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Clogging Potential in Constructed Vertical Flow Wetlands Employing Different Filter Materials for First-flush Urban Stormwater Runoff Treatment

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도시 초기 강우유출수 처리를 위한 수직흐름습지에서 여재별 폐색 잠재성 분석

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Abstract

The function of vertical subsurface flow wetlands can potentially be reduced with time due to clogging and are often assumed to be occurring when ponding and overflow is observed during rainfall. To investigate their clogging potential, three pilot-scale vertical subsurface flow (VSF) wetland systems were constructed employing woodchip, pumice, and volcanic gravel as main media. The systems received stormwater runoff from a highway bridge for seven months, after which the media were taken out and divided into layers to determine the amount and characteristics of the accumulated clogging matters. Findings revealed that the main clogging mechanism was the deposition of suspended solids. This is followed by the growth of biofilm in the media which is more evident in the wetland employing woodchip. Up to more than 30% of the clogging matter were found in the upper 20 cm of the media suggesting that this layer will need replacement once clogging occurs. Moreover, no signs of clogging were observed in all the wetlands during the operation period even though an estimation of at least 2 months without clogging was calculated. This was attributed to the intermittent loading mode of operation that gave way for the decomposition of organic matters during the resting period and potentially restored the pore volume.

Key words : media clogging, stormwater, vertical flow wetland

요 약

운전시간이 경과함에 따라 공극폐색 문제로 인하여 수직 흐름형 습지의 기능은 저하되는데 이와 같은 문제는 폰딩(ponding)이나 월류 현상에 의하여 쉽게 관측할 수 있다. 공극폐색 잠재성을 조사하기 위하여 도로주변에 설치된 파일럿 규모의 습지 운전자료를 분석하였다. 습지에는 각각 우드칩과 마사(부석), 그리고 화산석을 충진하였다. 약 7개월 동안 도로 강우유출수 처리시험을 수행한 후 충진된 여재를 비운 후 여재 층별로 분류하여 여재에 의해 포획된 고형물 입자의 양과 특성을 분석하였다. 분석결과 대부분의 포획물질은 외부기인 부유물질 이었으며 다음으로 여재표면에 증식한 생물막인 것으로 나타났다. 특히 다른 여재와 비교하여 유기성 여재인 우드칩에서 생물막의 증식이 왕성하였다. 또한 전체 포획량 중 30% 이상이 상부 20cm 이내에 집중되어 있어 폐색으로 인한 폰딩 발생시 이 부분의 여재를 우선적으로 교체하여야 할 것으로 판단된다. 또한 모델계산 결과 우드칩 충진 습지에서 폐색에 도달하는데 약 2달 정도가 소요될 것으로 산출되었으나 실제로는 전혀 폐색 기미는 발생하지 않았는데 이는 강우시에만 운영되는 특성상 강우활동이 없는 무강우 기간 동안 포획된 유기물질이나 생물막이 자연적으로 분해되어 일정기간이 경과되면 공극이 회복되었다.

핵심용어 : 도시 강우유출수, 수직흐름형 습지, 여재폐색

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1. INTRODUCTION

Structural best management practices (BMPs) are typically designed to reduce the negative impacts of stormwater pollutants and control the amount of urban sediment (Yong et al., 2013; Li and Davis, 2008). BMP structures such as vertical subsurface flow (VSF) constructed wetlands usually employ settling, filtration, and biological mechanisms in reducing diffuse pollutants from stormwater runoff. However, the performance of VSF wetlands can ipotentially be reduced with time due to clogging as can be observed through the occurrence of ponding and overflow. Clogging is a common phenomenon that occurs in any filtration system. It is defined as the formation of a semi-pervious layer throughout a range of depths due to the combined effect of physical, biological, and chemical processes (Langergraber et al. 2003; Bouwer, 2002). According to Blazejewski and Murat-Blazejewska (1997), the main factors affecting clogging are the accumulation of solids and vegetation debris, the growth of biofilm within the medium, roots and rhizomes, and the deposition of chemical precipitates. Langergraber et al. (2003) and Winter and Goetz (2003) reported that suspended solid loading plays a more vital role in clogging as compared to the growth of biomass.

Undesirable effects of wetland bed clogging include the creation of a highly polluted top media layer and reduction in the treatment volume of water due to an increase in overflow frequency (Larmet et al., 2007; Le Coustumer et al., 2012). Hence, of interest for wetland applications is the time until clogging occurs, which can be identified when overflow, ponding, and decrease in maximum water content is observed. Langergraber et al. (2003) conducted experiments on a pilot-scale vertical flow constructed wetlands dosed every 6 hours and observed clogging after 1 month, 2 months, and up to 18 months at hydraulic loading rates of 250, 150, and less than 180 mm/d. Bavor and Schulz (1993) reported up to 100 days without clogging on large-scale constructed wetland systems. However, clogging can also occur as early as 6-43 days under high-concentration loadings such as in the study of Zhao et al. (2004). Thus, the typical time period when clogging can possibly occur depends on a number of factors including the type and characteristics of the inflow, hydraulic loading rate, mode of operation (continuous or intermittent loading), media size, etc. Therefore in this study, three pilot-scale structural VSF wetland was operated and its treatment performance in terms of

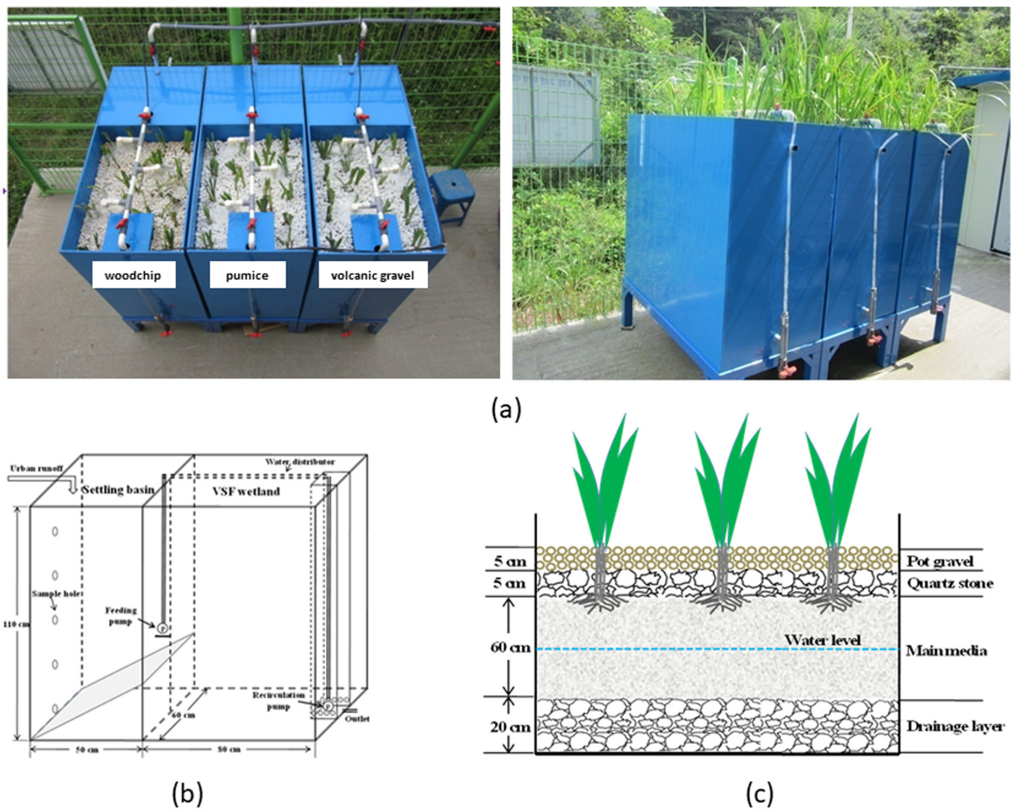

Fig. 1. (a) Photos (top and diagonal view), (b) schematic diagram, and (c) longitudinal section of the wetland portion of the VSF system (not to scale)

pollutant reduction as well as water retention with or without overflow was observed. To determine its clogging potential as well as to estimate its longevity without clogging, the accumulation of solid matters within the media were collected and analyzed after the operation period.

2. MATERIALS AND METHODS

2.1 Constructed VSF wetlands

To conduct the experiments, three vegetated pilot-scale wetland systems made of opaque acryl plates were constructed as shown in Fig. 1(a). Each wetland consists of a settling tank (0.5Lx0.6Wx1.1H m), a VSF wetland (0.8Lx0.6Wx1.1H m), and a pipe system Fig. 1(b). The pipe system is connected to a pump in the settling tank wherein the stormwater was stored for a period of time before being fed to the VSF wetland. On one side of the wetland, a recycling system was built to recirculate the effluent back to the surface of the bed thus providing multiple treatment. Sprinklers were provided to distribute the inflow or recycled stormwater evenly on the surface of the wetland.

The arrangement of the media in each wetland is shown in Fig. 1(c) and the physical properties of the main media are summarized in Table 1. Small pot gravel and quartz stones were laid at the surface to facilitate the distribution of incoming water and to provide space for the growth of plant roots. In the same manner, larger stones were employed at the bottom to provide proper drainage of the effluent. Woodchip, pumice and volcanic gravel were selected as the main media and are all locally available. Woodchip is a kind of renewable organic material, which have the lowest density of 260 kg/m^3 among the three media. The pumice used in this study is also a kind of lightweight material with a density of 400 kg/m^3 and the highest specific surface area of 29.55 m^2/g. Volcanic gravel is a porous material with a specific surface area of 4.56 m^2/g and a relatively higher density of 840 kg/m^3. All the media were washed with clean lake water before packed carefully avoiding unnecessary compaction.

To improve the treatment efficiency while providing aesthetics, *Acorus Calamus* (sweet flag) was planted in the wetlands. The roots were embedded between the small pot gravel and big stone layers and no soil was added to avoid clogging. Considering the porosity of the main media, the storage volumes were 0.245 m^3 for the woodchip and volcanic gravel wetlands, and 0.211 m^3 for the pumice wetland.

2.2 Operation, monitoring, and sampling

Stormwater runoff from a bridge was collected and stored in the settling tank for 24 hours before feeding to the VSF wetlands at an approach velocity of 55 m/d. This corresponds to a rainfall event that has a return period of 5 years. The treatment cycle corresponding to the hydraulic retention time (HRT) in the VSF wetland was designed as three days. Within this period, recycling is conducted every 6 hours and entails pumping the water at the bottom of the wetland back to the surface. After each treatment cycle, another batch of stormwater was fed into the systems.

To achieve the same water level in all the wetlands, the required inflow volume was 126, 102, and 120L for the woodchip, pumice, and volcanic gravel, respectively. Every stormwater influent as well as effluents per day were sampled for water quality analysis. Water levels in the tank were also recorded. The wetlands were operated throughout a total of 28 rainfall events from May to November for a total of seven months. After the end of operation, all the media were taken out and divided into 5 layers: 0-20, 20-30, 30-40, 40-50, and 50-60 cm from the surface. Each layer of the dirty media were washed and the wash water were sampled to measure the total suspended solids (TSS), chemical oxygen demand (COD), total nitrogen (TN), and total phosphorus (TP).

Table 1. Physical characteristics of the main media used in the study

Media	Size Range (mm)	d_{10}[a] (mm)	d_{50} (mm)	d_{60} (mm)	U[b]	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

[a]d_{10} = effective diamater (d_N = particle size wherein N% of the total amount by mass is smaller);
[b]U = uniformity coefficient

3. RESULTS AND DISCUSSION

3.1 Characteristics of the matters accumulated in the wetlands

Table 2 summarizes the accumulation of clogging matter in the wetlands throughout the operation period. The amount of these matter were determined to be 18.8 L, 5.1 L, and 2.3 L corresponding to void space reductions of 11.9%, 3.8%, and 1.4% in the wetlands containing woodchip, pumice and volcanic gravel, respectively. While the woodchip displayed the highest content of clogging matter, its TSS removal was the lowest among the three wetlands as shown in Table 3. Moreover, an increasing COD concentration along with retention time was observed. This shows that the accumulation of clogging matter in the woodchip wetland was mainly caused by the combination of incoming particulates deposition and possibly, biomass production. It has been reported that higher concentrations of COD should promote biofilm growth within the media bed. Woodchip is a biodegradable organic material and the debris generated from the process of biodegradation contributed to the amount of clogging matter.

On the other hand, very high TSS removals were observed in the wetlands containing pumice and volcanic gravel suggesting that the blockage of pores by inorganic solids has potential greater contribution to the removal of solids in these wetlands. Meanwhile, the idea of organic matter contributing to pore blockage has been arguable. Organic matters are subject to oxidation, especially during the resting period of a cycle, and can be removed at a rate depending on the decomposition process. Blazejewski and Murat-Blazejewska (1997) assumed that biofilm growth and decomposition can be balanced and do not contribute to clogging. However, Platzer and Mauch (1997) reported a linear decrease in bed conductivity with increasing COD loading, although it was likely that TSS loading also increased. Langergraber et al. (2003) concluded that biomass growth plays only a minor role compared to suspended solids over short terms.

Thus, for non-biodegradable inorganic media, the grain size as well as its solids trapping capacity mainly contributes to the speed of clogging matter accumulation. On the other hand, roots and biofilms were anticipated to block only a small portion of the pore.

Table 2. Accumulation of clogging matter in the wetlands

Media	Void volume (L)	Accumulated clogging matter (L)	Void space reduction (%)
Woodchip	158.4	18.8	11.9
Pumice	136.1	5.1	3.8
Volcanic gravel	160.8	2.3	1.4

3.2 Distribution of clogging matter

The distribution of clogging matter within the depth of the media also plays an important role in the development of the clogging process. Generally, distributed filtration is more beneficial than surface filtration when it comes to delaying clogging. At the end of the experiment, the distribution of clogging matters were measured and the profiles are shown in Fig. 2.

A sharp S-shaped distribution of mass as well as volume was observed in the woodchip wetland, showing more clogging matters accumulated in the top layer and the bottom layer (Fig. 2(a)). This is in contrast to previous reports wherein clogging matters mainly accumulated in the top layer (Zhao et al., 2009; Hua et al., 2010). However, this is most probably due to the fact that sand was used as the substrate in those studies whereas woodchip, which is bigger and provides more void spaces for sediment transport down the bed, was used in this study. Woodchip, as an organic material, can gradually decay under wet conditions. In this case, the clogging matters in the top layer were mainly from the entrapped solids and the growth of biofilm, while the accumulation in the bottom layer can be mainly due to the settling of the woody materials that

Table 3. Mean pollutant inflow concentrations, outflow concentrations, and pollutant removal efficiencies

Pollutant	Woodchip			Pumice			Volcanic gravel		
	In (mg/L)	Out (mg/L)	Rem. %	In (mg/L)	Out (mg/L)	Rem. %	In (mg/L)	Out (mg/L)	Rem. %
TSS	22.5	7.5	48.7	22.5	1.30	90.4	22.5	1.30	92.1
TCOD	65.0	119	-127.1	65.0	31	39.3	65.0	38.0	29.4
NH_4-N	1.10	0.12	82.8	1.10	0.14	88.0	1.10	0.04	88.7
TN	4.73	2.45	40.4	4.73	2.70	39.0	4.73	3.03	33.7
TP	0.16	0.11	29.0	0.16	0.03	79.3	0.16	0.05	59.6

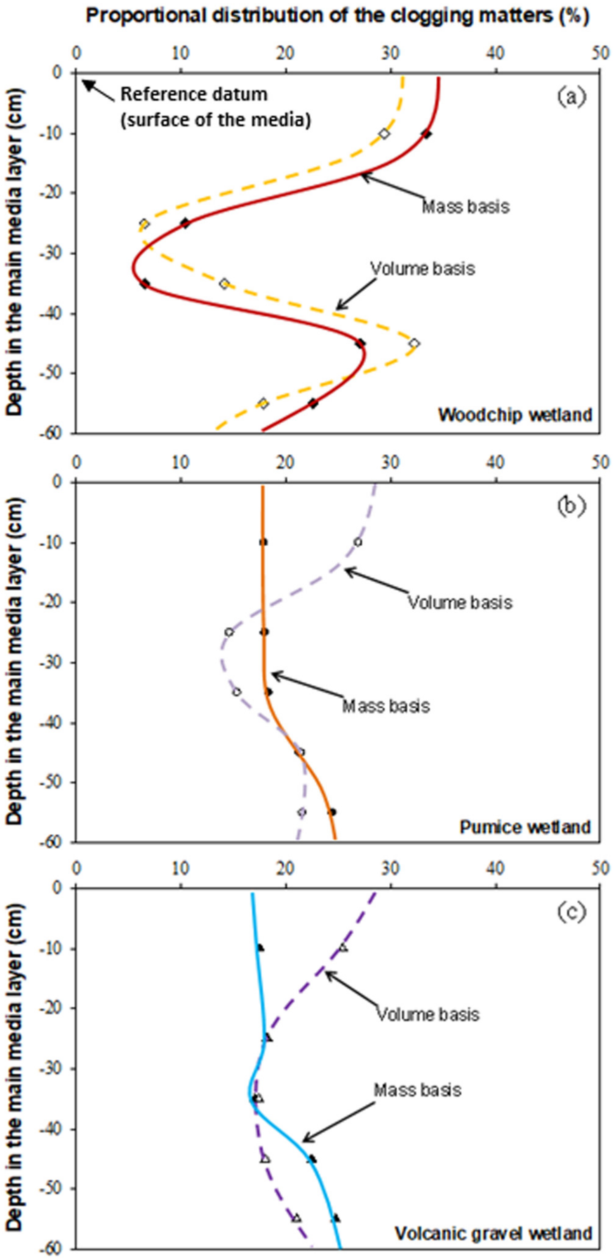

Fig. 2. Distribution of clogging matters in the VSF wetland beds

were detached from the submerged woodchip.

For pumice and volcanic gravel wetlands, similar trends were observed (Fig. 2(b) and 2(c)). Higher volume than mass percentages of the clogging matter at the top layer implies that they have lower densities as compared to that found in the lower layers. This means that at the tope laye of both wetlands, the accumulated matters were mostly organic in nature. The nutrients from inflow were always firstly trapped by the top layer and, if combined with good aeration, can enhanced the growth of the biofilm. In addition, the increase of clogging matters in the bottom layer were most probably due to the accumulation of broken debris from the media during the discharge.

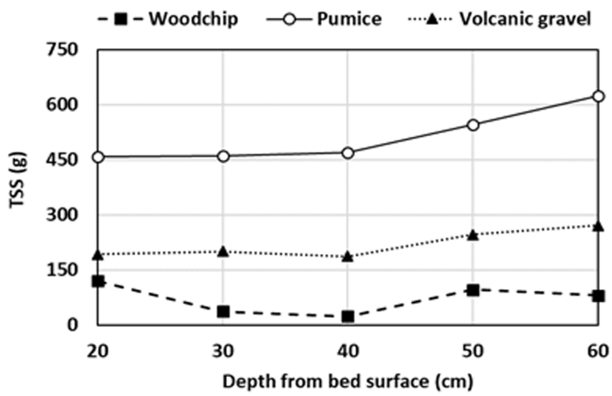

Fig. 3. Distribution of TSS in the VSF wetland beds

The detachment and settling of solid particles during the stormwater retention period can be confirmed by the distribution of TSS accumulated at the different layers of the media as shown in Fig. 3. It is apparent that the amount of accumulated solids increased with depth except at the upper layers of woodchip where biofilm growth was observed.

3.3 Distribution of COD, TN, and TP

To understand how basic pollutants collected within the wetland bed, the contents of COD, TN, and TP in the clogging matters were also measured. Fig. 4 illustrates the profiles of the pollutant distributions in these VSF wetlands. COD accumulation was found to be higher at the upper layers than the lower layers in all the wetlands. This corroborates the lower density of the clogging matter in the upper layers as observed in the previous section (Section 3.2). The accumulation of organic matter at the top layer forms a mat on the top of the bed which acts as a trap and spares the underlying layers from clogging. In the woodchip wetland, however, an increase in COD was observed at a depth 40-50 cm from the surface. This can be attributed to the leached COD from the woodchip material itself as well as to the biofilms created in that layer.

Higher amounts of TN were also observed in the top layer in all the wetlands suggesting that a large portion of this pollutant is particulate-bound and that filtration is more significant in this layer as compared to the lower layers. In the woodchip wetland, a sudden rise in accumulated nitrogen was observed in the 4th layer where the increase in COD was also observed.

As with nitrogen, most of the phosphorus were removed at the upper layers of the wetlands which is expected due to the high affinity of phosphorus to sediments. However, in the wetland containing volcanic gravel, TP was observed

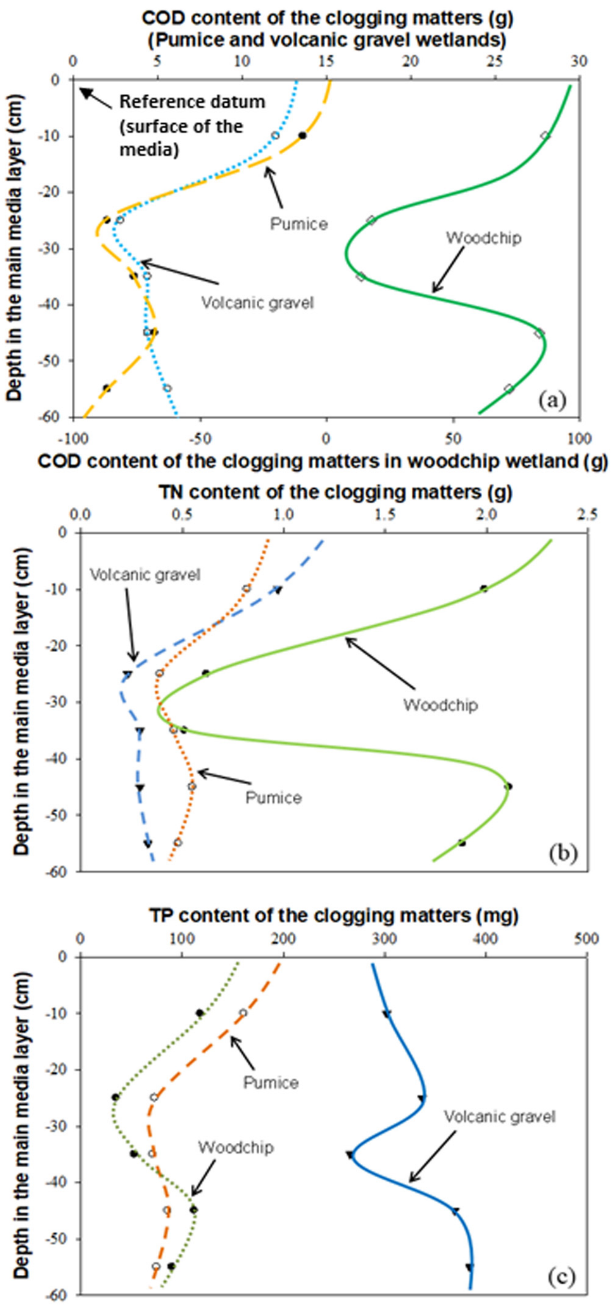

Fig. 4. Distribution of pollutants in the media layer of the VSF wetlands

to have been released by the media resulting to negative removal efficiencies and higher TP content as compared to woodchip and pumice.

3.4 Changes in water head

Clogging in granular medium is a process that develops with operational time and significant clogging can be ultimately reflected by the change of the water level or the occurrence of ponding on the surface of the wetlands. In this study, the factors influencing the change of water level in the VSF wetlands include transpiration, evaporation, daily collection of water quality samples, and the occurrence of rainfall. Fig.5 shows the fluctuation of the water depth in these wetlands over time. The significant declines of water levels in some periods, especially in the initial operation period of 10 to 30 days, were mainly caused by transpiration and evaporation. During these periods, no stormwater was fed into the wetlands to replace the treated stormwater because of the longer dry days. In contrast, sudden rises in water level occurred during rainfall and were caused by the raindrops which directly fell to the wetlands. Except for these instances, the water levels were stable throughout the operational time and no ponding was observed on the surface of these wetlands. Therefore, clogging did not happen within the operation period which lasted for 180 days or approximately 6 months.

Among the three media used, woodchip was found to be more susceptible to clogging due to the organic leaching, woody decay, and higher potential for biofilm growth. Therefore, the use of this media should be controlled and the right amount for a target organic requirements for biological removal processes should be determined.

3.5 Estimation of time to clogging

An early attempt to model clogging in VSF wetlands assumed that porosity was diminished cumulatively by the volume of influent suspended solids loaded into the system

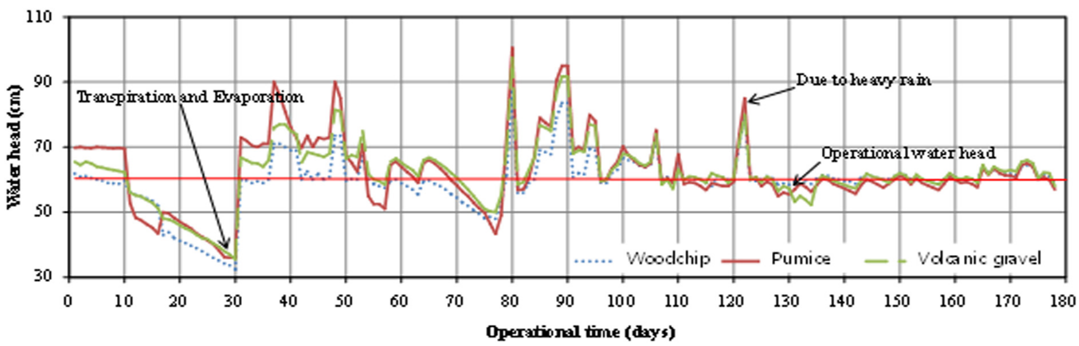

Fig. 5. Changes of the water heads in the VSF wetlands over time

Table 4. Estimation of time to clogging

Media	ρ_{solid} (kg/m^3)	q (m/d)	C_i (g/m^3)	α (m)	t_{clog} (days)	adjusted t_{clog} (days)
woodchip	20.0	55	22.5	2.98	0.048	69
pumice	518.1	55	22.5	0.74	0.311	448
volcanic gravel	489.4	55	22.5	1.56	0.617	888

over time, such that system longevity corresponded to zero porosity (Blazejewski and Murat-Blazejewska, 1997). Subsequently, this approach was validated and extended to make it applicable to solids fractions with a biodegradable component (Hua et al., 2010). Kadlec and Wallace (2009) summarized the time to clogging using the relationship below:

$$t_{c\log} = \alpha \frac{\rho_{solid}}{q_{Ci}} \quad \text{(Eq. 1)}$$

where t_{clog} = time to clogging in days, ρ_{solid} = bulk density of accumulating solids in kg/m^3, q = hydraulic loading rate in m/d, C_i = inlet TSS concentration, g/m^3, and α is an empirical coefficient determined using Eq. 2 as proposed by Blazejewski and Murat-Blazejeska (1997).

$$\alpha = 150\varepsilon * d \quad \text{(Eq. 2)}$$

In the equation above, ε is the porosity of the clean media in m^3/m^3 while d is the particle diameter in m. Using the properties of the employed media and the accumulated clogging matters as well, the time to clogging was estimated and is presented in Table 4.

It is important to note that the calculated time of clogging was adjusted to consider intermittent loading of stormwater as well as the resting period between cycles. As a result, the estimated clogging time was 2, 15, and 30 months for woodchip, pumice, and volcanic gravel wetlands respectively. However, the experimental data in this study shows that the wetlands were operated for 6 months without clogging which is 3 times longer than that estimated for woodchip wetland. The most probable factors to consider in this case is the settling of solid particles at the bottom of the bed and decomposition of organic matters during the resting period which opens up previously blocked voids and restores the hydraulic conductivity of the media bed (Platzer and Mauch, 1997). Previous studies have verified that Eq. 1 provides a reasonable approximation to clogging due to filtration. Therefore, an underestimation can be made if other factors that can restore pore volume is not considered. These factors include the detachment of previously attached particles, decay of the filter media, and decomposition of biofilms. In addition, variation in the inflow TSS concentration can also affect the time to clogging.

Nonetheless, the estimated values show that among the three media, woodchip is the most susceptible to clogging, followed by pumice, and volcanic gravel. This information is useful when deciding which filter media to select in terms of maintenance frequency and longevity of the constructed wetland.

4. CONCLUSIONS

The results of the experiments in the study revealed that the potential major contributors of clogging in vertical flow constructed wetlands are suspended solids deposition followed by the formation of biofilms within the filter interstices. Up to more than 30% of the clogging matter were found in the upper 20 cm of the media suggesting that this depth is required to be replaced once clogging occurs. For organic materials such as woodchip, the formation of biofilms were more evident through less dense accumulated matter and its occurrence on the deeper part of the bed. This contributed to a more rapid occurrence of clogging. Therefore, for this type of wetland, intermittent loading with periods of rest is a recommended mode of inflow to allow these organic materials to decompose thereby restoring pore volume. In addition, due to the affinity of most pollutants to TSS, majority of them were found in the upper layers of the bed, although a leaching of COD from woodchip and phosphorus from volcanic gravel was observed in the lower layers of the wetland. Meanwhile, no signs of clogging were observed during the operation period even though an estimated 2 months without clogging was calculated for the woodchip wetland. Thus, the equation for time of clogging used in the study clearly created underestimations. This can possibly be due to the intermittent feeding cycle which allowed the opening of previously blocked pores through detachment of solid particles from the media and decomposition of organic materials in the media interstices. Based on the findings, it can be concluded that woodchip was the media more susceptible to clogging due to biofilm growth and decay of the woody material under saturated conditions.

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References

Bavor HJ, Schulz TJ (1993). Sustainable suspended solids and nutrient removal in large-scale, solid-matrix, constructed wetland systems, *Constructed Wetlands for Water Quality Improvement*, Moshiri GA (ed.), Lewis Publishers: Boca Raton, Florida, pp. 646 – 656.

Blazejewski R, and Murat-Blazejewska S (1997). Soil clogging phenomena in constructed wetlands with subsurface flow. *Water Science and Technology*, 35(5), pp. 183 – 188. [DOI:10.1016/S0273-1223(97)00067-X]

Bouwer, H (2002). Artificial recharge of groundwater: Hydrogeology and engineering. *Hydrogeology Journal*, 10(1), pp. 121 – 142. [DOI: 10.1007/s10040-001-0182-4]

Hua, GF, Zhu, W, Zhao, LF, and Huang, JY (2010). Clogging pattern in vertical-flow constructed wetlands: Insight from a laboratory study. *J. of Hazardous Materials*, 180(1-3), pp. 668-674. [DOI:10.1016/j.jhazmat.2010.04.088]

Kadlec, R and Wallace, SD (2009). *Treatment Wetlands*. CRC Press, Inc., Boca Raton, Florida.

Langergraber, G, Haberl, R, Laber, J, Pressl, A (2003). Evaluation of substrate clogging processes in vertical flow constructed wetlands. *Water Science and Technology*, 48(5), pp. 25 – 34. [https://www.ncbi.nlm.nih.gov/pubmed/14621144]

Larmet, H, Delolme, C, Bedell, J (2007). Bacteria and heavy metals concomitant transfer in an infiltration basin: Columns study under realistic hydrodynamical conditions. *Proceedings of the NOVATECH 2007: 6th International Conference on Sustainable Techniques and Strategies in Urban Water Management*, Lyon, France, pp. 615 – 622.

Le Coustumer, S, Fletcher, TD, Deletic, A, Barraud, S, Poelsma, P (2012). The influence of design parameters on clogging of stormwater biofilters: A large-scale column study. *Water Research*, 46(20), pp. 6743 – 6752. [DOI: 10.1016/j.watres.2012.01.026]

Li, H and Davis, AP (2008). Urban particle capture in bioretention media. II: Theory and model development. *J. of Environmental Engineering*, 134(6), pp. 419 – 432. [DOI: 10.1061/(ASCE)0733-9372(2008)134:6(419)]

Platzer C, and Mauch K (1997). Soil clogging in vertical flow reed beds: Mechanisms, parameters, consequences and.......solutions? *Water Science and Technology*, 35(5), pp. 175 – 182. [DOI: 10.1016/S0273-1223(97)00066-8]

Winter, KJ and Goetz, D (2003). The impact of sewage composition on the soil clogging phenomena of vertical flow constructed wetlands. *Water Science and Technology*, 48(5), pp. 9 – 14. [https://www.ncbi.nlm.nih.gov/pubmed/14621142]

Yong, C, McCarthy, D, Deletic, A (2013). Predicting physical clogging of porous and permeable pavements. *J. of Hydrology*, 481, 48 – 55. [DOI: 10.1016/j.jhydrol.2012.12.009]

Zhao YQ, Sun G, Allen SJ (2004). Anti-sized reed bed system for animal wastewater treatment: a comparative study. *Water Research* 38(12), pp. 2907 – 2917. [DOI:10.1016/j.watres.2004.03.038]

Zhao, LF, Zhu, W, and Tong, W (2009). Clogging processes caused by biofilm growth and organic particle accumulation in lab-scale vertical flow constructed wetlands. *J. of Environmental Science*, 21(6), pp. 750-757. [DOI:10.1016/S1001-0742(08)62336-0]