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An integrated model of substrate clogging in vertical flow constructed wetlands

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Abstract

This paper presented an integrated conceptual model to describe the substrate clogging in constructed treatment wetland. The model is based on pore space reduction of the wetland substrate during the integrated treatment processes including physical, biological and plant-related processes. A group of laboratory scale constructed wetlands (CWs) was employed to set up the experimental trial, from which the model was developed. Comparative results obtained from the experiments and the literature indicated that the model predictions of the wetland clogging time are reasonably agreed each other. Additionally, this model seems reasonable to quantitatively simulate the contribution of the accumulated inert suspended solids, microbial biomass and plant roots clog material to the pore space reduction with wetland operation time. Accordingly, it is reasonable to believe that the model can be used for estimating clogging time of CWs in different operation conditions.

Key words: constructed wetland; clogging; microbial biomass; plant roots; organic suspended solids

1. Introduction

Substrate clogging of subsurface-flow constructed wetlands (SFCWs) is a tangible risk to affect the CWs function for wastewater treatment and has been well recognized as the most serious problem in practice. Clogging is mainly influenced by loading rates of BOD, COD, suspended solids (SS) (Winter and Goetz, 2003). In the operation, SS and particulate organic matters are removed rapidly by means of physical processes such as sedimentation, entrapment and adsorption. Subsequently, the trapped SS and particulate organic matters are hydrolyzed by anaerobic processes and then oxidized by means of aerobic respiration (Kadlec, 2000; García et al., 2004). Dissolved organic matters can be adsorbed to granular media, plant roots and detritus and oxidized by resident microbial populations (Burgoon et al., 1995). However, during the same time of pollutants' removal, these chemical, physical and biological processes contribute the pore blockage and cause detrimental changes in the hydrodynamic behavior of the system, such as short-circuiting, reduction of hydraulic retention time, surface ponding of wastewater, odors, presence of insects, and considerable reductions in treatment efficiency (Platzer and Mauch, 1997). Under worst-case scenarios, the life span of the wetland treatment system may be significantly reduced.

Although pore blockage is a common and pervasive problem in horizontal- and vertical-flow treatment wetlands, very few quantitative studies have been carried out to predict the rate at which clogging would. From the current knowledge, a simple theoretical clogging model was presented to calculate the clogging time based on a sand-media CWs (Platzer and Mauch, 1997). Langergraber et al., (2003) and Zhao et al., (2004) reported, respectively, a conceptual approach to estimate the clogging time by considering available void space of the substrate. Similarly, in our previous study, a conceptual model has been developed by using the parameter of influent SS concentration to estimate the clogging time (Hua et al., 2010). However, all these studies are only indicative because the models did not take into account of biofilm growth and the influence of vegetation and its contribution to the increase of recalcitrant detritus.

On the other hand, Rousseau (2005) developed a mechanistic model that estimates reductions in pore volume in CWs as a function of time. The model seems to be able to predict porosity change and might therefore be a useful tool to study clogging phenomena. But the model contains 26 state variables and thus 26 mass balances that make up the model contain in total 118 parameters, rendering the model extremely hard to calibrate and leaving not much hope to find a unique, identifiable parameter set. As such, a complex model is typically over parameterized, making it impractical to use.

It is desired that the clogging time estimation should consider the detached biofilm and plant residual in the CWs. Meanwhile, it is better to estimate the clogging time based on some simple parameters that are easily available. Ideally, parameters being used to quantify clogging should combine the characteristics of wastewater (e.g. SS and COD concentration etc.), wetland's media and plant. To date, no such approach for wetland clogging time estimation has been widely accepted.

In this study, a conceptual model to evaluate clogging time in SFCWs has been developed. The model incorporates physical processes (such as physical filtration), biological processes and plant-related processes to measure the pore space reduction. Data obtained from the experimental wetlands were used to calibrate the model. Thereafter, the clogging times under different operational circumstances are predicted by adopting the model.

2. Model development

2.1 Background

It is well recognized that the treatment processes in CWs include physicochemical, biological and plant-related processes. It is assumed, as considered in Wynn and Liehr (2001) model, that SS is mainly removed near the inlet (at less than 1/3 of the total length) under normal operating conditions. Only at higher flow rates, wash-out of solids proportional to the flow rate has been foreseen. One important consideration of this study is that SS removal is over 90%, this is based on the fact that effluent SS levels of the studied treatment wetland were very low for the coarse sand substrate. Although detachment of biofilm is a commonly acknowledged process, it is assumed that sloughed parts of the biofilm are retained within the pores and are still metabolizing, unless they are washed out by a peak flow.

In considering the biological process in CWs, aerobic and anoxic microbial carbon conversion processes are mainly based on the Activated Sludge Model (ASM1) (Henze et al., 2000). However, several improvements of the original model have been taken into account in order to be appropriate for CWs. For example, the values of the heterotrophic biomass yield coefficient (Y_H) and the heterotrophic biomass delay coefficient (K_d) are measured in this study to cope with the vegetation in the testing wetlands.

Following the example of considering the plant growth in Wynn and Liehr (2001), the plant growth and decay model is deliberately kept simple, despite the many influencing factors that have been reported in literature, such as nutrient availability, air temperature, irradiation, water level etc. Clogging is then evaluated in the proposed model in this study by means of pore volume reduction. In the model, pore volume reduction depends on: (1) the growth of bacteria, (2) solids retained and (3) plant residual. To this end, the masses of all the substance occupied the pore space were added up and converted to a volume by means of their estimated density and water content. If the amount of accumulated matter is so high that there is virtually no available void space inside the pores for further settlement of other matters, the clogging occurs. The CWs operating time to cause the point of clogging occurrence was defined as the clogging time, where the hydraulic conductivity of the CWs substrate is significantly reduced and the porosity of the substrate becomes zero.

2.2 Model set up

Mass balance has the following general structure:

$$\frac{d(mass)}{dt} = influx - efflux + conversion \quad (1)$$

Conversion includes biomass and plant roots accumulations with the operation time. Biomass conversion is based on ASM1 (Henze et al., 2000), which consists of three parts:

(I) The inert matter (M_{IS}) of the influent, which includes organic or inorganic substance: M_{IS} can fill the porosity of the substrate. It can be expressed as:

$$M_{IS} = Q_{in} \times C_{in} \times (1 - f_v + f_v \times f_{nv}) \quad (2)$$

Where, Q_{in} is the flow rate of the influent (m^3/d). C_{in} is the influent concentration of TSS (g/m^3). f_v is the proportion of organic matter of TSS (-), f_{nv} is the proportion of the inert (non-biodegradable organic) matter of TSS (-).

(II) The biomass (M_{BS}), which is conversed from the biodegradable organic matter: It can be expressed as:

$$M_{BS} = \frac{Q_{in} \times C_{BOD} \times Y_H}{1 + K_d \times \theta} \quad (3)$$

Where, C_{BOD} is the influent BOD (g/m^3), K_d is heterotrophic microbial endogenous decay coefficient (-), Y_H is the observed yield for heterotrophic biomass (-), θ is biosolids mean residence time (d).

(III) The biomass residues (M_{PS}) after microorganism’s endogenous respiration: M_{PS} can occupy the pore space of the wetland substrate. It can be described as:

$$M_{PS} = f_p \times K_d \times \theta \times M_{BS} \tag{4}$$

Where f_p is the fraction of microbial biomass converted to inert matter.

The total solids (M_{TS}) that are possible to accumulate in the pores can be expressed as:

$$M_{TS} = M_{IS} + M_{BS} + M_{PS} \tag{5}$$

Some fraction (M_{out}) of M_{TS} would be washed off to remain in the effluent, so the actual accumulated SS (M_{SS}) in the pores can be described as:

$$M_{SS} = M_{TS} - M_{out} \tag{6}$$

According to Equation (6), the SS accumulated in the pores of the first operation day (t_1) of the wetland, is termed as $M_{\mathrm{SS},1}$. The rest may be deduced by analogy. For example, $M_{\mathrm{SS},2}$ and $M_{\mathrm{SS,n}}$ are respectively the accumulated SS on second and n^{th} days' operation. Here $M_{\mathrm{SS},1}$ can be described as:

$$M_{SS1} = M_{TS1} - M_{out1} \tag{7}$$

The SS accumulated in the pores of the second operation day ($M_{\mathrm{SS},2}$) involves: (1) the net accumulated SS of the second operation day described as $M_{TS2} - M_{out2}$; (2) the biomass which is conversed from the biodegradable matter accumulated on the first operation day described as $M_{SS,1} \times \delta \times \frac{Y_H}{1 + K_d \times \theta}$ (Where, δ is the biological fraction of the accumulated solids on the previous day); and (3) the biomass residues after microorganism's endogenous respiration described as $M_{SS,1} \times \delta \times \frac{Y_H}{1 + K_d \times \theta} \times f_p \times K_d \times \theta$. Therefore, the $M_{\mathrm{SS},2}$ based on $M_{\mathrm{SS},1}$ can be described as:

$$M_{SS2} = M_{TS2} - M_{out2} + M_{SS1} \times \delta \times \frac{Y_H}{1 + K_d \times \theta} \times (1 + f_p \times K_d \times \theta) \tag{8}$$

After n days' operation, the SS accumulated in the pores ($M_{\mathrm{SS,n}}$) can be similarly calculated in the subsequent operating days according to Equation (9).

$$M_{SS,n} = M_{TS,n} - M_{out,n} + M_{SS,n-1} + (M_{SS,n-1} - M_{SS,n-2}) \times \delta \times \frac{Y_H}{1+K_d \times \theta} \times (1+f_p \times K_d \times \theta) \tag{9}$$

Regarding the consideration of wetland plants on the effect of clogging, it is recognized that the living plant biomass (M_{plantL}) increases during the growth season when adequate amounts of nitrate and/or ammonium are available in the wastewater. At the onset of senescence, living biomass is converted into dead biomass following a first-order rate (Wynn and Liehr; 2001). Thus, the plant growth can be expressed as:

$$\frac{dM_{plantL}}{dt} = M_{plantL} \times (f_{NH} + f_{NO} - b_p) \times L \times W \tag{10}$$

Where, b_p is the decay coefficient for living plant material, L and W is the length and width of the wetland, respectively. f_{NH} and f_{NO} are the plant growth coefficient on ammonium and nitrate, respectively, which can be expressed as:

$$f_{NH} = k_{pl} \times \left(\frac{C_{NH}}{K_{PNH} + C_{NH}} \right) \tag{11}$$

$$f_{NO} = k_{pl} \times \left(\frac{C_{NO}}{K_{PNO} + C_{NO}} \right) \times \left(\frac{K_{PNH}}{K_{PNH} + C_{NH}} \right) \tag{12}$$

Where, k_{pl} is the plant relative growth rate, K_{PNO} is the nitrate half-saturation coefficient for plant growth, K_{PNH} is the ammonium half-saturation coefficient for plant growth, C_{NH} and C_{NO} are ammonia and nitrate nitrogen concentration of the influent, respectively.

During winter, when there is no living plant biomass, dead plant biomass (M_{plantD}) is derived from living plant biomass after the growth season ended, and disappears through physical degradation processes, such as wind action, invertebrate consumption etc.

$$\frac{dM_{plantD}}{dt} = (M_{plantL} \times b_p + M_{plantD} \times k_{degradation}) \times L \times W \tag{13}$$

Where, $k_{degradation}$ is the first order plant physical degradation constant (day^{-1}).

After n days' operation, the plant biomass ($M_{plant,n}$) can be similarly calculated based on the previous day's plant biomass ($M_{plant,n\text{-}1}$) in the subsequent operating days according to Equation (14). Here, it should be pointed out that the plant growth is determined by season. In winter, it is expressed as $\frac{dM_{plantD}}{dt}$, otherwise it is described as $\frac{dM_{plantL}}{dt}$.

$$M_{plamt,n} = M_{plant,n-1} + \frac{dM_{plantL,n-1}}{dt} (or \frac{dM_{plantD,n-1}}{dt}) \tag{14}$$

However, in constructed wetlands, only the belowground part of the plant ($M_{plant\_belowground}$) can occupy the porosity and then have effect on clogging. $M_{plant\_belowground}$ can be expressed as Equation (15) (Mander et al., 2008; Collier et al., 2010).

$$M_{plant\_belowground} = M_{plant,n} \times \frac{\eta}{\alpha} \tag{15}$$

Where η is root shoot ratio, α is the turnover rate of the plant root converted into inert solids.

The entire solids accumulated in the pores are then calculated as:

$$M_{solids} = M_{SS} + M_{plant\_belowground} \tag{16}$$

Clogging is then evaluated in the model by means of pore volume reduction. To this end, the masses of all suspended solids were added up and converted to a volume by means of their estimated density and water content. If the amount of accumulated SS is so high that there is virtually no available void space inside the substrate for further settlement of SS, at that moment the clogging occurs. For convenience, the operation time to reach the point of clogging occurred is defined as the "clogging time" (t_c).

Program the modeling based on the software named Visual Basic 6.0 and operate the model until the conditions of:

$$\frac{M_{SSn}}{\rho_{ss} \times (1-\omega)} + \frac{M_{plant\_belowground}}{\rho_{plant}} \geq \varepsilon \times h_c \qquad (17)$$

Where, $\varepsilon \times h_c$ is the total pore space per unit area in the wetland substrate, ε is substrate porosity, h_c is the depth of filtration/clogging layer (cm), ρ and ω are the density (mg/cm^3) and moisture content (%) of SS, respectively, ρ_{plant} is the density (mg/cm^3) of the plant roots. The modeling process, by duplicated calculation of the entire accumulated SS (M_{solids}), will allow obtaining the clogging time, total reduced pore volume, inert matter volume, microbial biomass volume, plant roots volume, respectively, as the output of the modelling.

3. Materials and methods

3.1 Experimental wetlands setup and operation

Six identical laboratory scale wetland beds (made of Perspex columns of 100cm in height and 15cm in diameter) were used in the study. The beds were filled with the same coarse sand of d_{10} (0.23 mm) to the same depth of 75 cm, where d_{10} referred to the equivalent diameter where 10% of the particles (in mass) had smaller diameter. Among the six beds, Bed1, Bed3 and Bed5 were planted with *Typha angustifolia*, which has extensive root system, while Bed2, Bed4 and Bed6 remained unplanted for the purpose of investigating the agency of plant on clogging process. Along the side of each bed, there were seven outlet holes set up vertically for sampling purpose. The layout of the wetland is shown in Figure 1.

[Insert Fig. 1 here]

Wastewater was prepared by adding the starch as the source of suspended particulate solids and adding other organic matters to tap water. In addition, $(NH_4)_2SO_4$, $CO(NH_2)_2$ and K_2HPO_4 were added as major nutrients to the artificial wastewater. The six CWs beds were operated continuously in parallel with vertical down-flow pattern under hydraulic loading of $0.5m^3/m^2$ d from November 2008 to September 2009. The operational profile of the six beds is shown in Table 1.

[Insert Table 1 here]

3.2 Measurements

The pore volumes of the wetland beds were measured by emptying the water pre-saturated bed. The measured drainage volumes of each layer (via outlet) along the height of the beds were identified as the pore volumes. This was done every 15 days till serious ponding occurred in the surface of beds.

The accuracy of TSS, COD, TN and TP measurements were analyzed using standard methods as described in Water and Wastewater Monitoring and Analysis Methods (2002). The concentrations of TN, TP, COD and TSS of the influent were measured every day while the concentrations of COD and TSS of effluent were measured every 7 days.

The oxygen uptake rate (OUR) measurement (Stasinakisa et al., 2002) was adopted to determine the Y_H and K_d based on the parameters measurement of ASM1. For the effect of the plants and microbes growth on the clogging process, the Y_H and K_d were measured on the 15th, 75th and 120th operation day to represent the early, stable and later clogging stage. The density of plant root was determined according to the root’s quantity and its volume. The root volume was obtained using drainage method because the root displaced a bulk of water, which is equal to the volume of the root.

4. Results and discussion

4.1 Parameters estimation

Table 2 summarizes the applied symbols and parameters, their description, unit and default values, which are mainly from the literature. The parameters include wetland physical parameters, operational parameters, microbial and plant parameters.

[Insert Table 2 here]

Figure 2 shows that the variation of the measured Y_H values in different operation stage in this study. As a whole, the Y_H increases initially and then declines slightly with operation time. The reason of it might be that the microbe and plants grown in the first two months and then decayed when the clogging occurred.

It is noted that the Y_H values of the planted beds are higher than that of unplanted beds especially in the stable operation stage (75 days). There is a gap between them for the lowest Y_H value of 0.54 g/g COD and the highest of 0.64 g/g COD. It might be due to plant roots, which provide a large number of surface areas for microorganisms settling, leading to the improvement of the degradation rate of the organic matters and promoting the biofilm growth.

[Insert Fig. 2 here]

Figure 3 illustrates the K_d values. It is clearly seen that the K_d values decrease in different operation stage. The average K_d values of 0.11d^{-1}, 0.07d^{-1} and 0.04 d^{-1} on the 15th, 75th and 120th operation day are obtained, respectively. The reason of K_d value difference might be the reduction of the dissolved oxygen (DO) due to the clogging occurrence, which may lead to the aerobic microbes slowly degraded.

There is no obvious gap among bed1, bed3 and bed5, for the lowest K_d value of 0.12 d^{-1} and the highest of 0.13 d^{-1}. This indicates that the effect of organic load on K_d value is small because of the sufficient carbon source for the respiration of aerobic microbes. But it is interesting to note that the K_d values of the planted beds are higher than that of unplanted beds especially under the lower organic load.

[Insert Fig. 3 here]

4.2 Clogging time evaluation

The clogging times of the model predictions are obtained by compiling the Visual

Basic 6.0. The experimental clogging times of bed1 to bed6 in turn are 270, 245, 208, 189, 145 and 115 days, respectively, when the drainable pore volume of the six beds measured are all near zero and surface ponding can be obviously observed. The comparison between the predicted and experimental results is shown in Figure 4. It shows that there is a good agreement between the model predictions and experimental results. This agreement reflects the validity of the model over a wide size range of the sand employed in the CWs and varied concentrations of the organic matter during the clogging generation. However, there are still about 6-30 days remaining between the calculated theoretical clogging time and the time when clogging actually happened. In addition, it is noted that the clogging time of the planted are longer than those of unplanted beds, although there is no obvious difference between them. It might be that the effect of the plants on clogging is minor with the short operation time or the plant itself plays a weak role in clogging process.

[Insert Fig. 4 here]

The important aspect of the model developed in this study lies in the ability to make a quantitative assessment of the clogging behavior and operation characteristic of the wetland system. By using the model, clogging time can be computed at various operation conditions with varied hydraulic loading rate. For example, according to this model, at a COD concentration of 400 mg/L, hydraulic loading of 0.5 m^3/m^2 d, a treatment wetland with a coarse sand medium is expected to operate for 155, 213, and 292 days before clogging for f_{nv} value of 0.8, 0.5 and 0.2, respectively. Reducing the COD concentration to 100 mg/L could increase the expected period of operation to 292, 369, and 675 days, respectively. In the case of hydraulic loading of 0.1 m^3/m^2 d, and influent COD concentration of 50 mg/L, the treatment wetland operation period could be extended to 1511, 2312 (approximately 8 years), and 5528 days (approximately 18 years) for f_{nv} value of 0.8, 0.5 and 0.2, respectively.

The clogging time predicted by the model in this study seems to agree with that reported from the literature although it is reported not from a theoretical basis. For example, Behrends et al., (2006) reported about 30-68% of the pore void space was filled with recalcitrant organic sediments after 28 months of operation, with experimental vertical-flow systems loaded at 18.3 g COD/m^2 d. Platzer and Mauch (1997) and USEPA (2000) recommend not exceeding an organic load of 20 g BOD/m^2 d in the case of VFCWs to prevent the granular medium from becoming clogged very rapidly.

4.3 Pore space volume reduction evaluation

Figure 5 shows experimental and predicted pore space volume reduction. It can be seen that the depositions of inert matter, microbial biomass and plant roots have a significantly negative impact on porosity of the system over time. In bed1, about 40% of the pore void spaces of the substrate were filled within 220 days' operation while around 60% of them were filled in further operation of 70 days. The similar trends occur in other beds but the difference can be seen that the pore spaces decrease more quickly with the higher COD load.

Small deviations between measured and simulated reductions of the total pore volumes could be observed. The measured reductions of the total pore volumes are slightly bigger than those of predicted. This might be due to the neglect of the plant transpiration in the model. It should be noted that the microbial biomass and plant roots occupy small proportion of the pore spaces (6-8%) compared with the inert matters.

[Insert Fig. 5 here]

The model proposed in this study quantitatively analyzes the contributions of three parts, i.e. inert matter, microbial biomass and plant roots, to the pore space reduction. It can be summarized that the predicted data indicate that, for the investigated systems, biomass growth plays a minor role compared to the inert solid matter for the tested wetlands clogging. Although the influence of the organic load is an important factor leading to massive growth of bacteria in the form of biofilm, especially from long term point of view (Kim et al., 2010), the obvious accumulations of SS in the top of the wetland substrate seems to agree well with the view of Langergraber et al., (2003) and Zhao et al., (2009). It is such the SS that plays leading role in wetland clogging.

It is noted that the wetland plant does not show obvious influence on the pore space reduction in this study. In fact, plant plays an important and complicated role in microorganisms settling, which could promote the growth of biofilm and accordingly have some influence upon clogging process (Molle et al., 2006). From the literature it seems that plant can benefit the treatment wetland by making the substrate more porous. For example, Tanner and Sukias (1998) found that the planted wetlands retained higher apparent gravel porosity in comparison with the unplanted wetlands, despite great accumulations of organic matter. Fu et al., (2004) also indicated that the infiltration rate of the upper layer was slightly higher than that of the middle layer due to the existence of plant roots within surface layer.

It should be pointed out that the clogging behaviour in practice of treatment wetland is a complicated process with physical, biological and plant-related process functioning together. Clogging should be contributed by the integration of the inert matter, biomass and plant roots accumulation. Any detailed consideration of the individual process will help to understand the clogging behavior. Obviously, further study towards a perfect model for CWs clogging behavior is still desirable before the model is used for design purpose.

6. Conclusions

The model developed in this study to predict the clogging time in constructed treatment wetland represented valuable approach in considering the effects of physical, biological and plant-related processes on wetland substrate clogging. The simulated results of clogging time showed good match with the experimental data. Additionally, the contribution of the accumulated inert suspended solids, microbial biomass and plant roots clog material to the pore space reduction with operation time was quantitatively estimated in the model. It shows that the inert suspended solids had a significant influence on pore space reduction compared with microbial biomass and plant roots.

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Caption to Tables

Table 1 The operational profile of the six beds

	Bed 1	Bed 2	Bed 3	Bed 4	Bed 5	Bed 6
influent	planted	unplanted	planted	unplanted	planted	unplanted
COD (mg/L)	100.25 ±11.28		203.34 ±17.56		398.78 ±14.28	
TSS (mg/L)	80.36 ±15.32		152.56 ±4.29		275.18 ±14.36	
TN (mg/L)	10.24 ±3.32		10.67 ±2.28		10.09 ±4.08	
TP (mg/L)	1.98 ±0.58		2.45 ±0.47		2.69 ±0.98	

Table 2 Value and source of parameters used in this study

symbol	description	unit	values	reference
Wetland physical parameters:				
D	Diameter of the wetland	m	0.15	This study
h_c	Depth of clogging layer	m	0.03	Platzer and Mauch, 1997; Nguyen, 2001; Blazejewski et.al 1994
ε	Porosity of the substrate	/	0.26	This study
d_{10}	d_{10} value of the substrate	m	0.12	This study
Operation parameters:				
Q_{in}	Daily flow rate	m^3/d	0.009	This study
C_{in}	TSS concentrations of the influent	g/m^3	80~275	This study
C_{NH}	Ammonia nitrogen concentration	g/m^3	5	This study
C_{NO}	Nitrate nitrogen concentration	g/m^3	0	This study
ρ_{SS}	Density of SS	g/cm^3	1.05	Platzer and Mauch, 1997; Zhao et al., 2004
ω	Moisture content of SS	/	0.9	Platzer and Mauch, 1997; Zhao et al., 2004
Microbial parameters:				
f_v	The proportion of organic matter in TSS	/	1	This study
f_{nv}	The proportion of non-biodegradable organic matter in TSS	/	0.6~0.8	This study
f_p	Fraction of microbial biomass converted to inert matter	/	0.1	Henze et al., 2000
Y_H	Observed yield for heterotrophic biomass	g/gCOD	0.57~0.64	This study

K_d	The heterotrophic biomass decay coefficient	d^{-1}	0.04~0.12	This study
θ	The biosolids mean residence time	d	3	Henze et al., 2008
δ	The biodegradable fraction of the accumulated solids on the previous operation day	/	0.1	Caselles-Osorio et al., 2007

Plant parameters:

k_{pl}	Plant relative growth rate, function of season	day^{-1}	0.033	Romero et al., 1999
K_{PNO}	Nitrate half-saturation coefficient for plant growth	$gNO_3\text{-}N\ m^{-3}$	0.1	Kadlec and Wallace, 2009
K_{PNH}	Ammonium half-saturation coefficient for plant growth	$gNH_4\text{-}N\ m^{-3}$	0.3	Romero et al., 1999
b_P	Decay coefficient for living plant material, function of season	day^{-1}	0.05	Rousseau, 2005
$k_{degradation}$	First order plant physical degradation constant	day^{-1}	0.01	Rousseau, 2005
η	Root shoot ratio	/	0.35	Afrousheh et al., 2010
α	Percent conversion from COD to mass of the plant biomass	/	1.17	Rousseau, 2005
ρ_{plant}	The density of the plant roots	mg/cm^3	1.457	This study

Caption to Figures

Fig.1 Constructed wetland model bed

Fig.2 The variation of Y_H in different operation stage

Fig.3 The variation of K_d in different operation stage

Fig.4 Experimental and predicted clogging time

Fig.5 Experimental and predicted pore space volume reduction

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Fig.1 Constructed wetland model bed

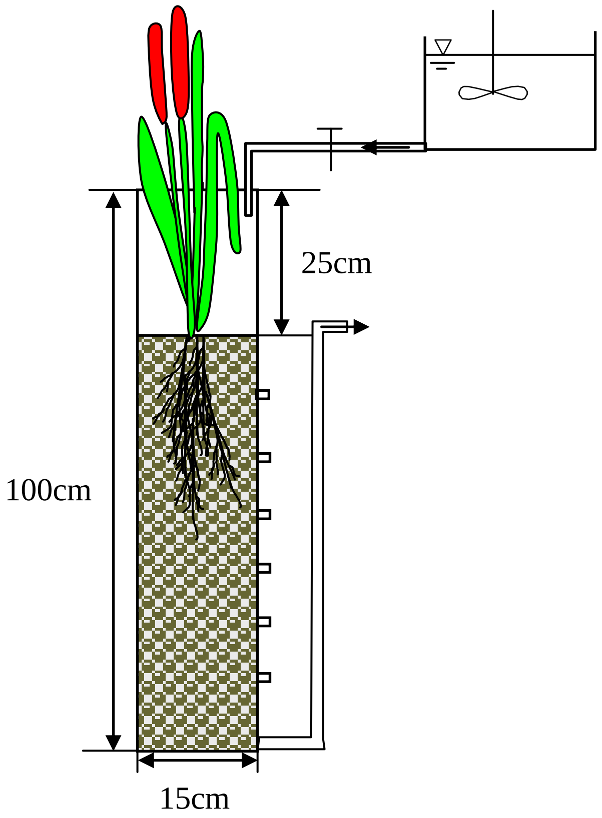

Fig.2 The variation of Y_H in different operation stage

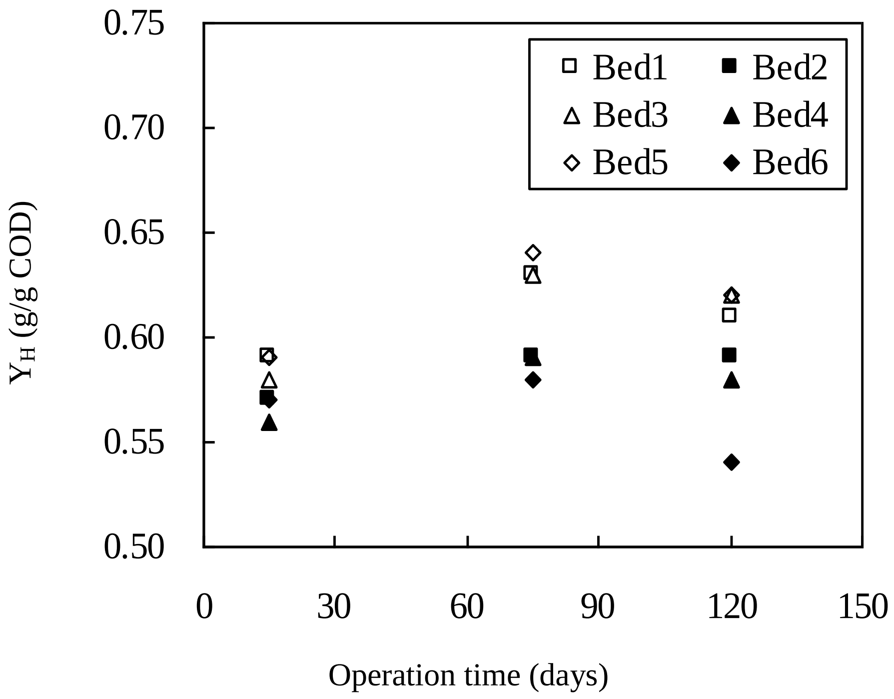

Fig.3 The variation of K_d in different operation stage

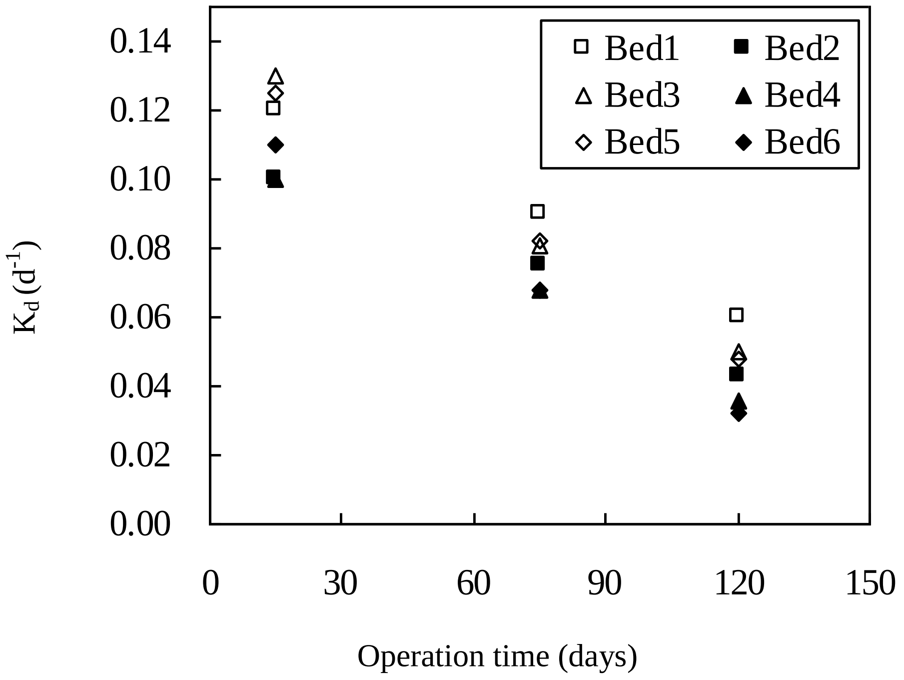

Fig.4 Experimental and predicted clogging time

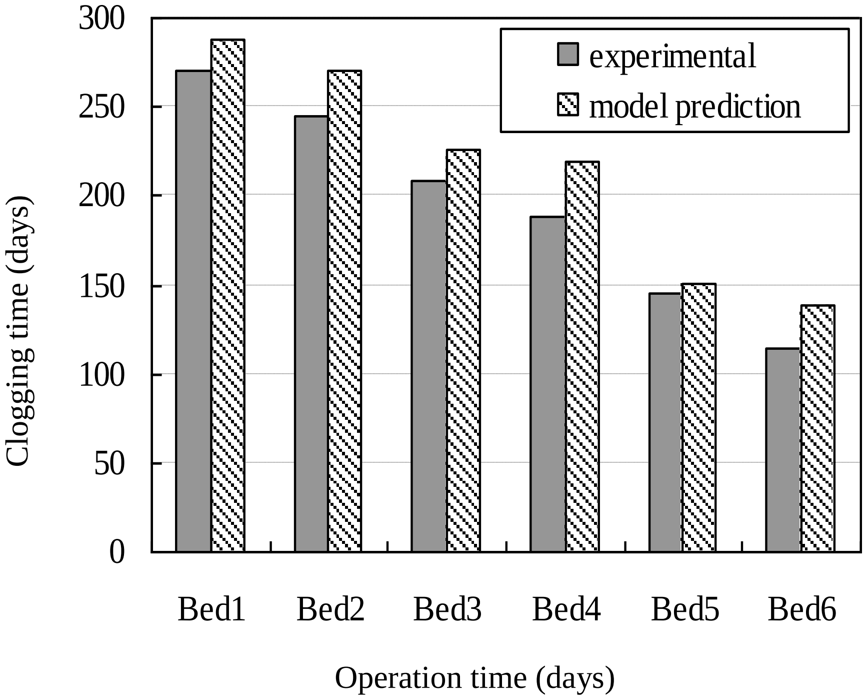

Fig.5 Experimental and predicted pore space volume reduction