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여재의 형태와 선행강우일수가 충진형 습지의 성능에 미치는 영향

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Effect of Media Type and Number of Dry Days on the Performance of Packed-bed Wetland

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요 약
본 연구에서는 강우유출수 처리목적의 충진형 습지에서 여재의 형태와 선행강우일수(NDDs)가 처리에 미치는 영향을 조사하였다. 여재에 따라 강우유출수에 함유된 오염물질 저감에 기여하는 독특한 특성을 갖는 것으로 밝혀졌다. 또한 NDDs가 습지 유출수의 TSS, TN, TP에 미치는 영향은 매우 컸는데 그 이유는 강우활동이 없는 기간 동안에 실시되는 재순환이 처리시간의 확대 및 증가에 큰 영향을 미쳤기 때문인 것으로 사료된다. 그러나 우드칩 충진 습지에서는 우드칩 자체에서 방출되는 유기물질로 인하여 COD 제거효율은 저조한 반면에 방출된 유기물질(탄소원)로 인한 탈질촉진으로 질산성 질소 NO^{3-}-N 농도는 가장 낮았으며, 부석의 일종인 다공질의 Pumice 충진 습지에서도 흡착효과에 의하여 NO^{3-}-N 농도는 상대적으로 낮았다. Pumice 습지와 화산석 충진 습지에서 TSS 제거효율은 유사한 수준을 보인 반면에 우드칩 습지에서는 습기에 약한 목편으로부터 탈리된 파편으로 인하여 TSS 농도가 유입수보다 높게 배출되었다.
핵심용어 : 여재, 선행강우일수(NDDs), 강우유출수, 충진형 습지

Abstract
This paper deals with how type of media and number of dry days(NDDs) in the packed-bed wetlands for stormwater treatment affect their performance. Depending on the media, there are some clear features contributing to the reduction of specific pollutants in the stormwater. In the first place, effect of NDDs on the effluent TSS, TN, and TP concentrations was significant, indicating that more time or chance for the treatment were provided as an increase in the number of passage through the media through recycling except for COD in woodchip wetland due to the release of organics by itself and NO^{3-}-N in pumice and volcanic gravel wetlands due to the lack of carbon source. However, It was found out that woodchip wetland was the best one in reducing nitrogen due to the abundant carbon supplied from the woodchip and pumice wetland was the better one due to its nice adsorption capacity. Removal efficiencies of TSS by pumice wetland and volcanic gravel wetland were similar while wetland filled with woodchip was worse due to the debris by itself.
Key words : media, number of dry days, stormwater, packed-bed wetland

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1. 서 론

In general, the materials selected as packed-bed wetland substrates is the key to the success of treatment process. It is important to emphasize that the media merely provides surface area for bacteria to colonize. It is the bacteria that mainly do the actual work of the treatment. In order for bacteria to play their role effectively, the wetland design must provide an even distribution of nutrients and oxygen while removing dissolved and suspended matters.

The heart of packed bed-wetland is the filter media. The type of media used strongly influenced both the capital and operating costs of wetland. In practice, some characteristics may be mutually exclusive and it may be necessary to trade off one feature for another.

Sand usually has smaller particle size and lower porosity. Small particle size indicates large specific surface area which is available for biofilm establishment and surface chemistry and thus enhances treatment performance (Vymazal and Krŏpfelová, 2011). But, it is highly prone to clogging if they are operated incorrectly and also due to overloading(Cooper, 1996; Winter and Goetz, 2003).

Gravel is typically very inert and durable with excellent mechanical strength. In general, the pore size is directly related to gravel size. Unfortunately, the specific surface area is inversely related to gravel size. Generally, the effluent quality, loading rate, type of media and the calcium, aluminum, and iron content of the substrate dominate the phosphate retention (Pant et al., 2001). Gravel usually do not contain high concentrations of these elements, therefore, the removal of phosphate is generally poor (Korkusuz et al, 2005).

In certain regions, volcanic gravel is abundant. This porous material is expected to expand the growth of biofilm and a selectable grain size. It was reported that the performance of volcanic in comparison to other media was tested in wetlands for the treatment of road runoff (Chen et al., 2012). Pollutants removal by the wetland systems was efficient for TSS (>80%), COD (>75%) and NH_4^+-N (>55%).

One of the major problems associated with the classic nitrogen removal route in wetland system is the lack of organic carbon for denitrification, due to the dependability of synthesis and activity of denitrifying enzymes on organic carbon availability (Lavrova and Koumanova, 2010). In this case, organic media can be one of the solutions. several literatures (Gray et al., 2000; Aslam et al., 2007; Wang et al., 2010; Saeed and Sun, 2011; Chen et al., 2012) have reported that release of organic carbon (from organic media) intensified denitrification in wetlands.

The most common use of industry wastes were blast furnace granulated slag (BFGS) and fly ash. The former is a porous nonmetallic co-product produced in the iron and steel industry, and has a high P-sorption capacity as have been shown earlier in batch and column experiments (Korkusuz et al., 2007).

Synthetic fiber is a kind of thin, soft and light material. Synthetic fiber was commonly applied as physical and biological filter. It was used in stormwater wetland by Chen et al. (2012) and Cheng et al. (2019). There have been numerous studies using various media including limestone and shale (Johansson, 1997; Zurayk et al., 1997), LWA (commercial light weight aggregates, Zhu et al., 1999), LECA (a reactive porous media, Zhu et al., 2012), zeolite (Sakadevan and Bavor, 1998), clay either alone or in combination with soils (Sakadevan and Bavor, 1998), pumice (natural porous mineral, Njau et al., 2003), wollastonite (a calcium metasilicate, Brooks et al., 2000), alum, dolomite and calcite (Ann et al., 1999; Pant et al., 2001).

Stormwater wetland is normally used during only rainy days, which means that it is not very economic in terms of its use, especially in case of single pass packed-bed wetland. Recirculation may be a good option to increase the utility of this type of wetland during dry days. As number of dry days(NDDS) increases, more chance or time is provided for the treatment. In addition, recirculation improves flow pathways inside the wetland and also it can help to maintain a proper moisture preventing the inside eco-microcosm from drying.

Recirculation is very common in water and waste water treatment plants because it can significantly improve the effluent water quality. In order to further improve the performance of wetlands, recirculation has been employed in some studies. Prost-Boucle and Molle (2012) demonstrated that nitrification in packed-bed wetlands is strongly dependent on the recirculation rate. Sun, *et al.* (2003) showed that the NH_4-N removal efficiency was increased by about 50% after effluent recirculation was used.

However, the use of recirculation in the packed bed wetlands treating stormwater is rarely used in stormwater wetland. The primary objective of this study is to evaluate how type of media and number of day days(recirculation) affect the performance of pilot scale packed-bed wetlands established to treat a high way runoff.

2. Materials and Methods

2.1 Pilot-scale Wetlands

The pilot-scale wetland system had a rectangular configuration and consisted of a settling tank and wetland. For the wetland bed, a special component was the built-in recycle device, which was designed to recycle the effluent to the wetland surface to provide multiple treatment.

All the three wetlands were constructed with the following dimensions: length=1.33 m, width = 0.6 m and height = 1.1 m. The settling tank and the wetland bed had the same width and height of 0.6 m and 1.1 m, respectively. The length of the former was 0.5 m, while the latter was 0.8 m.

These pilot-scale wetland systems were constructed and each one had the same structure and dimension (Fig. 1). These wetlands were constructed with blue opaque acryl plate. This opaque material prevented sunlight penetration which gives stress on the roots and restricts the growth of autotrophic organisms. Additionally, low thermal conductivity of the material was benefit for eliminating the effect of heat exchange from the ambient and therefore kept the internal environment relatively stable.

2.2 Media preparation

Woodchip, pumice and volcanic gravel were selected as the main media. All the media were locally available and each medium had its special characteristics. Woodchip was a renewable organic material, which had the lowest density of 260kg/m^3 among the three media.

Pumice used in this study was also a lightweight material with a density of 400 kg/m^{3}and the highest specific surface area of 29.55m^2/g. Volcanic grave was a porous material with a specific surface area of 4.56m^2/g and a relatively higher density of 840kg/m^3. The physical characteristics of the media are shown in Table 1.

According to Table 1, woodchip had the larger size and higher uniformity coefficient, while pumice was the finest one. All the three media had porosity ranged from 55% to 65% depending on the media type. In addition, small pot gravel (diameter: 4.8-5.5mm), medium stone (diameter: 22.3-31.7mm) and big stone (diameter: 24-36mm) were utilized as the auxiliary media.

Acorus Calamus was used as wetland vegetation to provide landscape and to improve treatment efficiency in terms of filtration. The plants were transplanted into the wetlands. The roots of the plants were directly inserted to the interface between the top big stone layer and the top auxiliary media of big stone and small pot gravel were directly used as the support soil. A density of 41 plants/m^2 was used for each wetland to provide the suitable row spacing and to ensure the initial appropriate biomass.

2.3 Operation and Motoring

Considering the design water level and the media porosity, the volume of inflow required were 126, 102, and 120L for the wetlands packed with woodchip, pumice, and volcanic gravel, respectively.

In the operational period, each wetland was fed with stormwater intermittently. Initially, the stormwater was

Fig. 1. Construction of the pilot-scale stormwater wetlands

introduced into a storage tank through a pipe system by gravity and subsequently was transferred into the settling tank through the pump system.

After settling for 24 hours, the settled stormwater was fed into the wetland using a set of pump system with an approach velocity of 55m/day, corresponding to the rainfall event that has a return period of approximately 5 year. As a batch through the surface and then gradually percolated downward through the unsaturated zone and accumulated at the saturated zone of the bed. In order to enhance treatment efficacy and/or shorten the treat period, after a retention time of 6 hours, the effluent was completely recycled to the surface of the wetland and flowed through the media again for multiple passages with the same flow rate.

The treatment cycle in the wetland was designed as three days, and the recycle frequency was set as 3 times in the first day after feeding the new inflow and 4 times in the second and the third day. The recycle interval between every two recycles was 6 hours, and the recycle times were set at 0:00, 6:00, 12:00, and 18:00. After the ending of each treatment cycle, another batch of stormwater was fed into the systems. The distribution of rainfall events during the operational study was illustrated in Fig.2.

3. Results and Discussion

3.1 Performance of woodchip wetland

The changes of pollutant concentration in the effluent from the wetland is provided with respect to rainfall event and number of dry days(NDDs). NDDs represents a time span of treatment spent in the media-packed wetland system, so that longer NDD means that more time or chance for the treatment is provided as an increase in the number of passage through the media through recycling.

Generally, woodchip wetland achieved good removal of TSS, nutrients except the release of organic compounds. As shown in Fig.3a and Fig.4a and Table 2 during the operation period, the inflow TSS concentration ranged between 4.5mg/L and 95mg/L with an average of 22.5mg/L. The inflow concentration of TSS was reduced by 18.5%, 37.3% and 48.7% to 10.9mg/L, 8.5mg/L and 7.5mg/L at NDDs being equal to 1, 2 and 3, respectively.

The effect of NDDs on the effluent TSS concentration was significant, suggesting that much more solids were trapped as an increase in the number of passage through the media in the recycling courses. During the events between 7 and 17, wash-out of particles were occurred. This indicates that some solid particles were washed out from the wetland. But this just happened when influent TSS concentration was low and the effluent concentration was not high. Similar results were reported by Ruane et al. (2011 and 2012).

It was observed that organic matters, mainly in soluble form, were released during the operational period (Fig.3b and c, and Fig.4b and c). This is because some organics were leached out from woodchip media via microbial courses. The average outflow TCOD concentration was 101mg/L for NDDs=1, 115mg/L for NDDs=2 and 119mg/L for NDDs=3.

It is obvious that the effluent COD concentration increased as NDDs increased, which means that more organic matters were released with a longer retention time. The leaching of organic compounds from woodchip during the initial period has been reported in many documents (Robertson et al., 2005; Schipper et al., 2010; Warnekea et al., 2011). Robertson and Cherry (1995). Also it was reported that the amount of organics released from hardwood and softwood is different and organics leached from the them increases with the longer retention time.

Fig.3d and Fig. 4d show the performance of wetland in the removal of nitrogen. During the operational stage, the inflow TN concentration varied from 2.01mg/L to 12.63mg/L, with a mean value of 4.73mg/L. In woodchip wetland, TN was reduced by 38.2%, 39.0% and 40.4%, respectively (Table 2), and there was no significant difference of the TN removal from different NDD. In woodchip wetland, nitrogen was removed mainly by denitrification and plant uptake. Generally, denitrification was not limited by carbon source because woodchip

Table 1. Specific information of the main media used in pilot-scale study

Media	Range (mm)	$^*d_{10}$(mm)	d_{50}(mm)	d_{60}(mm)	$^*U$	Porosity (%)
Woodchip	15.0~65.0	20.0	31.0	34.0	1.70	64.0
Pumice	6.0~13.0	7.0	9.0	9.0	1.29	55.0
Volcanic gravel	11.0~20.0	13.5	16.0	16.5	1.22	65.0

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

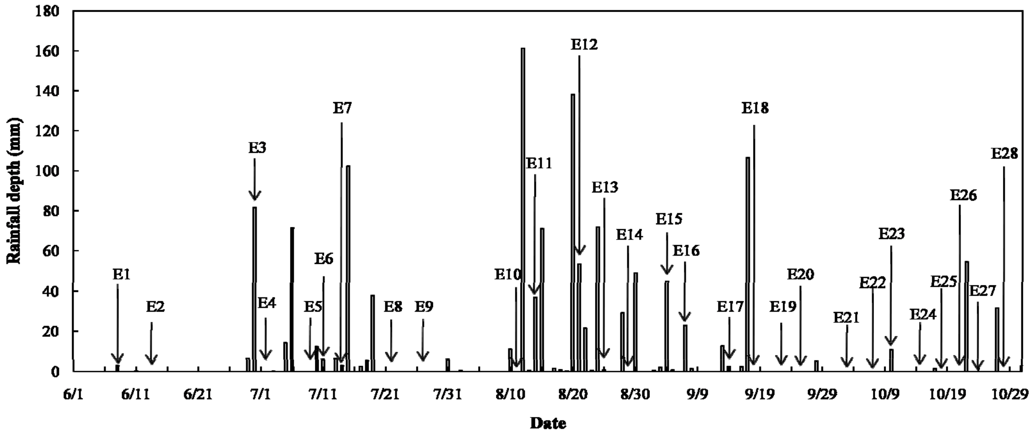

Fig. 2. Information on rainfalls and operational events

release a plenty of organic carbon.

The woodchip-packed wetland undergone pretty good nitrification that NH_4^+-N was removed by 53%, 81% and 83% at NDD as 1, 2 and 3 (Table 2). The release of organic compounds enhanced the oxygen consumption in the wetland, which might be not good for nitrification. But this adverse effect was offset by recycling courses during which more oxygen was supplied.

NO^{3-}N was reduced by 49.0%, 55.0% and 52.6% giving an average outflow concentration of 0.28mg/L, 0.22mg/L and 0.23mg/L at NDD as 1, 2 and 3, respectively (Fig.3f and Fig.4f, Table 2). Except for several occasions, the inflow NO^{3-}-N was lower than 1.0mg/L, and might be a limiting factor for denitrification which using nitrate as the electron acceptor (Tchobanoglous et al., 2003; Schipper et al., 2010).

The removal of TP (Fig.3g and Fig.4g, Table2) and PO_4-P was pursued in this study(Fig.3h, Fig.4h, and Table 2). It was observed that phosphorus was not always removed especially in the initial stage. This is because the leaching of phosphorus occurred from wood media (Chen et al., 2012; Healy et al., 2012). In this case, the adsorption capacity of woodchip is low, thus the phosphorus removal by adsorption was limited, and then phosphorus mainly removed by uptake of the plants.

3.2 Performance of pumice wetland

The performance of pumice wetland in removal of pollutants was summarized in Fig.5, Fig.6 and Table 3. Except for NO_3^-, the other pollutants were obviously removed.

The inflow TSS was reduced by 86.1%, 92.8% and 90.4% to 2.1 mg/L, 1.1 mg/L and 1.3 mg/L at NDD equal to 1, 2 and 3, respectively (Fig.5a, Fig.6a and Table 3). The performance of pumice wetland in removing TSS was very stable, wherein ripening was not observed. The effect of NDD on the TSS removal was not significant, indicating that most of solid particles could be trapped by media within NDD as 1 day. As to gravel filter, Korkusuz et al. (2005) reported that TSS removal efficiencies ranged from 4-82%, whereas Aslam et al. (2007) documented that TSS removal efficiencies ranged from 39-58%. The result of our study was higher than their study.

As shown, the inflow TCOD was decreased from 65 mg/L to 35 mg/L, 32 mg/L and 31 mg/L at NDD as 1, 2 and 3, respectively (Fig.5b); wherein SCOD was decreased from 49 mg/L to 28 mg/L, 25 mg/L and 23 mg/L at NDD as 1, 2 and 3, respectively (Fig.5c). Furthermore, the organic matters in the outflow were mainly soluble. Also it is clear that the effluent COD concentration in the different NDD was not greatly different, which means that the settable and biodegradable organics were rapidly removed by the deposition, filtration and biodegradation within 1 day and the remaining were non-biodegradable. In addition, compared to biodegradation, uptake of organic compounds by the plants was negligible (Watson et al., 1989).

Table 2. Removal efficiencies of pollutants in woodchip wetland (%)

Parameters	NDD 1	NDD 2	NDD 3
TSS	18.5	37.3	48.7
TCOD	-85.7	-114.3	-127.1
SCOD	-89.9	-117.7	-127.3
TN	38.2	39.0	40.4
NH_4^+-N	53.3	81.0	82.8
NO_3^--N	49.0	55.0	52.6
TP	13.9	22.8	29.0
PO_4-P	40.2	42.2	34.2

Except for several occasions (Fig.6f), the outflow NO^{3-}−N concentrations were higher than that of inflow. The average outflow concentration was 0.97mg/L, 0.92mg/L and 0.96mg/L at NDD as 1, 2 and 3, respectively (Fig.5f).

It is proven that the major removal mechanism of nitrogen in most of the constructed wetlands is microbial nitrification/denitrification (Vymazal et al., 1998). In an intermittently vertical flow wetland, oxygenation in the wetland matrix is increased by several fold compared to the HSSF systems, which may result in efficient nitrification

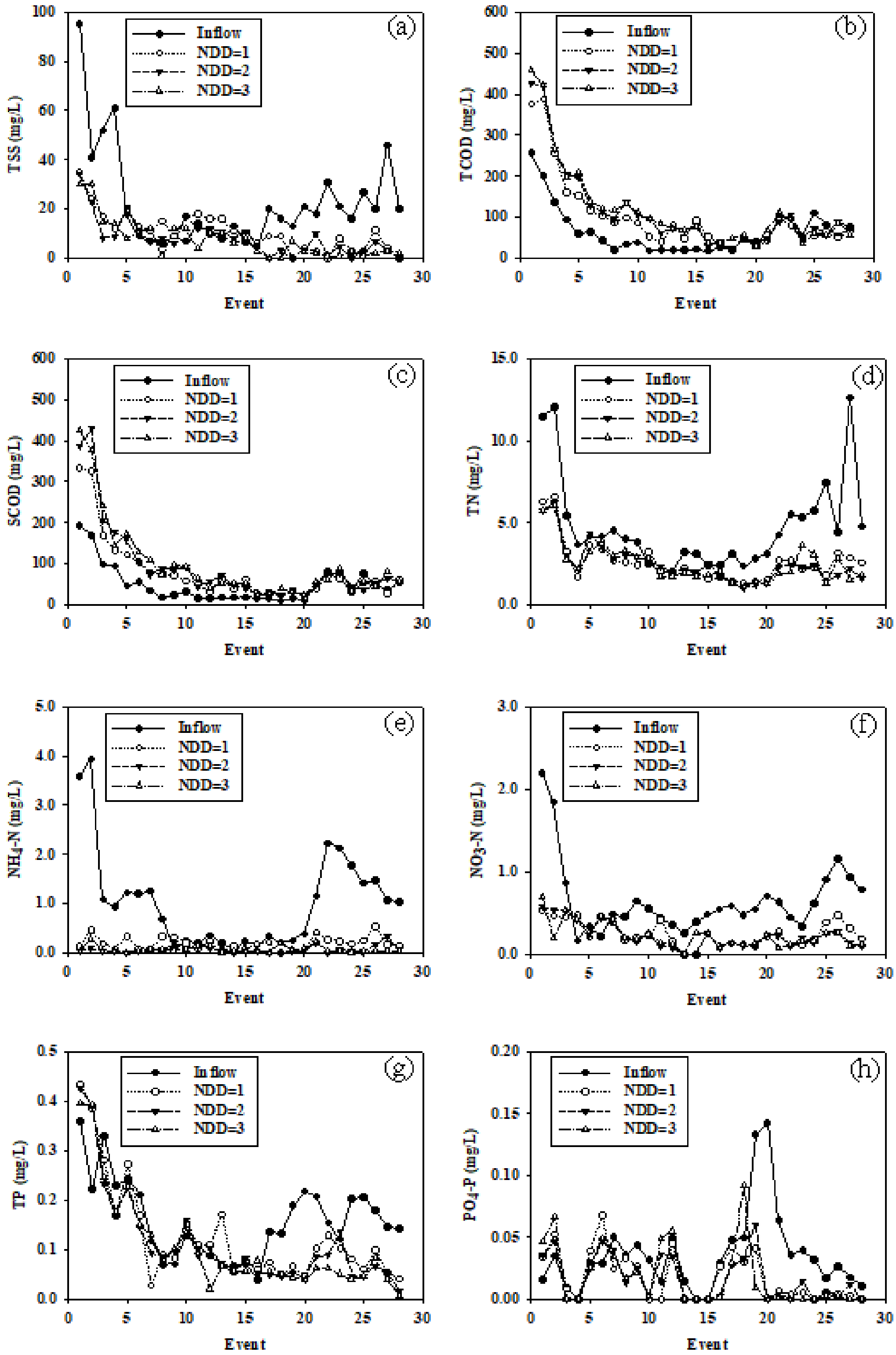

Fig. 3. Change of pollutant concentrations between in the inflow and outflow of woodchip wetland with respect to operational events

processes. The nitrate produced can subsequently be reduced by biological denitrification if there is readily available carbon source (Haberl et al., 1995; Vymazal et al., 1998). In this case, adsorption, denitrification and plant uptake might be the mechanisms of nitrogen removal. However, denitrification might be limited by available carbon source.

It is reported that the removal of phosphorus may be enhanced by using gravel as substrate (Korkusuz et al., 2005). Pumice wetland achieved good removal of TP and

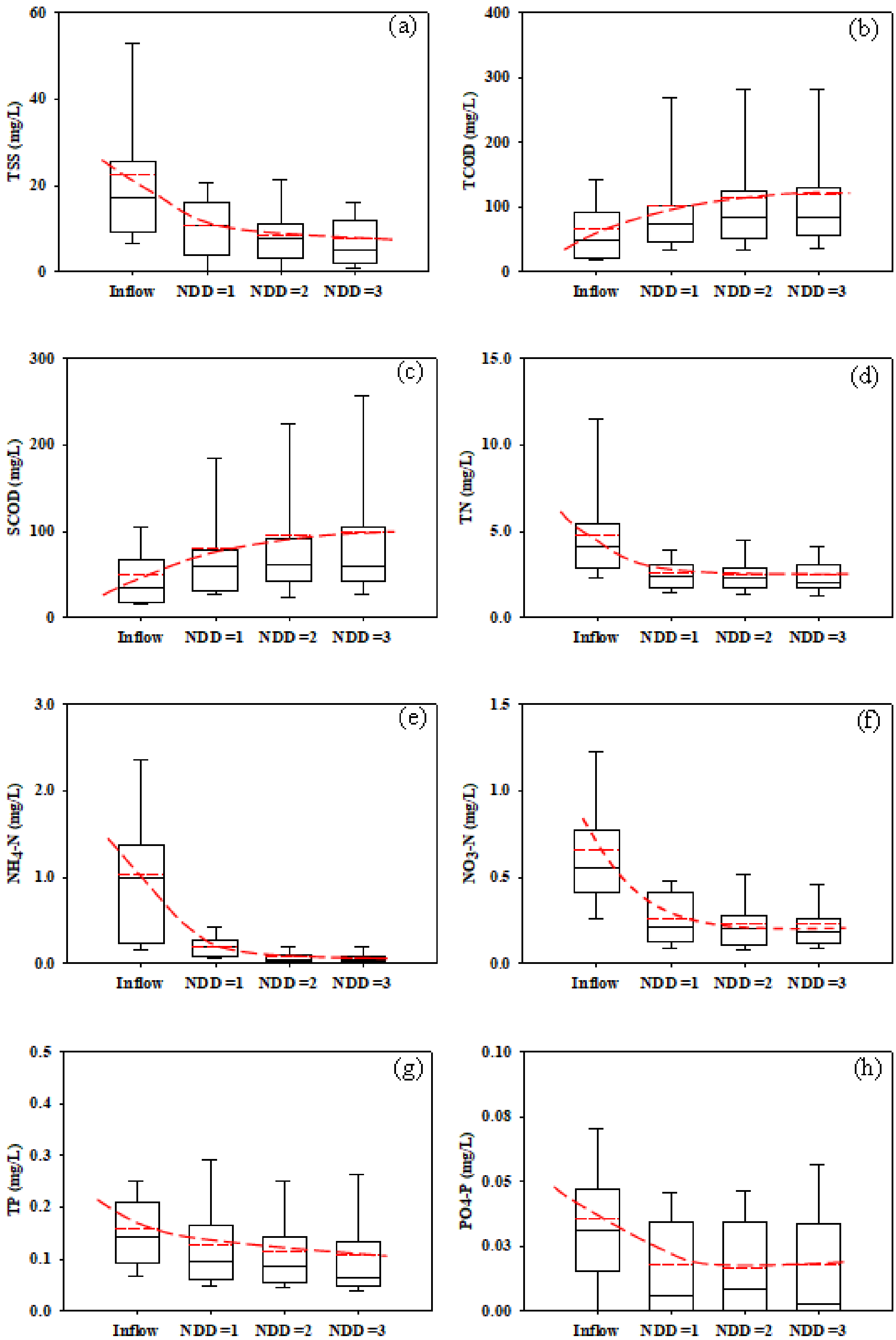

Fig. 4. Comparison of the pollutants concentrations in the inflow and outflow of the woodchip wetland

PO_4-P. During the operational stage, TP was reduced from 0.16mg/L to 0.05mg/L, 0.03mg/L and 0.03mg/L (Fig.5g), while PO_4-P was removed from 0.04mg/L to 0.01mg/L, 0.01mg/L and 0.01mg/L at NDD equal to 1,2 and 3, respectively(Fig.5h). The removal of phosphorus in pumice was attributed to adsorption, biological assimilation and plant uptake. The amount of phosphorus removed by different pathway could be be calculated.

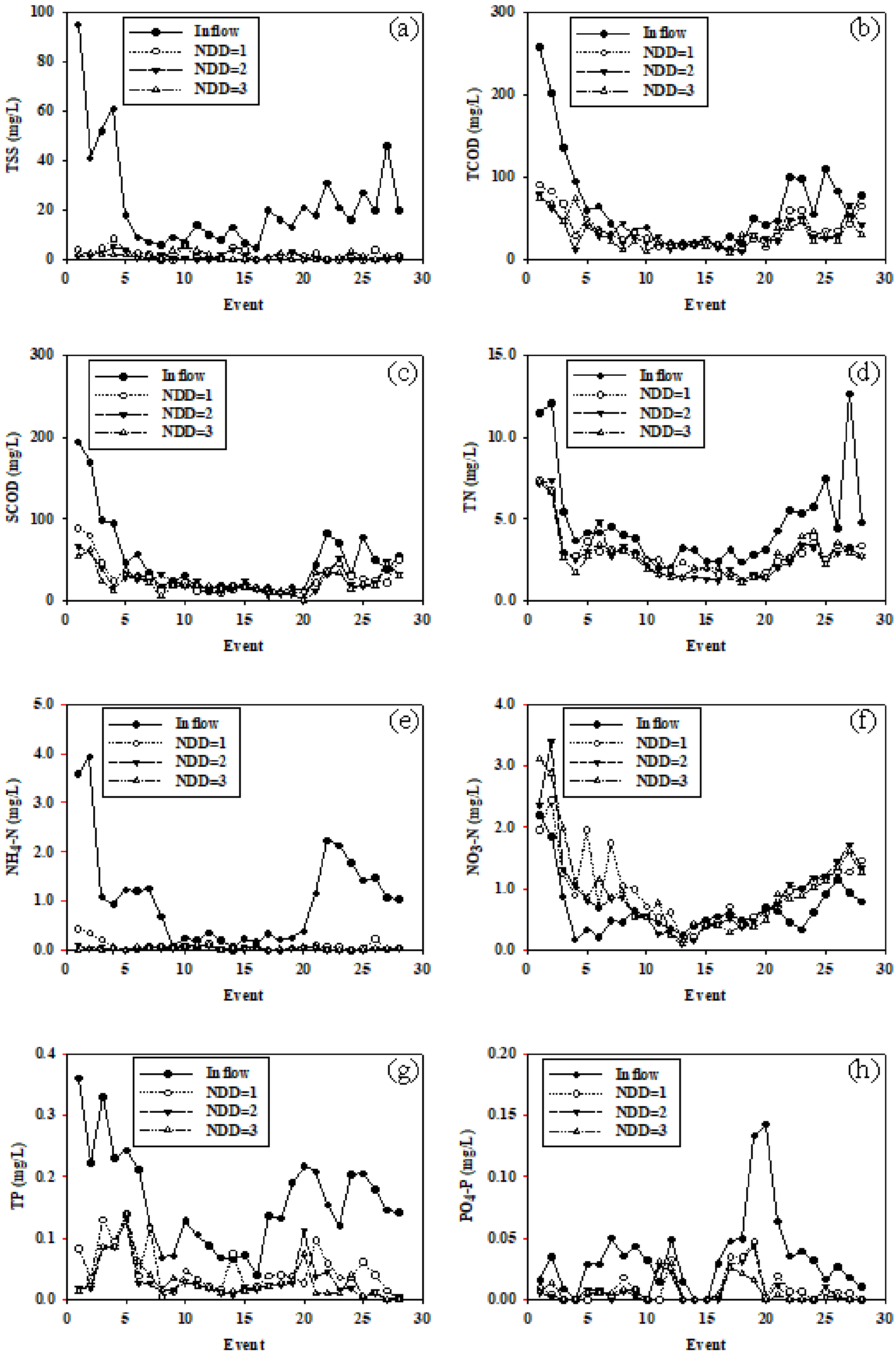

Fig. 5. Change of pollutant concentrations between in the inflow and outflow of pumice wetland with respect to operational events

3.3 Performance of volcanic gravel wetland

Volcanic gravel wetland also gave a good removal of TSS, COD and nutrients except NO_3^- and PO_4-P(Fig.7, Fig.8 and Table 4).

In the volcanic gravel wetland, the inflow TSS was reduced from 22.5mg/L to 2.4mg/L, 1.3mg/L and 1.3mg/L by 87.0%, 92.7% and 92.1% on an average at NDD equal to 1, 2 and 3, respectively (Fig. 7a and Table 4). Volcanic gravel wetland also showed very stable performance in removal TSS (Fig.7a). When NDD increased from 1 to 3,

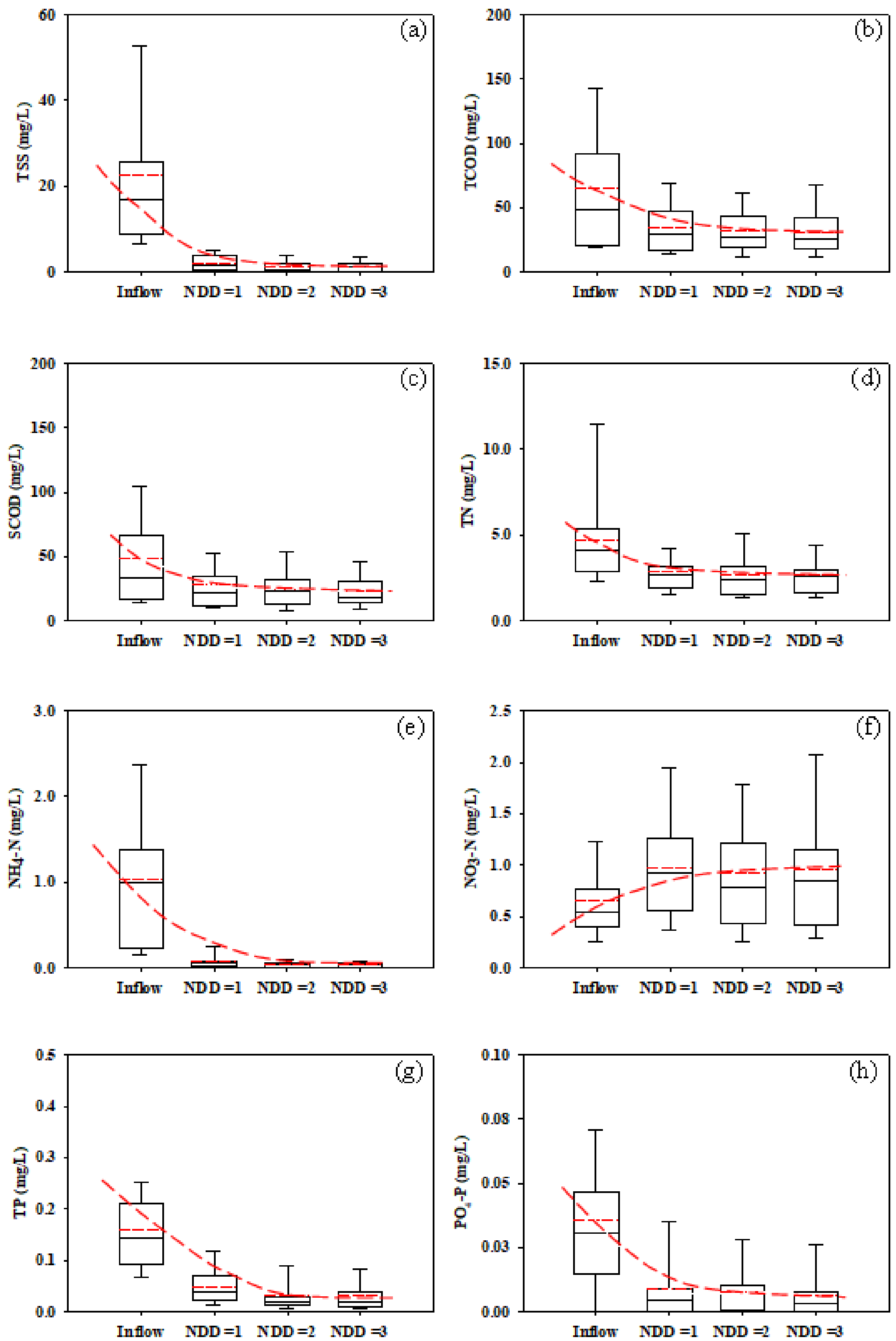

Fig. 6. Comparison of the pollutant concentrations in the inflow and outflow of the pumice wetland

TSS removal efficiency slightly increased, which means that most of solid particles could be rapidly trapped by wetland media.

Fig.7b and c, Fig.8b and c, and Table 4 present the removal of organic compounds in volcanic gravel wetland. TCOD in inflow was removed by 34.4%, 36.1% and 29.4% with outflow concentration of 36mg/L, 34mg/L and 38mg/L on average at NDD as 1, 2 and 3, respectively,

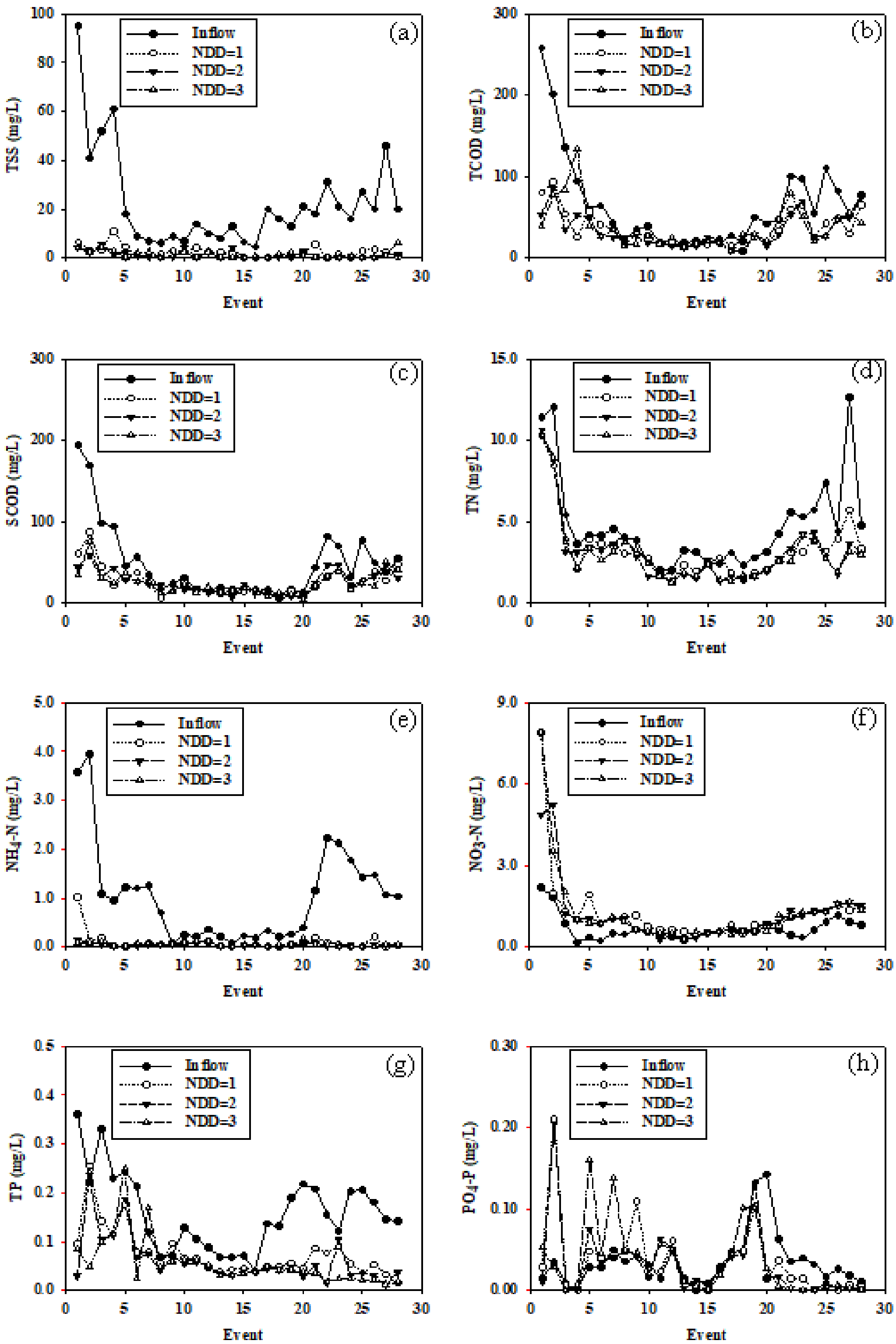

Fig. 7. Change of pollutant concentrations in the inflow and outflow of the volcanic gravel wetland with respect to operational events

wherein SCOD was removed by 34.5%, 34.1% and 35.1% with 26.5mg/L, 25.5mg/L and 24.2mg/L. It is obvious that the effluent COD concentration in different NDD also was not significantly different. Similar to pot gravel wetland, the settable and biodegradable organics were greatly removed within 1 day.

In volcanic gravel wetland, TN was reduced to 3.33mg/L, 3.15mg/L and 3.03mg/L by 26.6%, 31.1% and 33.7% on average, respectively (Fig.7d and Table 4). Removal efficiencies only slight increased as an increase in NDD.

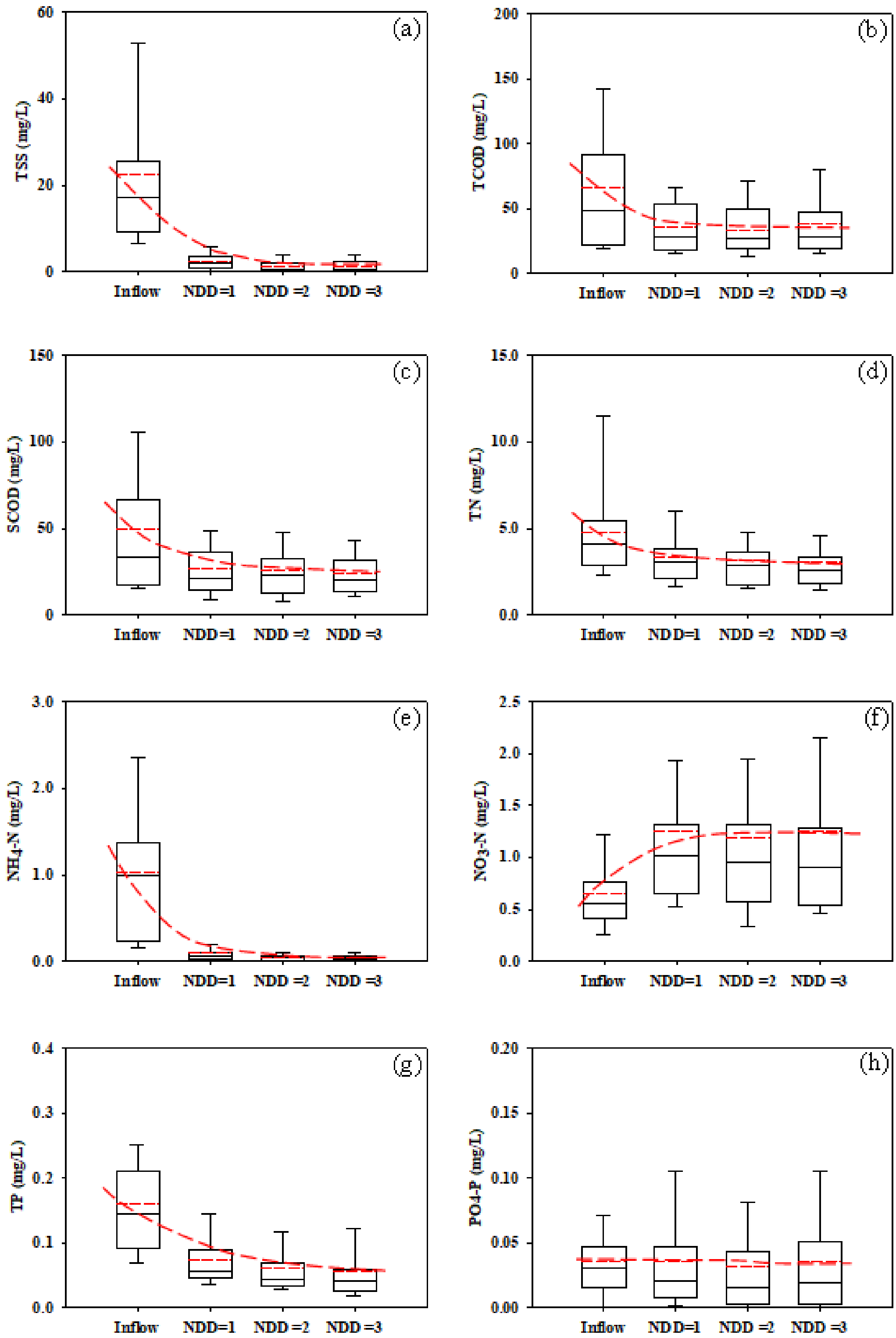

Fig. 8. Comparison of the pollutants concentrations in the inflow and outflow of the volcanic wetland

Table 3. Removal efficiencies of pollutants in pumice wetland (%)

Parameters	NDD 1	NDD 2	NDD 3
TSS	86.1	92.8	90.4
TCOD	35.2	34.1	39.3
SCOD	31.9	32.6	38.7
TN	33.0	39.4	39.0
NH_4^+-N	85.8	88.5	88.0
NO_3^--N	-77.8	-55.5	-67.0
TP	67.2	79.7	79.3
PO_4-P	76.1	75.4	76.6

In pumice wetland, NH_4^+−N was removed by 86.6%, 90.6% and 88.7% at NDD as 1, 2 and 3 (Table 4), which means that inflow NH_4^+−N was greatly reduced just within 1 day. The removal of NH_4^+−N was very stable with average outflow of 0.09 mg/L, 0.04mg/L and 0.04mg/L.

Except for several occasions, the outflow NO^{3-}−N concentrations were higher than that of inflow (Fig.8f and Table 4). Similar to pumice wetland, the accumulation of NO^{3-}−N occurred in the duration of operation.

In volcanic gravel wetland, adsorption, denitrification and plant uptake were the main mechanisms of nitrogen removal. However, denitrification might be limited by carbon source because the amount of organic compounds was not available.

Through volcanic gravel wetland, good removal of TP was achieved (Fig.7g, Fig.8g and Table 4), while it did not give a good removal of PO_4−P(Fig.7 g and Fig.8g). During the operational stage, TP was reduced from 0.16mg/L to 0.07mg/L, 0.06mg/L and 0.05mg/L on average at NDD equal to 1, 2 and 3, respectively. The removal of phosphorus was attributed to adsorption and uptake of plants. PO_4−P was not always removed, especially in the initial stage due to the release from the material(Chen et al., 2012).

3.4 Performance comparison between different wetlands

The removal efficiencies of TSS by pumice wetland and volcanic gravel wetland were similar (Fig. 9). Woodchip wetland performed worse than the other two wetlands in removing TSS. The reasons are as follows: (1) it is easy for particles to detached out from woodchip wetland because the porosity of woodchip was higher than that of the two media; (2) when woodchip was exposed to water, it expanded and became softer and weaker which made it easier to break into smaller particles. Among the three wetlands, woodchip wetland release organics in soluble for, but the other two wetlands showed similar COD removal efficiencies.

Table 4. Removal efficiencies of pollutants in volcanic gravel wetland (%)

Parameters	NDD 1	NDD 2	NDD 3
TSS	87.0	92.7	92.1
TCOD	34.4	36.1	29.4
SCOD	34.5	34.1	35.1
TN	26.6	31.1	33.7
NH_4^+-N	86.6	90.6	88.7
NO_3^--N	-106.8	-89.6	-90.0
TP	47.8	56.3	59.6
PO_4-P	-7.7	1.6	-12.0

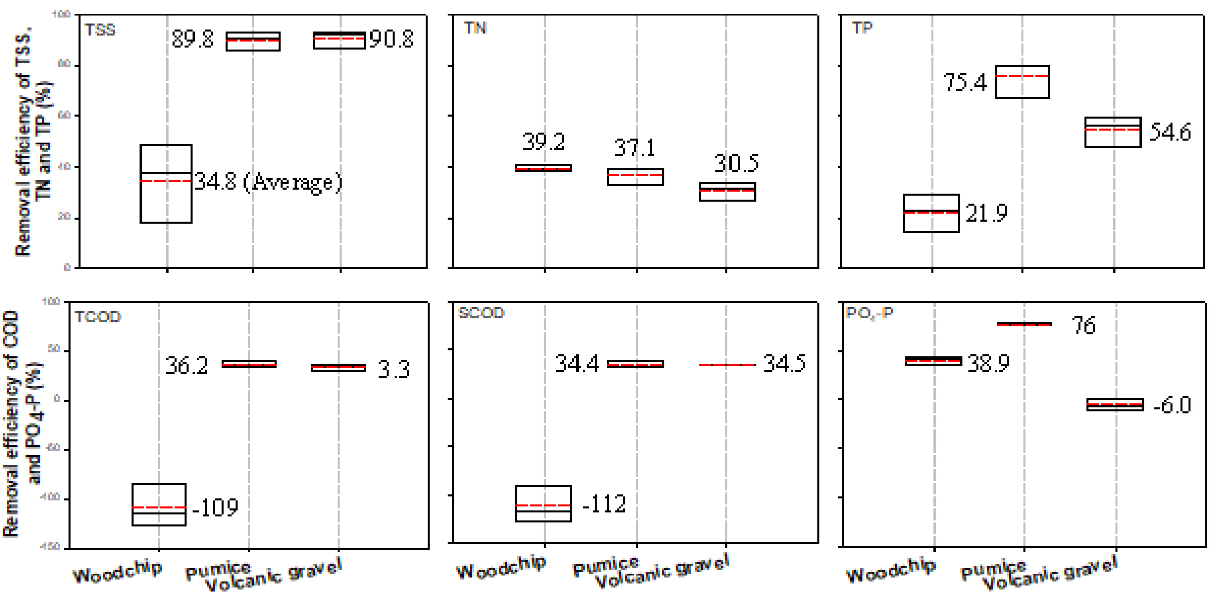

Fig. 9. Comparison of the removal efficiencies among the three wetland beds

Woodchip wetland was the best one in reducing nitrogen due to the more carbon source supplied by woodchip; and pumice wetland was the better one due to the good adsorption capacity (Fig.10). However, the removal of TKN by woodchip wetland was poor, which was attributed to the release of TKN from woodchip (Camern and Achipper, 2010).

Comparison of the Org.-N concentration in outflow of the pumice wetland and the volcanic gravel wetland, it was found out that there was significant amount of Org.-N that is not removed, even though NDDs was increased.

Pumice wetland was the best one in removal of TP due to its best adsorption capacity. Woodchip wetland was the worst due to the lower adsorption capacity. Volcanic gravel wetland was better than woodchip wetland, whereas these two wetlands has a potential of leaching phosphorus. The retention of phosphorus was closely related to the adsorption capacity of media. Unfortunatelythere are roughly two or three ways of phosphorus removal. One is plant uptake and the other one is adsorption and chemical precipitation in high pH increased by excessive algal growth.

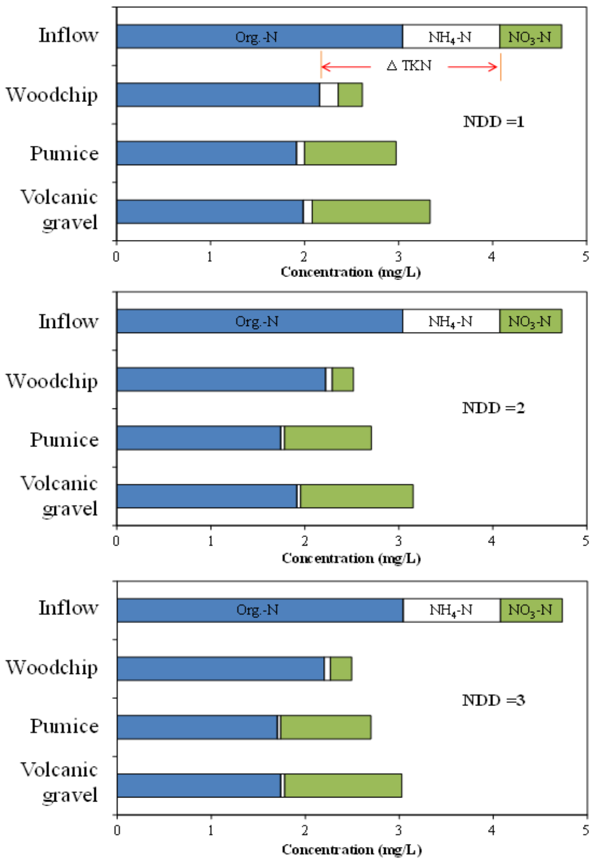

Fig. 10. Comparison of the nitrogen conversion among the three wetland beds

4. Conclusions

In this study, performance of the three different media-packed wetlands were compared. There were distinct characteristics by the media contributing to the removal of specific pollutants in the stormwater. First of all, the effect of NDDs on the effluent TSS, COD, TN, and TP concentrations was significant, suggesting that much more treatment time were provided as an increase in the number of passage through the media in recycling courses except for COD in woodchip wetland and NO^{3-}-N in pumic and volcanic gravel wetlands. Removal efficiencies of TSS by pumice wetland and volcanic gravel wetland were similar while wetland filled with woodchip was worse due to the debris by itself. For the organic matter, very similar results were derived because of the release of COD from the woodchip. It was found out that woodchip wetland was the best one in reducing nitrogen due to the more carbon source supplied from the woodchip by itself; and pumice wetland was the better one due to the good adsorption capacity.

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