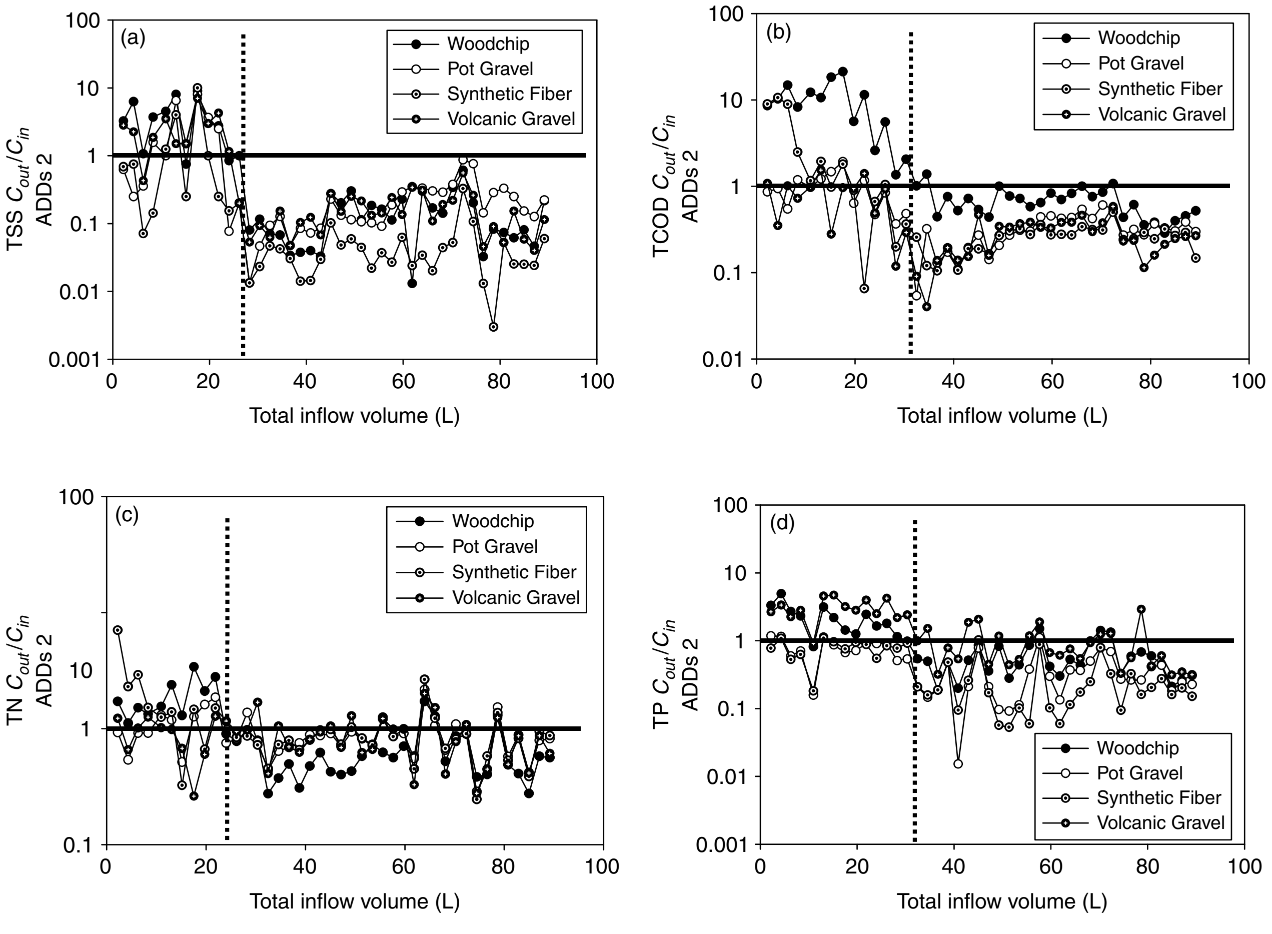


Fig. 3. Changes of inflow and outflow concentrations with respect to the cumulative feed volume.

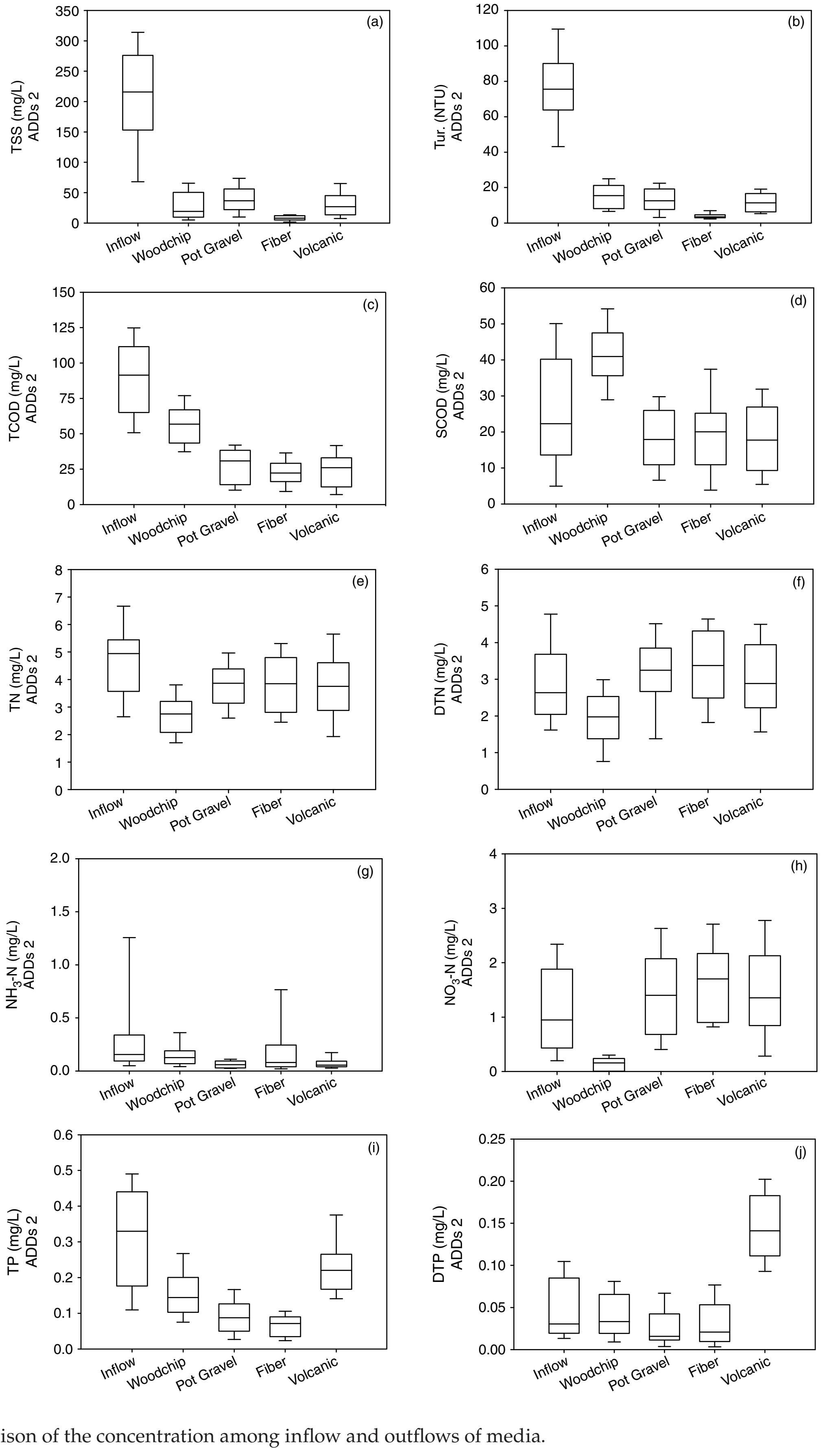


Fig. 4. Comparison of the concentration among inflow and outflows of media.

phosphorus. However, this group showed a weak treatment for organics (Fig. 4(c), (d) and Fig. 5).

The efficiency for TCOD removal were 30.2%, 19.2% and –17.8%, and were –148.6%, –186.3% and –343.1% for SCOD removal with 2, 4 and 8 ADDs, respectively. This is natural because some organics in woodchip were leach out via microbial fermentation and dissolved into the fed stormwater during the period of operation, in spite of the treatment of particulate organic matter in fed stormwater by adsorption and degradation.

The removal efficiency for NO$_3$–N was more than 33% for all the columns in woodchip group (Fig. 4(h) and Fig. 5). On the other hand, the efficiencies were negative for the other three media.

This is in agreement with the report that wood particle media such as sawdust and woodchips have shown an ability to deliver consistent longer term (5–15 y) NO$_3$ removal rates (1–20 gNm^{-3} media d^{-1}), while requiring minimum maintenance [11–13]. The removal of NO$_3$–N in wetlands is mainly via denitrification of microorganism, which demands the supply of carbon source and an anaerobic environment. Carbon source can provide energy for denitrification microorganisms [14,15], and it is also considered as a restricting factor in the process of denitrification.Rich organic matter and oxygen-deficient environment due to fermentation in woodchip group provided a better support for denitrification than the other three media.

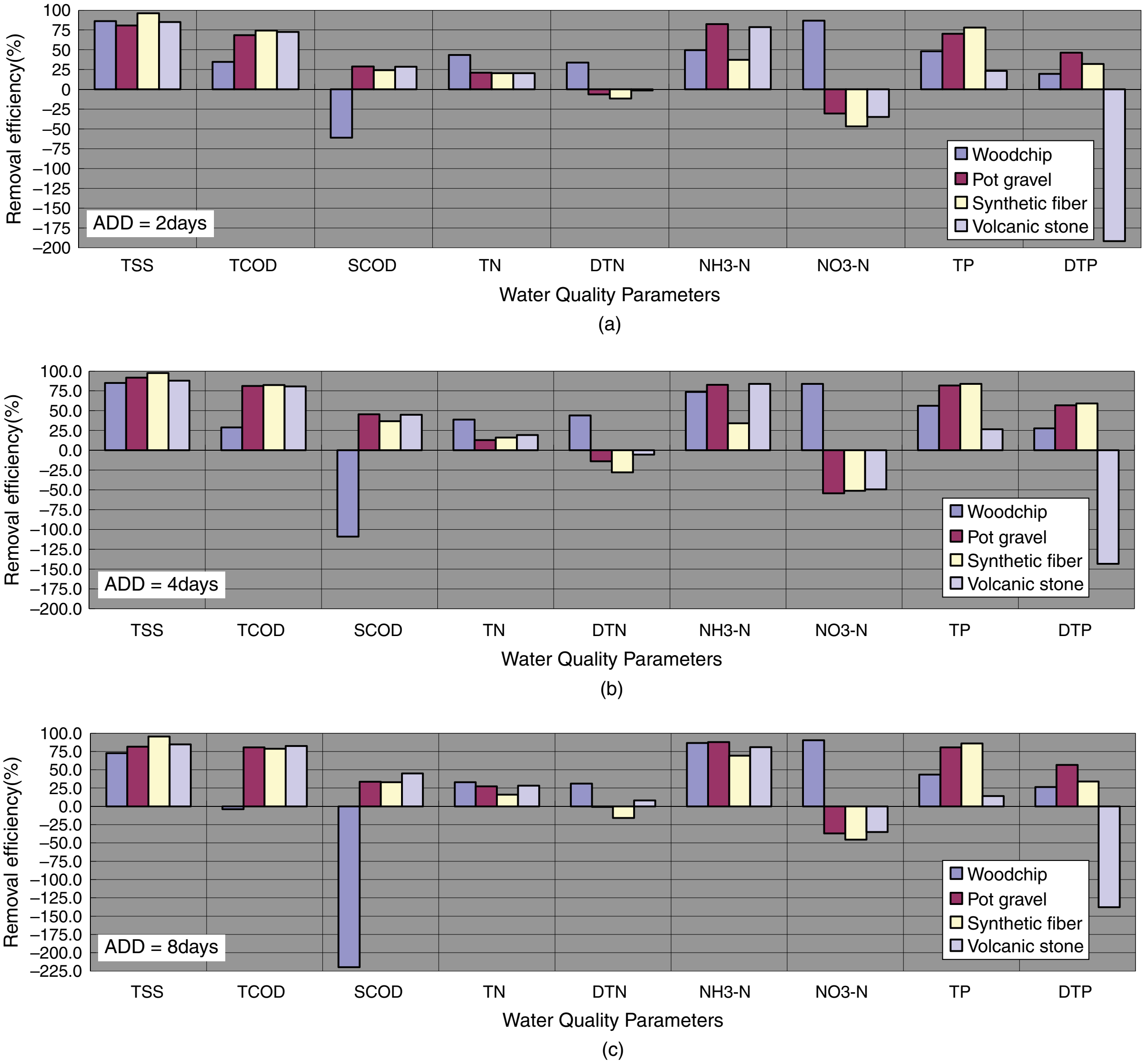


Fig. 5. Pollutants removal efficiency with respect to media.

Meanwhile, woodchip show the best efficiency for the reduction of TN (45.5%, 51.7% and 25.8% with ADDs equal to 2, 4 and 8, respectively) among all the media. It was mainly attributed to the removal of NH_3–N (16.0%, 65.0% and 60.6% with different ADDs) and NO_3–N by nitrification and denitrification in woodchip. Numerous studies have proven that the central pathways for nitrogen removal in constructed wetlands are microbial nitrification followed by denitrification [16]. It means that the TN reduction is mainly related to the removal of NH_3–N and NO_3–N.

For phosphorus removal, woodchip showed a relatively low efficiency. The removal of TP was 38.8%, 46.4% and 22.7% for 2, 4 and 8 ADDs, respectively, while that of DTP was 41.1%, 15.3% and –33.6% respectively. This is in comparison with pot gravel and synthetic fiber.

3.2.2. Pot gravel

From Fig. 4, it is shown that pot gravel is effective for reducing TSS and organics. The removal efficiency was more than 74% for TSS and more than 72% for TCOD, respectively. For TP, the removal efficiencies were 64.4%, 86.3% and 74.8% respectively for ADDs equal to 2, 4, and 8 respectively while that of DTP were 71.6%, 73.0% and 45.2% respectively.

In addition, an acceptable relationship was observed between outflow TSS and TP ($R^2 = 0.446$). It is reported that phosphorus and suspended solids are often closely related with respect to non-point source pollution. They are readily adsorbed to solids surface, and this pathway is the most prevalent mode of phosphorus transport in stormwater wetlands [17].

The significant decrease of NH_3–N and increase of NO_3–N provide evidence of strong nitrification and weak denitrification in this group.

3.2.3. Synthetic fiber

Generally, among the four groups, synthetic fiber has the highest efficiency for the removal of TSS (95.7%, 96.3% and 96%) and reduction of turbidity (94.2%, 97.5% and 95.4%) for 2, 4, and 8 ADDs (Fig. 4(a) and Fig. 5). Although it has the highest porosity among all the media, it has the smallest pore size that is effective for filtration.

As for the organics, this media showed a high removal efficiency with 73.0%, 84.0% and 78.1% for TCOD but a relatively low removal of SCOD with 8.2%, 40.2% and 10.1% for ADDs equal to 2, 4 and 8, respectively.

It was also observed that there were obvious higher concentrations of NH_3–N in the outflow of wetlands with synthetic fiber during the acclimation phase. This is attributed to the probable dissolution of ammonia from the fiber (Nylon and Amine synthetics) at the beginning period. After the end of the acclimation phase, the decrease of ammonia (55.0%, 57.4% and 46.7% with ADDs equal to 2, 4 and 8, respectively) and the increase of nitrate proved the existence of strong nitrification.

Synthetic fiber also indicated a good efficiency on phosphorus removal. The respective removal efficiencies were 74.5%, 92.9% and 81.2% for TP with ADDs equal to 2, 4 and 8. On the other hand, the corresponding values for DTP were 42.3%, 72.5%, 7.4%, respectively.

3.2.4. Volcanic stone

Volcanic stone showed an efficient treatment for TSS and organic matter. The removal efficiency was more than 82% for TSS and more than 74% for TCOD. This high removal of organics is partly because of the fact the concentration of outflow TCOD was positively related to TSS ($R^2 = 0.54$).

The decrease of NH_3–N by more than 45% and increase in NO_3–N by no less than 85% indicated that nitrification also took place in volcanic stone media. In addition, the TN reduction was in the range of 12.0–29.4% in this group.

Compared to the other three groups, the removal of TP was poor (13.3%, 7.2% and –10.1% respectively for ADDs of 2, 4 and 8), and the DTP removal showed a negative performance. The DTP concentration of outflow was significantly larger than inflow (Fig. 4 (J)). This may be caused by the release of phosphorus from the volcanic stone itself during the period of operation.

Overall, the four types of media used in this study showed different performances when it comes to removal of pollutants. They all indicated an efficient removal of TSS. Woodchip showed a better performance for TN and DTN which is considered to be caused by nitrification and denitrification. However it is poor in organics removal because it releases organics during the operation. Pot gravel, synthetic fiber and volcanic stone indicated the same performance in organics removal. However, they showed a poor treatment for DTN. Furthermore, nitrification was observed in these three groups. Volcanic stone showed a significant negative treatment for DTP due to phosphorus release during the operation.

3.3. Effect of ADDs

One innovative operation utilized in this study is the incorporation of a recycling process. It takes advantage of the use of the BMP during dry days and its effect on pollutants removal was analyzed based on the removal efficiency.

We differentiated the impacts of ADDs based on the difference in removal efficiency among the analyzed parameters. Table 4 shows the summary of these effects.

The differences in ADDs were described to increase, decrease or have no significant effect on pollutant removal.

The difference in ADDs showed no significant effect on the removal of TSS and reduction of turbidity among all the four groups except for woodchip. This is because the governing removal mechanism for the removal of solids is filtration. Most of the solids can be removed by a single passage through the media and they can be easily removed on the top layer of the wetland. Furthermore, the solids concentration after the first passage was relatively low, thus the efficiency cannot be improved significantly.

For COD, the removal efficiency decreased with increasing recycling times through the woodchip (*see* Table 4 and Fig. 6(a)). This is probably caused by the organics release from the woodchip during the period of recycling. Since woodchip is an organic material, it is expected to release some organics as the stormwater passes through it. And the more it comes in contact with stormwater, the more it releases organics. Recycling frequency showed no significant effect on the COD removal in pot gravel group and synthetic fiber group, but it increased the COD removal in volcanic stone (Table 4 and Fig. 5).

For NH_3–N, higher recycling frequency increased the removal efficiency in woodchip group (Fig. 6(b)). This is probably due to the fact that the increased contact with stormwater provided more chances for nitrification. Longer ADDs also improved the NH_3–N treatment in synthetic fiber after the acclimation, even though it decreased the removal at the acclimation stage (Fig. 7). The efficiency decrease at the acclimation stage was due to the nitrogen release from the synthetic fiber which contains basic nitrogen atom. Generally, longer ADDs did not affect TN removal for all the wetland groups.

For DTP, woodchip showed a decreasing trend along ADDs equal to 2, 4 and 8 (41.1%, 15.3%, –33.6%). The essential reason is due to the release of dissolved organic phosphorus from woodchip. One of the characteristics of organic matter is the high phosphorus content, which was decomposed by microorganism and dissolved into the fed stormwater. Organic phosphorus in the form of

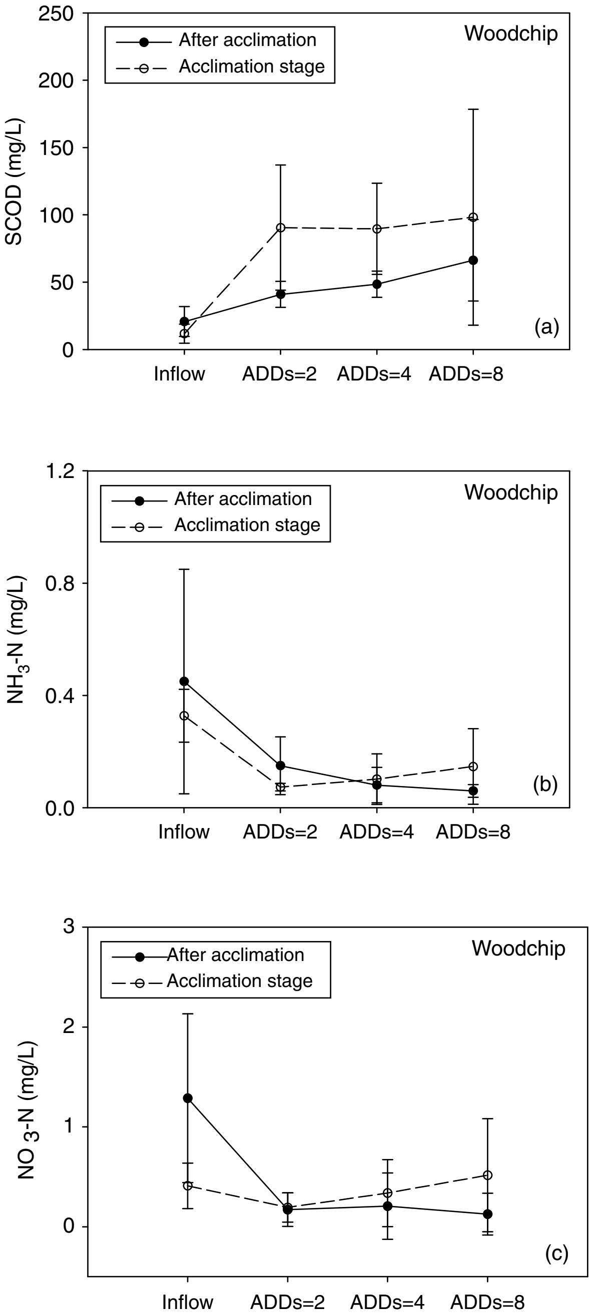


Fig. 6. Pollutants changes with recycling times in woodchip.

Table 4
Effects of varying ADDs on treatment efficiency

Item	TSS	Tur.	TCOD	SCOD	TN	DTN	NH_3–N	NO_3–N	TP	DTP
Woodchip	D	D	D	D	N	N	I	N	N	D
Pot gravel	N	N	N	N	N	N	N	N	N	N
Synthetic fiber	N	N	N	N	N	D	N	D	N	N
Volcanic stone	N	N	I	I	N	D	N	N	D	D

I: Increase efficiency; N: No effect; and D: Decrease efficiency.

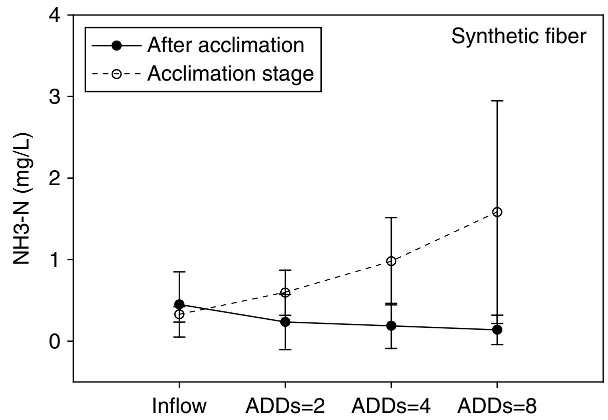


Fig. 7. Release of ammonia from synthetic fiber.

plant is often present in nature, and makes an important contribution to TP of waters and soils. As for volcanic stone, the treatment decreased with increasing ADDs due to the pollutants release from the stones itself (Fig. 8). However, there was no effect in pot gravel and synthetic fiber.

The removal of phosphorus in wetland system is a complicated process, and it is mainly contributed by adsorption and sedimentation in filter media [18]. Furthermore, it is closely associated with the physical, chemical and hydraulic properties of the filter media. In the gravel systems, PO_4^{-3} and TP removal efficiency was predominantly affected by porous media size and type [19].

It was expected prior to the study that more recycling can improve the pollutants removal efficiency because recycling provide more chances of contact between the pollutants and the media. Unfortunately, the ADDs showed no significant effect on the treatment for most of the parameters in this study (Table 4). This is due to the water quality condition of the water fed into the system. The inflow was the stormwater runoff collected from a bridge surface. The pollutants contained in this kind of runoff are complicated, and it can be highly toxic due to the heavy metals and hydrocarbon [20]. These factors reduce the pollutants degradation and result in poor conditions for biochemical reactions, such as the growth of biofilm and bacteria, nitrification and denitrification. Moreover, the concentration of pollutants was reduced to a low level after the first pass. This can also reduce the effect of recycling frequency.

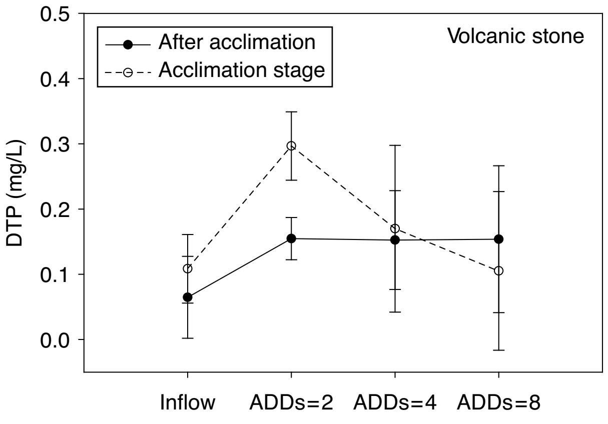


Fig. 8. Release of dissolved TP from volcanic stone.

However, it cannot be entirely concluded that the recycling process did not have an impact on the treatment efficiency of the system. This is due to several reasons. First, the recycling process provided maintenance of the vegetation cover which also contributes in the stormwater treatment. Second, the operation time may not be long enough to obtain accurate results for the study.

4. Conclusions

This study demonstrated the stormwater treatment of runoff from an asphalt-paved bridge using a VSF wetland system with an intermittent recycle. Four kinds of medium were used to show different characteristics for the pollutants removal.

An acclimation phase occurred in the initial period of the operation, and then the VSF wetland system stabilized as the total inflow volume reaches to around 25 l, 18 l, and 9 l, for ADDs equal to 2, 4 and 8, respectively.

All the media showed efficient treatment for TSS and turbidity. Pot gravel, synthetic fiber and volcanic stone implicated an efficient removal for TCOD and SCOD while they showed a poor treatment on the removal of TN and DTN.

Woodchip showed negative removal efficiency on soluble COD due to the release of organics from itself during the operation. However, the removal of TN is significant in this group. For TP removal, pot gravel and synthetic fiber showed a better performance than woodchip and volcanic stone.

Moreover, for most of the parameters, the recycling frequency did not have a significant effect on the pollutants removal. This is mainly due to the characteristics of treated runoff which may be highly toxic. Determination of heavy metals and organic compound content of the stormwater inflow may be incorporated in the analysis to obtain better results.

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