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Clogging pattern in vertical-flow constructed wetlands: Insight from a laboratory study

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ABSTRACT

Substrate clogging caused by the accumulation of the particulate solids is the worst operational problem for vertical-flow constructed wetlands (VFCW). In this paper, the effects of particulate solids distribution and their accumulation in the substrate with different gravel sizes were investigated. The results demonstrated that the clogging layer can be considered as two parts: one is the blanket-like deposition layer, and the other is the upper substrate clogging layer. Furthermore, the clogging process shall be partitioned as three stages of puncture phase for the pollutants; the formation of the blanket-like deposition layer; and the formation and compaction phase to the whole clogging layer. With reference to the clogging mechanism, it is believed that the particulate solids (<100 μm) were absorbed firstly by electrostatic forces and van der Waals' forces. This is followed by the "bridging" made by the accumulated solids which act as a "sieve", thus further restricting larger particulate solids to flow through.

1. Introduction

Vertical-flow constructed wetlands (VFCWs) have been increasingly popular for the treatment of wastewaters. The major operational problem of VFCWs is the substrate clogging of the granular medium with organic and inorganic matters. Substrate clogging is a process that develops over the operational time and accordingly leads to a reduction of the infiltration capacity of the wetlands. In VFCWs, clogging would critically obstruct the oxygen transport and the consequences resulted in a significant decline of the system's ability to treat the wastewater [1,2]. Henceforth the essential requirement is to create a smooth operation of constructed wetlands without substrate clogging. Keeping this in view, various efforts to mitigate wetlands clogging have become prominent research topic and development goals in constructed wetland technology.

However, the clogging process is extremely complicated and not well understood. Mostly, it is believed that the total accumulation of suspended solids (SS) and the microbial biomass sedimentation through various processes, filtration and the growth of microorganisms blocked the pore volume of VFCWs are considered to be the major factors related to the clogging [3–5]. Besides, the organic composition in the total matter accumulated in pores is also an important cause of clogging in CWs system [6,7]. Furthermore, Langergraber et al. [1] and Winter and Goetz [8] stated that the loading of SS plays a crucial role on clogging but the growth of biomass has only a minor effect compared with the SS accumulation. Moreover, it was observed that the accumulated solids were mostly mineral in origin, in which the volatile fraction is about 20–25% of the total solids [4,9,10]. Even if the clogging risk is also controlled by substrate size since large-size substrate can prevent or delay clogging [11,12], the accumulated solids can lead to an inward and outward blockage of the filter substrate by reducing the active pore volume and therefore reducing the hydraulic conductivity of the substrate. Therefore, evaluating the clogging process from pore perspective is an effective way because the time of the pore fully filled is considered as the clogging time and the process of the pore reduced is thought to be the clogging pattern.

It is obvious that the grain size distribution of the substrate influences the pore-size distribution, active pore volume and the clogging process. If the reduction of the pore volume being essentially a process of net physical accumulation, the impact of the grain size distribution on the clogging would be a vital factor. However, despite its importance, the physical mechanisms that lead to clogging of porous media are still not well understood. Physically, the gravel substrate is porous media with a distribution of pore sizes that determines the smallest filtrate to be removed from suspension. The simplest possible pattern of clogging is one of pure size exclusion, where blockage events occur only if particles enter a pore that is smaller than their own diameter. However, in many instances clogging is observed even when the pores are much larger than the suspended particles. Therefore a detailed investigation on

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Table 1
Characteristics of the gravel.

	d_{10} (mm)	d_{30} (mm)	d_{60} (mm)	Cu	Cc	Porosity
Bed 1	2.5	3.5	5.8	2.32	0.84	0.34
Bed 2	6	8.2	11.4	1.90	0.98	0.44
Bed 3	15	20	25	1.67	1.07	0.47

Note: Cu (non-uniformity coefficient) = d_{60}/d_{10}; Cc (coefficient of curvature) = $d_{30} \times d_{30}/(d_{60} \times d_{10})$.

the clogging processes within the black-box "constructed wetland" is necessary.

The aim of this study is to determine new insights of porous substrate clogging. This can be accomplished by investigating the pattern of clogging and the effects of grain size distribution on the rate and degree of clogging. This paper reports on the first phase of a laboratory scale investigation into clogging pattern that occur within model CWs systems packed with different size of gravel as substrate. The process of the pore space filled with suspended particles was then interpreted from the comparison between the pore-size and gravel-size distribution.

2. Materials and methods

2.1. Constructed model wetland set up

The experimental model CWs consists of three identical beds named bed 1, bed 2, and bed 3 that were made of perplex columns. Each bed comprised of 15 cm diameter and 40 cm depth because clogging normally occurs in the upper layer (10–20 cm) of the substrate [13,14]. Three beds were filled with 30 cm depth with different sized gravels of around 3 mm for bed 1, 10 mm for bed 2 and 20 mm for bed 3, respectively. These sizes can represent the size of large, medium and small substrate. The particle size of gravel was relatively uniform, which can be seen from Fig. 1 (left). Other parameters of the gravels are presented in Table 1. The beds were planted with *Oenanthe stolonifera*. Along the side of each bed, there were nine outlet holes set up vertically for sampling purpose.

2.2. Constructed model wetland operation

The three CWs beds were operated in parallel with vertical down-flow pattern for about 240 days since May 2008. To speed up the clogging phenomena, this study was conducted under a high loading by continuously pumping wastewater with SS of around 600 mg/L under hydraulic loading of 0.5 m^3/m^2 d. The sediments of White Horse Lake in Jiangsu Province of China were used as the source of suspended particle solids for the CWs influent after necessary dilution. The solution has the similarity between the accumulated solids and the sediment composition [9]. The solution has d_{50} of 18 μm and the full particle size distribution is shown in Fig. 1 (right). In order to make the suspended solids more evenly in the system, electric stirrer was used in the feeding tank allowing the rotation pace of 45 rpm. During the operation period, samples of the influent and effluent from each outlet of all the three beds were taken every 7 days for SS concentration and particle size distribution measurement, whereas the infiltration rate and the pore volume were determined every 15 days till serious ponding occurred on the bed surface.

2.3. Measurements

(1) The infiltration rate measurement was carried out in accordance with standard for soil test method [15] based on the constant water head method. The infiltration rate of the gravel substrate (K) in the infiltration beds was determined by using the Darcy's formula: $q = K(\Delta H)/z$, where q is the specific discharge (in cm/s), K is the infiltration rate (in cm/s), ΔH is the hydraulic head (in cm) and z is the thickness of the gravel section (in cm). In the experiment, z is the height of the gravel substrate (in cm) and ΔH is 8.0 cm. The water flow in wetland can be considered as the flow in the pores of the substrate. In order to determine the flow within the beds, Reynolds number (Re) was calculated according to the formula:

$$Re = \frac{\upsilon \times d_{10}}{s} \quad (1)$$

where, υ is the flow rate, cm/s, d_{10} is the equivalent diameter which is defined as 10 mass% (of the particles) of the powder has a smaller diameter and hence the remaining 90% is coarser, cm, s is the viscosity of flow (SS solution), cm^2/s. According to the flow rate (5.79×10^{-6} m/s), d_{10} (15 mm max) used in the beds and the viscosity of water at 20 °C (1.00×10^{-2} cm^2/s), calculated Re is 0.087, which belongs to laminar flow ($Re \le 5$) [16].

(2) Effective porosity was tested through the balance of the water saturation and venting volume of the substrate. It can be expressed as a ratio of the values of drainage volume divided by the total volume before filling with gravel.

(3) TSS (total suspended solids) was measured using standard methods [17], a low-angle scattering method (Malvern particles size analyzer) was used to measure particles size distribution (PSD). The quantity of accumulated SS was calculated through the difference between the influent and effluent concentration.

(4) The screening method based on the standard for soil test method [15], was used for particle size analysis of the gravel in model wetlands.

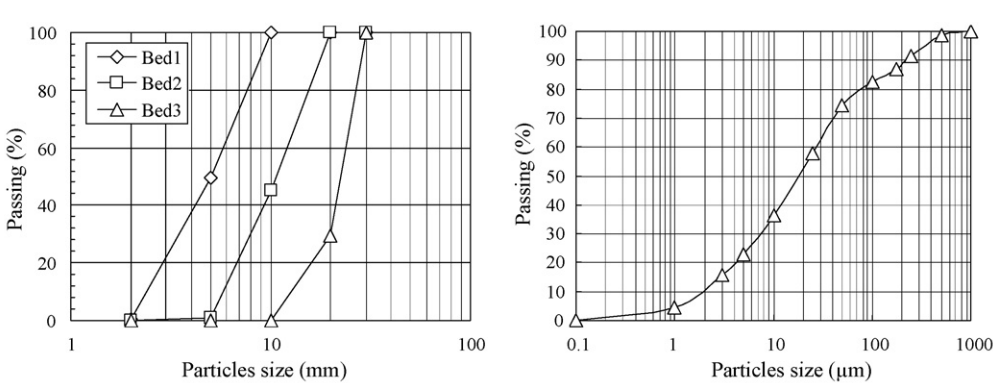

Fig. 1. Particles size distribution of the gravel (left) and the influent (right).

Fig. 2. The phenomena before (left) and after (right) clogging.

3. Results

3.1. The clogging phenomena

Once the high concentrations of suspended particles (about 600 mg/L) flow into the model wetland system, it was clearly seen that the suspended solids were carried with the water deeper into the wetlands. In the process of downward movement SS were filtered and trapped inside the wetlands. During the first 2 weeks of operation, the concentrations of the effluent SS were 48 mg/L for bed 1, 64 mg/L for bed 2 and 103 mg/L for bed 3, respectively. As the operation time increased, water ponding on the bed surface was observed in all the three beds which showed the sign of bed clogging. Subsequently with the increased trapping of SS, the blanket-like deposition layer was gradually developing at the surface of the substrate. For beds 1 and 2, the blanket-like deposition layer was observed after about 20–30 days' operation, while the obvious formation of such the layer in bed 3 was identified after 80 days of operation. Thereafter the blanket-like deposition layer was developed, owing to the concentrations of effluent SS significantly decreased and the infiltration rate decreased rapidly. Fig. 2 provides a glance of the bed 2 before and after clogging. Obviously, the compressed blanket-like clogging layer leads to an increased resistance and the significant reduction of the infiltration rate which leads to clogging. The occurrence of clogging was observed earlier in bed 1 as the reduced pore space in gravel media due to particles and slime blockage. Surface ponding and the time of surface sealing started to appear in 90 days, 130 days and 210 days, respectively for the bed 1, bed 2 and bed 3.

3.2. The clogging pattern

Measurement of infiltration rate along with bed operation time allowed the determination of various stages of the clogging development. The profile of the infiltration rate is shown in Fig. 3. At the beginning the infiltration rate does not change significantly. The rapid decline of the infiltration rate for bed 1, bed 2 and bed 3 is observed, respectively, during the operation time of around 50 days or 60 days, 80 days and 120 days, which implies the development of the bed medium clogging. It is noted that the infiltration rate of bed 1 decreased significantly compared with that of bed 2 and bed 3 due to the small size of the gravel in bed 1. Relatively, bed 3 has large size of gravel and thus maintains longer regarding the decrease of infiltration rate, as shown in Fig. 3. More significantly, Fig. 3 clearly shows that once the infiltration rate drops down, it continues in an enhanced manner with the further operation of the system. However this is not the case described by Blazejewski and Murat-Blazejewska [18] whose view was that the infiltration rate declined rapidly and then slowly. The reason might be that the fine sand was used as the substrates in their study [18] whereas the gravel was used in this study.

The SS accumulation inside the beds illustrated in Fig. 4 provides other evidence on the clogging development. It was observed that the SS accumulation was progressively increased with clear sign of steep increase at the later stage of the system operation.

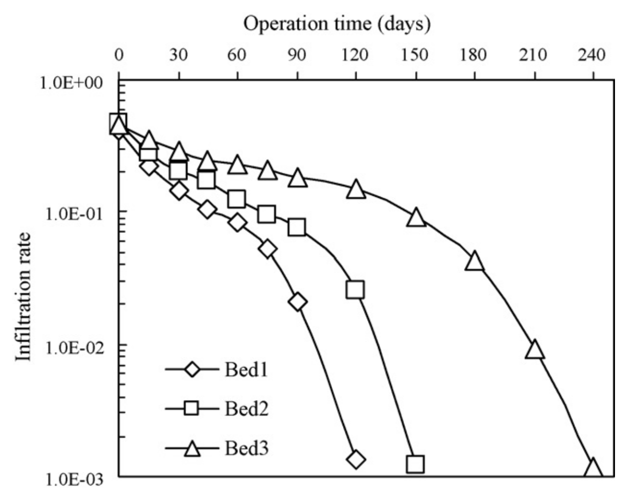

Fig. 3. The change of infiltration rate with operation time.

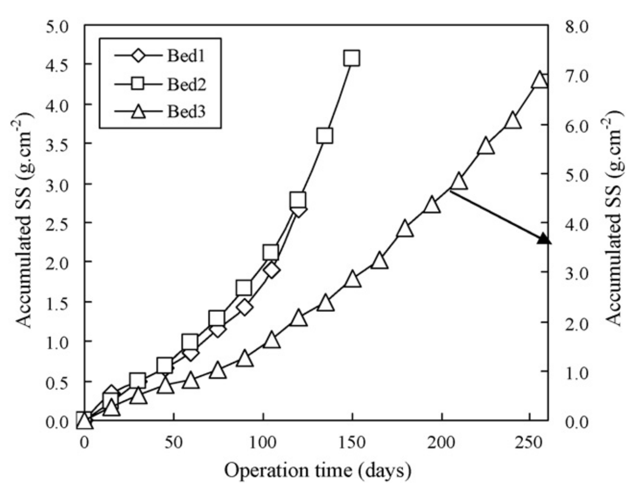

Fig. 4. Accumulated SS with operation time.

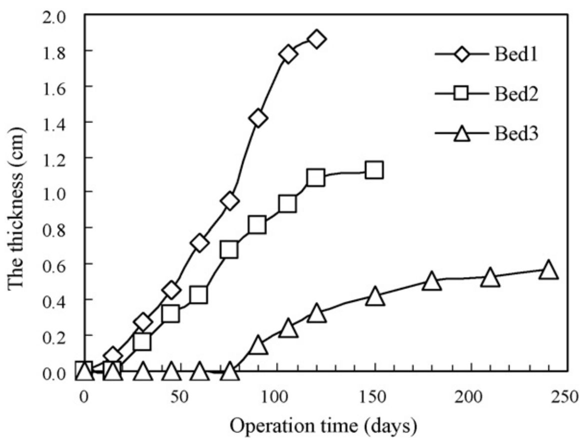

Fig. 5. The thickness of blanket-like deposition layer.

3.3. Development of blanket-like deposition layer

Once the clogging is developed, the blanket-like deposition layer on the top of the beds is observed. The thickness of the layer was identified by using a needle to puncture the blanket-like deposition layer and then measure the puncture depth by vernier caliper. The development of deposition blanket-like layer is shown in Fig. 5. It shows that for beds 1 and 2, the blanket-like deposition layer is formed soon after the operation of the system, the obvious formation of such layer in bed 3 is identified after 80 days of operation. The difference of the blanket-like layer formed in the beds may suggest that the gravel size is the key factor to control the deposition layer formation. Besides, such layer formed in beds will grow and become thicker and thicker over time.

Although there is no direct evidence to show that the blanket-like deposition is closely linked with the significant reduction of the gravel porosity, it is reasonable to speculate that the layer acts as a barrier, preventing the particles in the influent from passing through the substrate and accelerating the accumulation of solids on the top layer of the bed media, which considerably decreases infiltration rate and accelerate the occurrence of clogging.

3.4. Characterization of the upper substrate clogging layer

3.4.1. The effective porosity at different depth of the upper layer

The formation of the deposition blanket-like layer is an important sign of bed substrate clogging. However, during the operation, bed substrate is primarily contacted with the influent, which is full of suspended solids. As a result, pore space is filled with the suspended particles and the clogging developed from substrate. Accordingly it is desirable to investigate the vertical profile of the trapped suspended solids to provide the insight into "where" and "to what degree" of the clogging occurred. The variation of effective porosity in different layers with operation time is shown in Fig. 6. For the upper layer (0–2, 2–10 cm) the effective porosity decreased sharply, while for the underneath layer (20–30 cm) the effective porosity declined relatively slow. The presence of this low impermeable zone causes the infiltration to be remarkably declined, while the lower parts of the substrate remain permeable. A different behavior of the decline of effective porosity could be observed in the three beds for the different size of the gravels. The

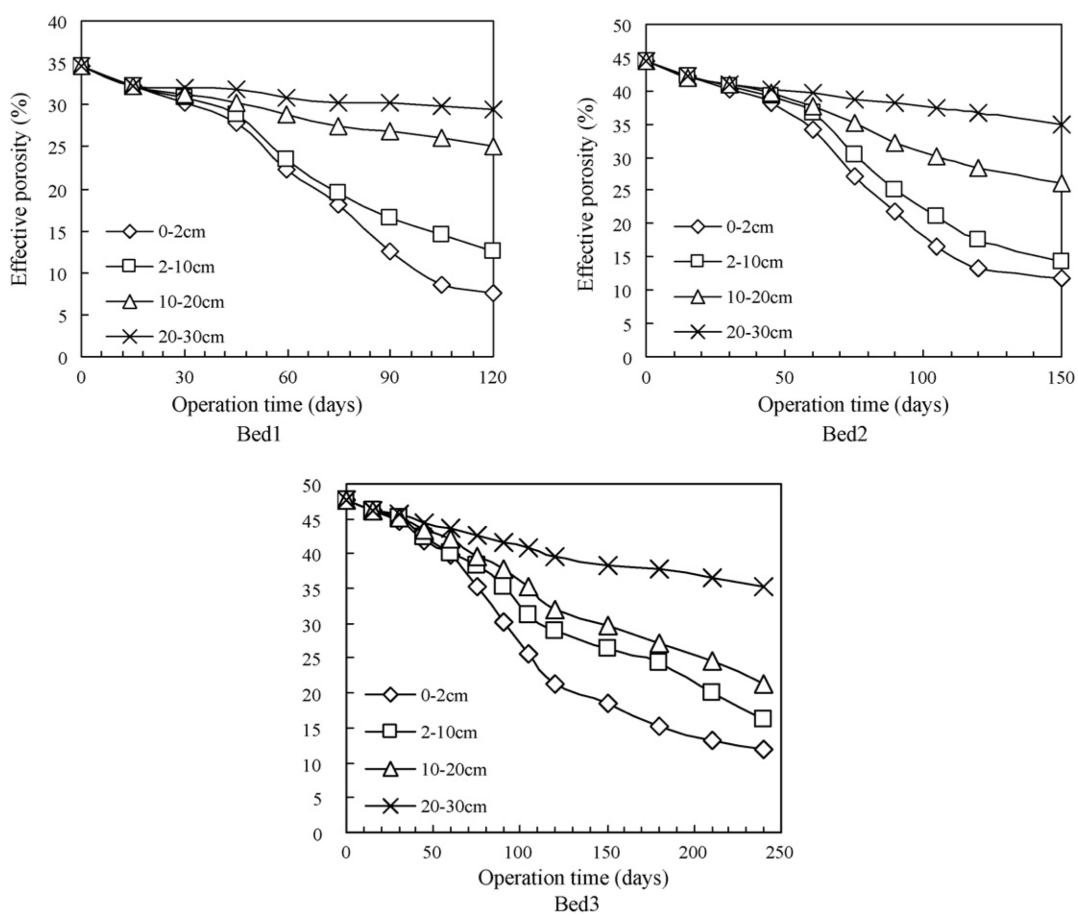

Fig. 6. The variation of effective porosity in different layers.

effective porosity decreases more obviously in depth corresponded to larger size gravel despite similar trends (Fig. 6). For the Layer between 10 and 20 cm the decline of effective porosity followed the order of bed 3 > bed 2 > bed 1. Therefore it can be assumed that the degree of clogging is mainly associated with the depth. It is generally believed that the clogging depth is less than 20 cm in the gravel wetland beds.

3.4.2. The accumulated suspended particles in the pores of the substrate

Fig. 7 shows that approximately 80–90% particle solids are accumulated in the first 0–6 cm depth of the bed and the amount of infiltrated material obviously decreased with depth. It has been seen that suspended particles are trapped mainly in the near-surface layer, which agrees with other studies, claiming that the occurrence of clogging was mainly in the upper layer [13,14]. It is interesting to note that, regardless of the grain size distribution, the lower parts of all profiles in Fig. 7 are characterized by similar amount of clogging material. Such behavior of the decrease of porous deposits can be characterized by an exponential curve.

The distribution of accumulated suspended solids in each wetland bed is illustrated in Fig. 8. It shows that the fraction of the accumulated suspended particles >250 μm occurred very close to the surface (0–4 cm), whereas the fraction size of 25–100 μm is completely trapped in the depth of 0–6 cm. Most of the particles of 0–25 μm are trapped in the depth of 0–2 cm, but small portion of them are carried out deeper by the flow and then accumulated in the bed. This result is also confirmed by examining the vertical distribution of the SS concentration profiles for clay, fine silt, medium silt and coarse silt particles in other study [19], which showed that the majority of particles that reached the interface were less than 20 mm for all constant water level experiments. It is also noted that there is no obvious difference between the effects of grain size distribution on the accumulation of particles fractions (>250 μm). On the contrary, the accumulation of the fractions of 0–25, 25–50, 50–100 and 100–250 μm are increased in depth, which correspond to the increase in the size of the gravel.

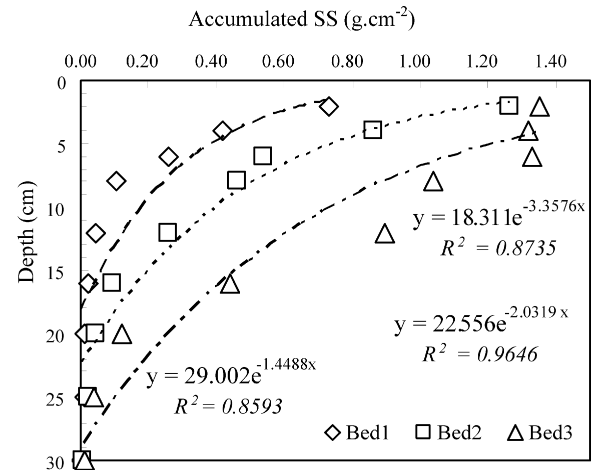

Fig. 7. Content of clogging material trapped in model wetland.

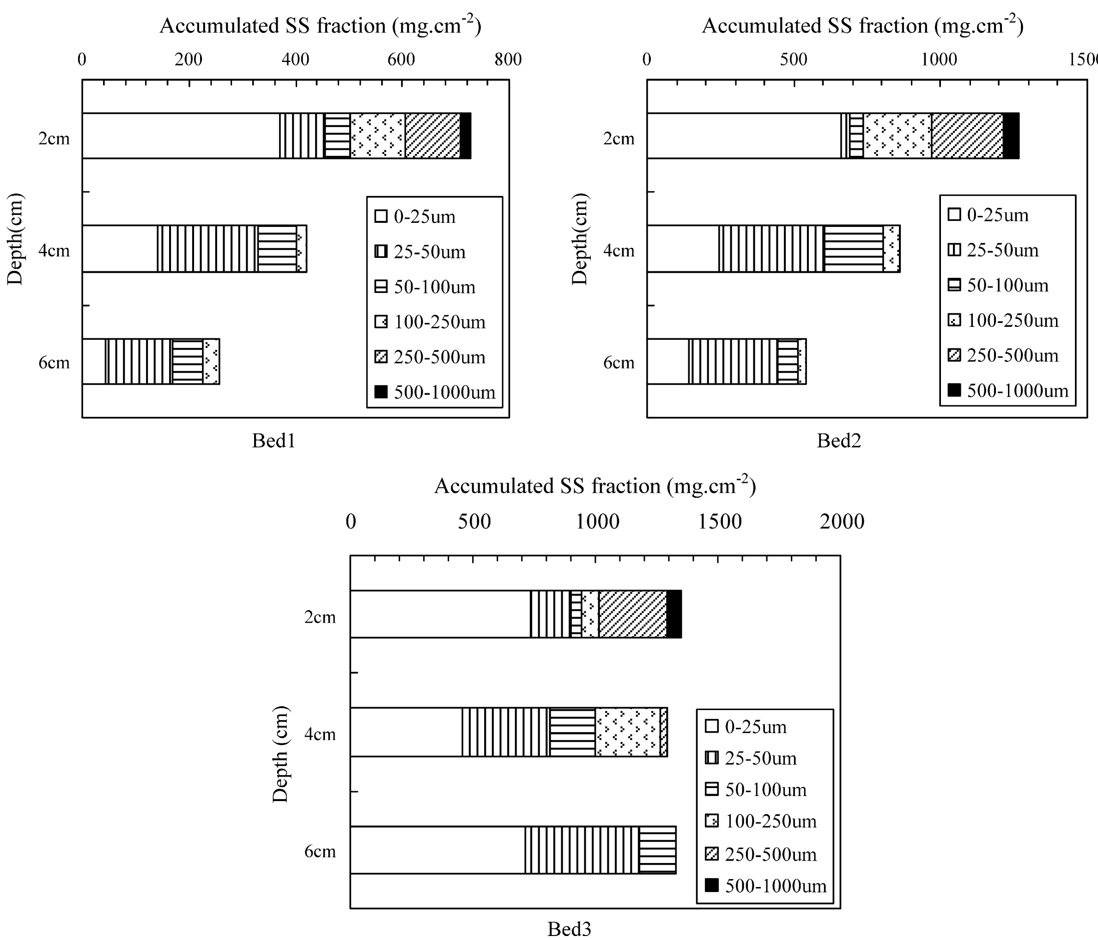

Fig. 8. Content of clogging material fractions trapped in depth.

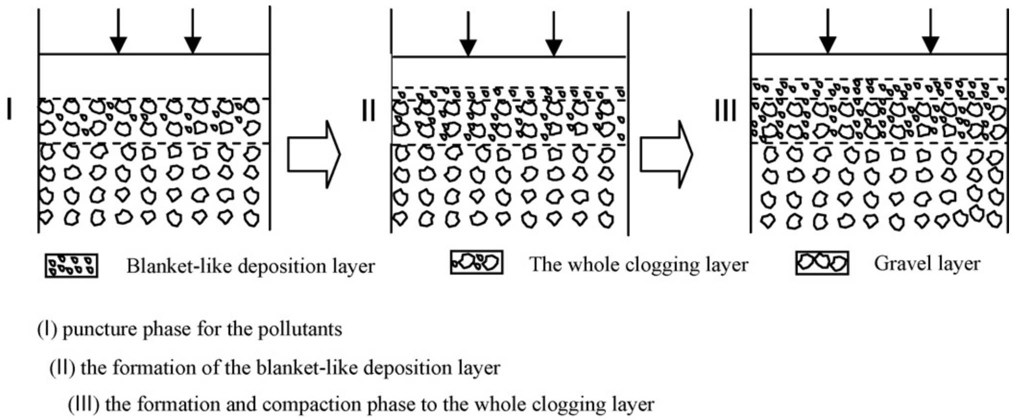

Fig. 9. The conceptual description of the clogging process.

4. Discussion

4.1. Clogging pattern visualization

Based on the phenomena of the clogging observed and the process of clogging analyzed through infiltration rate and the interception for SS, the development pattern of the clogging in vertical subsurface-flow wetlands can be conceptually described as shown in Fig. 9. In the first stage, i.e., puncture phase for the SS (Fig. 9I), the constructed wetlands can be operated normally and the infiltration rate drops slowly. The suspended particles flow into the deep layer with the water flow when SS can be trapped inside the pores by adsorption and ion exchange/van der Waals' forces.

In the second stage, i.e., the formation of the blanket-like deposition layer (Fig. 9II), as the continuous operation of the wetlands, most of the SS are trapped while the infiltration rate significantly decreased. As the fine suspended particles flow into the substrate with water, the coarse particles have been deposited on the surface and thus form a blanket-like deposition layer. Once the blanket-like deposition layer is formed, it develops gradually and becomes thick in due course of time. It should be pointed out that there is no obvious time division between the first and second stage.

In the third stage, i.e., the formation and compaction phase of the whole clogging layer (Fig. 9III). The blanket-like deposition layer becomes thick and is compacted as a result of the SS being retained after the formation of deposition blanket layer that acts as a barrier to prevent most particles from reaching the clogging layer. Accordingly, the thick and compact clogging layer will sharply reduce the infiltration rate, which leads to the serious surface ponding.

4.2. The processes of the particle solids accumulation

Furthermore, the mechanism of the particle accumulation inside the wetlands, attempt has been made to estimate the pore volume was made under some assumptions. Because the gravel used in this study was basically uniform, assumed single gravel to be a single sphere, the pore volume can then be calculated considering that the gravel is closely packed. If the gravel is closely packed, there will be two kinds of pores, one is tetrahedral pores, and the other is octahedral pores. Therefore, the calculated volume of the model wetland used in this study is 4,615,800 mm^3. The porosity for rhombohedra (the most compact arrangement) is 25.96% [20]. Other parameters were also calculated and are shown in Table 2.

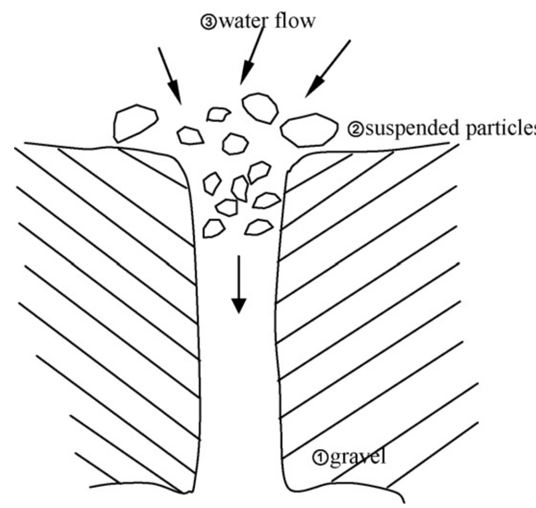

Fig. 10. The "bridging" between particles.

It shows that when the diameter of the gravel is 5 mm, the diameter of the "hypothesis ball" to fit the tetrahedral shape pore is 1.13 mm, and that to fit the octahedral voids is 2.07 mm. However, in general, the d_{50} of the suspended solids employed is not more than 20 μm. This clearly indicates that the size between the pore and the particles is not in the same order of magnitude. If the physical trap alone is considered, all the particles were supposed to pass through the wetland bed and flow out with the water, as conceptually illustrated in Fig. 10. However, it is not the actual case in the experiment. This is reasonable to assume that the particles

Table 2
The calculated diameter of accommodated ball in tetrahedral and octagonal gap.

The diameter of the sphere (mm)	Volume (mm^3)	Number	Tetrahedral gap (mm^3)	Diameter of accommodated ball in tetrahedral gap (mm)	Octagonal gap (mm^3)	Diameter of accommodated ball in octagonal gap (mm)
2	4.18	816401.25	1632802.5	0.45	816401.25	0.828
5	65.41	52249.68	104499.36	1.125	52249.68	2.07
10	523.33	6531.21	13062.42	2.25	6531.21	4.14
15	1766.25	1935.17	3870.34	3.4	1935.17	6.21
20	4186.66	816.40125	1632.8025	4.5	816.40125	8.28

accumulated in the pores are absorbed in the course of downward movement with water flow. Simultaneously, substances dissolved in the solution (as iron compounds) may precipitate mostly by an electro kinetic process or van der Waals' force [21].

Fig. 10 illustrated the model of the particles trapped in the pores to form "bridges" [22], which acts as a "sieve", preventing emplacement of suspended particles larger than the diameter of the sieve from reaching the clogging layer. Due to the existence of the "bridging", more suspended particles are further restricted to enter the wetland substrate after a time period of operation. The wide coarse pore system is not a continuum. At the narrow parts of the pore channels smaller particles are also filtered so that the pore spaces become even smaller. Because of this sieving effect the pores at the surface can be blocked and the infiltration rate decreases rapidly. At the end, the clogging layer is developed by trapped suspended particles under both the mechanical and electro kinetic processes.

The amount and the range of particle size of adsorbed SS were measured in this study. It was found that the amount of adsorbed SS is 0.5–1.4 mg/g, which agreed with the fact that there was a much greater amount of accumulated interstitial solids (99%) than solids adhered to gravel (<1%) in all the subsurface-flow constructed wetlands [14]. The particle size of the SS absorbed was almost less than 100 μm. It can be assumed that the SS whose particle size were less than 100 μm were absorbed firstly, then the bigger size of the particles were intercepted through the bridge and were accumulated at the end. Winter and Goetz [8] claimed that the content of SS with particle size of >50 μm to play a key role for substrate clogging. However, there is no detailed explanation and discussion of such range based on particle size.

It should be pointed out that the constructed wetland wastewater treatment is a complicated process with physical, chemical and biological process functioning together. It is difficult and even impossible to fully separate each processes. Possibly clogging contributed to the biomass accumulation, rather than the physical or the mineralization process of SS filtration and simple trap, like considered in this study. However, SS is the important step in causing the clogging, either organic or inorganic. Once the accumulation and movement processes of particulate solids in wetlands well identified, the whole clogging process can be better understood. Therefore, this current study provides insight into a better understanding of the clogging behavior. Nevertheless further study, especially the consideration of the organics degradation and the biomass accumulation to clogging occurrence, is highly desirable.

5. Conclusions

Laboratory scale model constructed wetlands were designed to explore the substrate/gravel clogging behavior, which have shown that the clogging layer caused by the particulate suspended solids in vertical subsurface wetlands was gradually developed from the upper substrate layer and the formation of the deposition blanket-like layer on the top of the substrate. The process of clogging can be divided into three phases: (I) puncture phase for the pollutants; (II) the formation of deposition blanket-like layer; and (III) the formation and compaction phase of the clogging layer.

The clogging degree decreased with depth of the substrate and most of the suspended materials were trapped in the near-surface layer especially in 0–4 cm upper layer. In addition, it is believed that the particulate solids (<100 μm) were absorbed firstly by electrostatic forces and van der Waals' force. This is followed by the "bridging" that was made by the accumulated solids acting as a "sieve", thus further restricting the larger particulate solids to flow through.

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