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1 An integrated model of substrate clogging in vertical
2 flow constructed wetlands

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4

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17

18 **Abstract**

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

31

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

34

35 1. Introduction

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

53 Although pore blockage is a common and pervasive problem in horizontal- and
54 vertical-flow treatment wetlands, very few quantitative studies have been carried out
55 to predict the rate at which clogging would. From the current knowledge, a simple
56 theoretical clogging model was presented to calculate the clogging time based on a
57 sand-media CWs (Platzer and Mauch, 1997). Langergraber et al., (2003) and Zhao et

58 [al., \(2004\)](#) reported, respectively, a conceptual approach to estimate the clogging time
59 by considering available void space of the substrate. Similarly, in our previous study,
60 a conceptual model has been developed by using the parameter of influent SS
61 concentration to estimate the clogging time ([Hua et al., 2010](#)). However, all these
62 studies are only indicative because the models did not take into account of biofilm
63 growth and the influence of vegetation and its contribution to the increase of
64 recalcitrant detritus.

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

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

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

85 2. Model development

86 2.1 Background

87 It is well recognized that the treatment processes in CWs include physicochemical,
88 biological and plant-related processes. It is assumed, as considered in [Wynn and Liehr](#)
89 [\(2001\)](#) model, that SS is mainly removed near the inlet (at less than 1/3 of the total
90 length) under normal operating conditions. Only at higher flow rates, wash-out of
91 solids proportional to the flow rate has been foreseen. One important consideration of
92 this study is that SS removal is over 90%, this is based on the fact that effluent SS
93 levels of the studied treatment wetland were very low for the coarse sand substrate.
94 Although detachment of biofilm is a commonly acknowledged process, it is assumed
95 that sloughed parts of the biofilm are retained within the pores and are still
96 metabolizing, unless they are washed out by a peak flow.

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

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

115 was defined as the clogging time, where the hydraulic conductivity of the CWs
116 substrate is significantly reduced and the porosity of the substrate becomes zero.

117

118 2.2 Model set up

119 Mass balance has the following general structure:

$$120 \quad \frac{d(\text{mass})}{dt} = \text{influx} - \text{efflux} + \text{conversion} \quad (1)$$

121 Conversion includes biomass and plant roots accumulations with the operation time.

122 Biomass conversion is based on ASM1 (Henze et al., 2000), which consists of three
123 parts:

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

$$126 \quad M_{IS} = Q_{in} \times C_{in} \times (1 - f_v + f_v \times f_{nv}) \quad (2)$$

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

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

$$132 \quad M_{BS} = \frac{Q_{in} \times C_{BOD} \times Y_H}{1 + K_d \times \theta} \quad (3)$$

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

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

138
$$M_{PS} = f_p \times K_d \times \theta \times M_{BS} \quad (4)$$

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

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

141
$$M_{TS} = M_{IS} + M_{BS} + M_{PS} \quad (5)$$

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

144
$$M_{SS} = M_{TS} - M_{out} \quad (6)$$

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

149
$$M_{SS1} = M_{TS1} - M_{out1} \quad (7)$$

150 The SS accumulated in the pores of the second operation day ($M_{SS,2}$) involves: (1) the
151 net accumulated SS of the second operation day described as $M_{TS2} - M_{out2}$; (2) the
152 biomass which is converted from the biodegradable matter accumulated on the first

153 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

154 the accumulated solids on the previous day); and (3) the biomass residues after
155 microorganism's endogenous respiration described as

156 $M_{SS,1} \times \delta \times \frac{Y_H}{1 + K_d \times \theta} \times f_p \times K_d \times \theta$. Therefore, the $M_{SS,2}$ based on $M_{SS,1}$ can be described

157 as:

158
$$M_{SS2} = M_{TS2} - M_{out2} + M_{SS1} \times \delta \times \frac{Y_H}{1 + K_d \times \theta} \times (1 + f_p \times K_d \times \theta) \quad (8)$$

159 After n days' operation, the SS accumulated in the pores ($M_{SS,n}$) can be similarly

160 calculated in the subsequent operating days according to Equation (9).

$$161 \quad M_{SS,n} = M_{TS,n} - M_{out,n} + M_{SS,n-1} + (M_{SS,n-1} - M_{SS,n-2}) \times \delta \times \frac{Y_H}{1 + K_d \times \theta} \times (1 + f_p \times K_d \times \theta) \quad (9)$$

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

$$167 \quad \frac{dM_{plantL}}{dt} = M_{plantL} \times (f_{NH} + f_{NO} - b_p) \times L \times W \quad (10)$$

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

$$171 \quad f_{NH} = k_{pl} \times \left(\frac{C_{NH}}{K_{PNH} + C_{NH}} \right) \quad (11)$$

$$172 \quad f_{NO} = k_{pl} \times \left(\frac{C_{NO}}{K_{PNO} + C_{NO}} \right) \times \left(\frac{K_{PNH}}{K_{PNH} + C_{NH}} \right) \quad (12)$$

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

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

$$181 \quad \frac{dM_{plantD}}{dt} = (M_{plantL} \times b_p + M_{plantD} \times k_{degradation}) \times L \times W \quad (13)$$

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

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

187 as $\frac{dM_{plantL}}{dt}$.

$$188 \quad M_{plant,n} = M_{plant,n-1} + \frac{dM_{plantL,n-1}}{dt} \text{ (or } \frac{dM_{plantD,n-1}}{dt} \text{)} \quad (14)$$

189 However, in constructed wetlands, only the belowground part of the plant
 190 ($M_{plant_belowground}$) can occupy the porosity and then have effect on clogging.
 191 $M_{plant_belowground}$ can be expressed as Equation (15) (Mander et al., 2008; Collier et al.,
 192 2010).

$$193 \quad M_{plant_belowground} = M_{plant,n} \times \frac{\eta}{\alpha} \quad (15)$$

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

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

$$197 \quad M_{solids} = M_{SS} + M_{plant_belowground} \quad (16)$$

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

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

206
$$\frac{M_{SSn}}{\rho_{ss} \times (1 - \omega)} + \frac{M_{plant_belowground}}{\rho_{plant}} \geq \varepsilon \times h_c \quad (17)$$

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

214

215 3. Materials and methods

216 3.1 Experimental wetlands setup and operation

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

226 **[Insert Fig. 1 here]**

227 Wastewater was prepared by adding the starch as the source of suspended particulate
 228 solids and adding other organic matters to tap water. In addition, $(\text{NH}_4)_2\text{SO}_4$,
 229 $\text{CO}(\text{NH}_2)_2$ and K_2HPO_4 were added as major nutrients to the artificial wastewater.
 230 The six CWs beds were operated continuously in parallel with vertical down-flow

231 pattern under hydraulic loading of $0.5\text{m}^3/\text{m}^2 \text{ d}$ from November 2008 to September
232 2009. The operational profile of the six beds is shown in [Table 1](#).

233 **[Insert Table 1 here]**

234 3.2 Measurements

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

239 The accuracy of TSS, COD, TN and TP measurements were analyzed using standard
240 methods as described in *Water and Wastewater Monitoring and Analysis Methods*
241 (2002). The concentrations of TN, TP, COD and TSS of the influent were measured
242 every day while the concentrations of COD and TSS of effluent were measured every
243 7 days.

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

251

252 4. Results and discussion

253 4.1 Parameters estimation

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

257

[Insert Table 2 here]

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

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

268

[Insert Fig. 2 here]

269 Figure 3 illustrates the K_d values. It is clearly seen that the K_d values decrease in
270 different operation stage. The average K_d values of 0.11d^{-1} , 0.07d^{-1} and 0.04d^{-1} on the
271 15th, 75th and 120th operation day are obtained, respectively. The reason of K_d value
272 difference might be the reduction of the dissolved oxygen (DO) due to the clogging
273 occurrence, which may lead to the aerobic microbes slowly degraded.

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

279

[Insert Fig. 3 here]

280 4.2 Clogging time evaluation

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

282 Basic 6.0. The experimental clogging times of bed1 to bed6 in turn are 270, 245, 208,
283 189, 145 and 115 days, respectively, when the drainable pore volume of the six beds
284 measured are all near zero and surface ponding can be obviously observed. The
285 comparison between the predicted and experimental results is shown in Figure 4. It
286 shows that there is a good agreement between the model predictions and experimental
287 results. This agreement reflects the validity of the model over a wide size range of the
288 sand employed in the CWs and varied concentrations of the organic matter during the
289 clogging generation. However, there are still about 6-30 days remaining between the
290 calculated theoretical clogging time and the time when clogging actually happened. In
291 addition, it is noted that the clogging time of the planted are longer than those of
292 unplanted beds, although there is no obvious difference between them. It might be that
293 the effect of the plants on clogging is minor with the short operation time or the plant
294 itself plays a weak role in clogging process.

295 **[Insert Fig. 4 here]**

296 The important aspect of the model developed in this study lies in the ability to make a
297 quantitative assessment of the clogging behavior and operation characteristic of the
298 wetland system. By using the model, clogging time can be computed at various
299 operation conditions with varied hydraulic loading rate. For example, according to
300 this model, at a COD concentration of 400 mg/L, hydraulic loading of 0.5 m³/m² d, a
301 treatment wetland with a coarse sand medium is expected to operate for 155, 213, and
302 292 days before clogging for f_{nv} value of 0.8, 0.5 and 0.2, respectively. Reducing the
303 COD concentration to 100 mg/L could increase the expected period of operation to
304 292, 369, and 675 days, respectively. In the case of hydraulic loading of 0.1 m³/m² d,
305 and influent COD concentration of 50 mg/L, the treatment wetland operation period
306 could be extended to 1511, 2312 (approximately 8 years), and 5528 days
307 (approximately 18 years) for f_{nv} value of 0.8, 0.5 and 0.2, respectively.

308 The clogging time predicted by the model in this study seems to agree with that
309 reported from the literature although it is reported not from a theoretical basis. For

310 example, Behrends et al., (2006) reported about 30-68% of the pore void space was
311 filled with recalcitrant organic sediments after 28 months of operation, with
312 experimental vertical-flow systems loaded at 18.3 g COD/m² d. Platzer and Mauch
313 (1997) and USEPA (2000) recommend not exceeding an organic load of 20 g
314 BOD/m² d in the case of VFCWs to prevent the granular medium from becoming
315 clogged very rapidly.

316

317 4.3 Pore space volume reduction evaluation

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

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

331 **[Insert Fig. 5 here]**

332 The model proposed in this study quantitatively analyzes the contributions of three
333 parts, i.e. inert matter, microbial biomass and plant roots, to the pore space reduction.
334 It can be summarized that the predicted data indicate that, for the investigated systems,
335 biomass growth plays a minor role compared to the inert solid matter for the tested
336 wetlands clogging. Although the influence of the organic load is an important factor

337 leading to massive growth of bacteria in the form of biofilm, especially from long
338 term point of view (Kim et al., 2010), the obvious accumulations of SS in the top of
339 the wetland substrate seems to agree well with the view of Langergraber et al., (2003)
340 and Zhao et al., (2009). It is such the SS that plays leading role in wetland clogging.

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

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

358

359 6. Conclusions

360 The model developed in this study to predict the clogging time in constructed
361 treatment wetland represented valuable approach in considering the effects of physical,
362 biological and plant-related processes on wetland substrate clogging. The simulated
363 results of clogging time showed good match with the experimental data. Additionally,
364 the contribution of the accumulated inert suspended solids, microbial biomass and

365 plant roots clog material to the pore space reduction with operation time was
366 quantitatively estimated in the model. It shows that the inert suspended solids had a
367 significant influence on pore space reduction compared with microbial biomass and
368 plant roots.

369

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373

374 References

375 Afrousheh, M., Ardalan, M., Hokmabadi, H., Afrousheh, M., 2010. Nutrient
376 deficiency disorders in *Pistacia vera* seedling rootstock in relation to
377 eco-physiological, biochemical characteristics and uptake pattern of nutrients.
378 *Sci. Hortic.* 124, 141-148.

379 Behrends, L.L., Bailey, E., Jansen, P., Houke, L., Simth, S., 2007. Integrated
380 constructed wetland systems: design, operation, and performance of low-cost
381 decentralized wastewater treatment systems. *Water Sci. Technol.* 55(7), 155-161

382 Blazejewski, R., Rembeza. L., G órski ,P., 1994. New concepts in hydraulic design of
383 horizontal constructed wetlands. Jiang C. (ed.) *Proceedings of the 4th*
384 *International Conference on Wetland Systems for Water Pollution Control*, 6–10
385 November 1994; IWA: Guangzhou, P.R. China, pp: 752–759.

386 Burgoon, P. S., Reddy, K.R., DeBusk, T. A., 1995. Performance of subsurface flow
387 wetlands with batchload and continuous-flow conditions. *Water Environ Res.*
388 67(5) , 855-862.

389 Caselles-Osorio, A., Puigagut, J., Segú E., Vaello, N., Granés, F., García, D., García,
390 J., 2007, Solids accumulation in six full-scale subsurface flow constructed
391 wetlands. *Water Res.* 41, 1388-1398.

392 Collier, M.H., Keane, B., Rogstad, S.H., 2010. Productivity differences between
393 dandelion (*Taraxacum officinale*; Asteraceae) clones from pollution impacted
394 versus non-impacted soils. *Plant soil.*329, 173-183

395 Fu, G.P., Wu, Z.B., Zhang, S., Cheng, S.P., He, F., 2004. Studies on clogging of the
396 constructed wetland. *Chin Environ Sci.* 25(3), 144–149.

397 García, J., Chiva,J., Aguirre,P., Álvarez,E., Pausierra,J., Mujeriego, R., 2004.
398 Hydraulic behaviour of horizontal subsurface flow constructed wetlands with
399 different aspect ratio and granular medium size. *Ecol. Eng.*23, 177-187.

400 Henze, M., Gujer,W., Mino, T., Van Loosdrecht, M., 2000. Activated sludge models
401 ASM1, ASM2, ASM2d and ASM3. Scientific and Technical Report No. 9. IWA
402 Publishing, London, UK.

403 Henze, M., Van Loosdrecht,M.C.M., Ekama,G.A., Brdjanovic,D., 2008. Biological
404 wastewater treatment principles, modelling and design. IWA Publishing, London,
405 UK. pp: 53-86.

406 Hua, G.F., Zhu, W., Zhang. Y.H., 2010. A conceptual approach based on suspended
407 solids to estimate clogging time in constructed wetlands. *J. Environ. Sci. Health.*
408 Part A ., Submitted.

409 Kadlec, R.H., 2000. The inadequacy of first-order treatment wetland models. *Ecol.*
410 *Eng.* 15, 105-119.

411 Kadlec, R.H., Wallace, S., 2009. *Treatment wetlands* second edition. CRC Press, Boca
412 Raton FL, pp: 59-100

413 Kim, J.W., Choi, H., Pachepsky, Y.A., 2010. Biofilm morphology as related to the
414 porous media clogging. *Water Res.* 44,1193-1201

415 Langergraber, G., Haberl, R., Laber, J., Pressl, A., 2003. Evaluation of substrate
416 clogging processes in vertical flow constructed wetlands. *Water Sci. Technol.*
417 48(5), 25-34.

418 Mander, Ü., Löhmus, K., Teiter, S., Mauring, T., Nurk, K., Augustin, J., 2008.
419 Gaseous fluxes in the nitrogen and carbon budgets of subsurface flow
420 constructed wetlands. *Sci Total Environ.* 404, 343-353.

421 Molle, P., Li énard, A., Grasmick, A., Iwema, A., 2006. Effect of reeds and feeding
422 operations on hydraulic behavior of vertical flow constructed wetlands under
423 hydraulic overloads. *Water Res.* 40, 606–612.

424 Nguyen, L., 2001. Accumulation of organic matter fractions in a gravel-bed
425 constructed wetland. *Water Sci. Technol.* 44 (11-12), 281-289.

426 Platzer, C., Mauch, K., 1997. Soil clogging in vertical flow reed beds- mechanisms,
427 parameters, consequences and.....solutions? *Water Sci. Technol.* 35 (5),
428 175-181.

429 Romero, J.A., Brix, H., Comn, F.A., 1999. Interactive effects of N and P on growth,
430 nutrient allocation and NH₄ uptake kinetics by *Phragmites australis*. *Aquat Bot.*
431 64, 369-380.

432 Rousseau, D.P.L., 2005. Performance of constructed treatment wetlands: Model-based
433 evaluation and impact of operation and maintenance. Ph D. Thesis, Ghent
434 University, Ghent, Belgium, pp. 300.

435 Stasinakisa, A.S., Mamais, D., Thomaidisa, N.S., Lekkas,T.D., 2002. Effect of
436 chromium (VI) on bacterial kinetics of heterotrophic biomass of activated sludge
437 *Water Res.* 36, 3341–3349

438 Tanner, C. C., Sukias, J. P. S., Upsdell, M. P., 1998. Organic matter accumulation
439 during maturation of gravel-bed constructed wetlands treating farm dairy
440 wastewaters. *Water Res.* 36(10), 3046–3054.

441 USEPA, 2000. Constructed wetland treatment for municipal wastewater.

442 EPA/625/R-99/010. office of research and development, Cincinnati, OH. 166.

443 Water and Wastewater Monitoring and Analysis Methods (4th ed.), 2002 State
444 Environmental Protection Administration of China. China Environmental
445 Science Press, Beijing, pp: 212-216

446 Winter, K.J., Goetz,D., The impact of sewage composition on the soil clogging
447 phenomena of vertical flow constructed wetlands. Water Sci. Technol. 48, 9-14.

448 Wynn, T.M., Liehr, S.K., 2001. Development of a constructed subsurface-flow
449 wetland simulation model. Ecol. Eng. 16, 519 - 536.

450 Zhao, L.F., Zhu, W., Tong, W., 2009. Clogging processes caused by biofilm growth
451 and organic particle accumulation in lab-scale vertical flow constructed wetlands.
452 J. Environ. Sci. 21,750-757

453 Zhao,Y.Q., Sun, G., Allen, S.J., 2004. Anti-sized reed bed system for animal
454 wastewater treatment: a comparative study. Water Res. 38, 2907-2917.

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459 **Caption to Tables**

460 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	

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476 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 Platzer and Mauch, 1997;
h_c	Depth of clogging layer	m	0.03	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	$gNO_3-N m^{-3}$	0.1	Kadlec and Wallace, 2009
K_{PNH}	Ammonium half-saturation coefficient for plant growth	$gNH_4-N m^{-3}$	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

478 **Caption to Figures**

479 Fig.1 Constructed wetland model bed

480 Fig.2 The variation of Y_H in different operation stage

481 Fig.3 The variation of K_d in different operation stage

482 Fig.4 Experimental and predicted clogging time

483 Fig.5 Experimental and predicted pore space volume reduction

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504 Fig.1 Constructed wetland model bed

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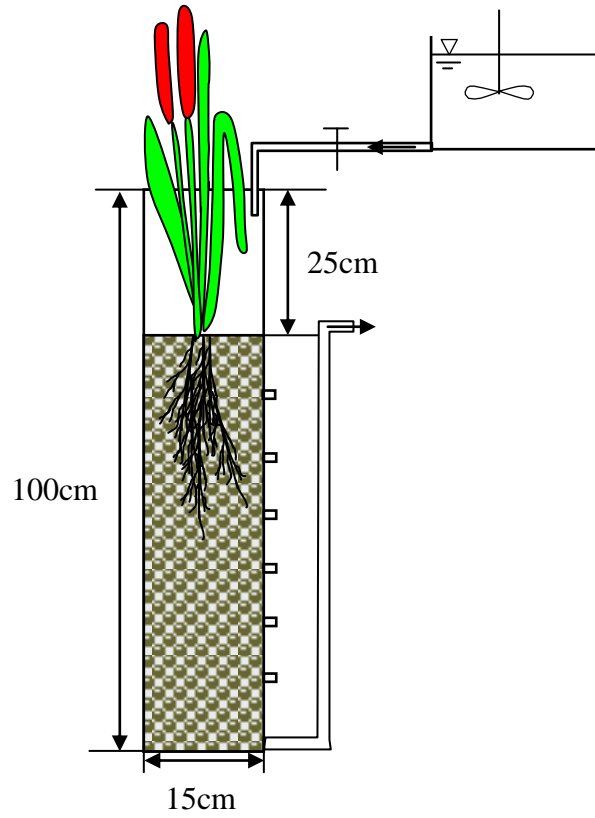
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530 Fig.2 The variation of Y_H in different operation stage

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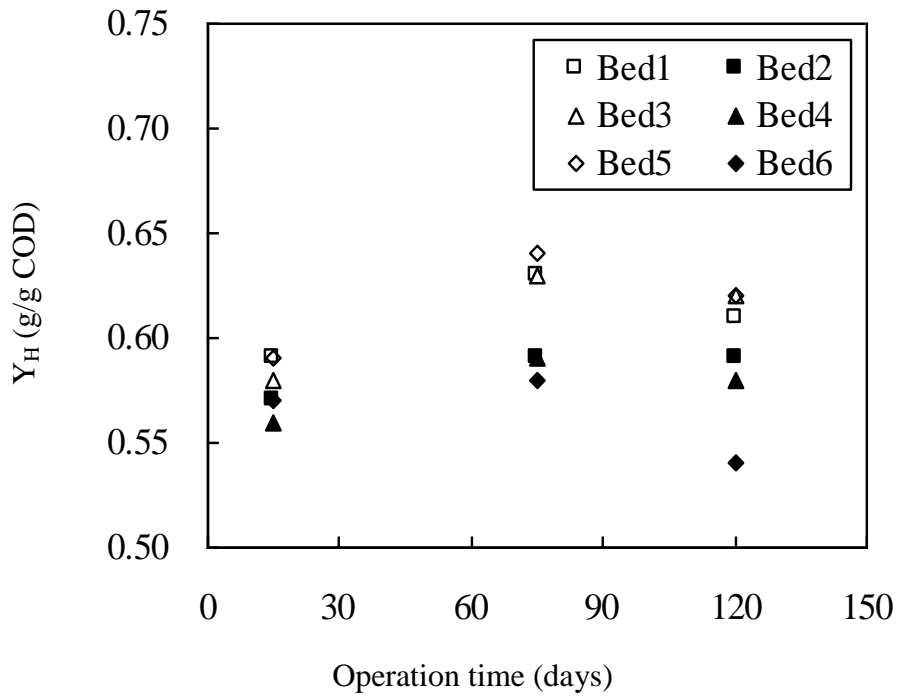
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557 Fig.3 The variation of K_d in different operation stage

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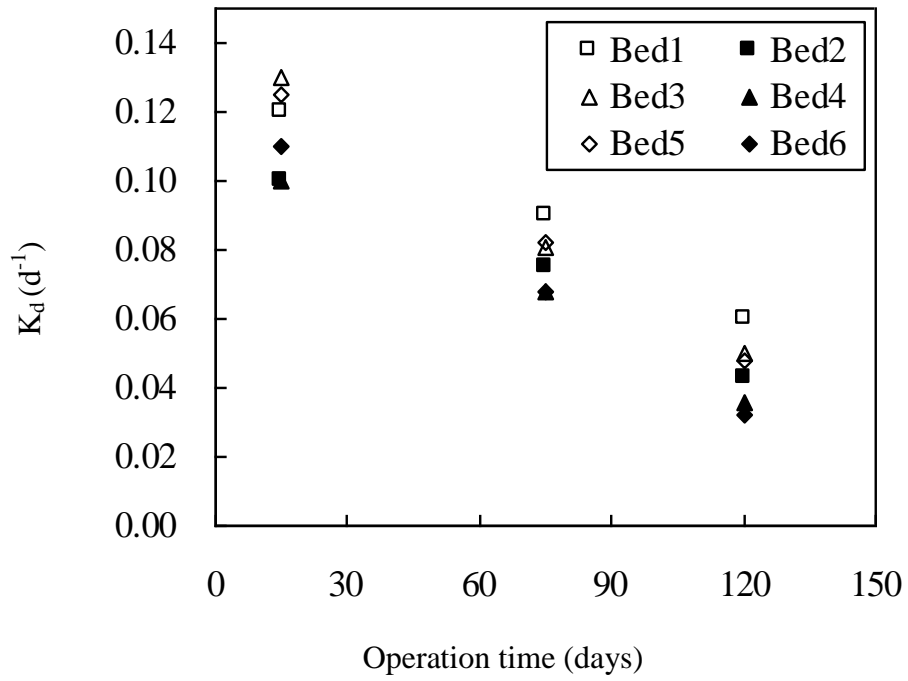
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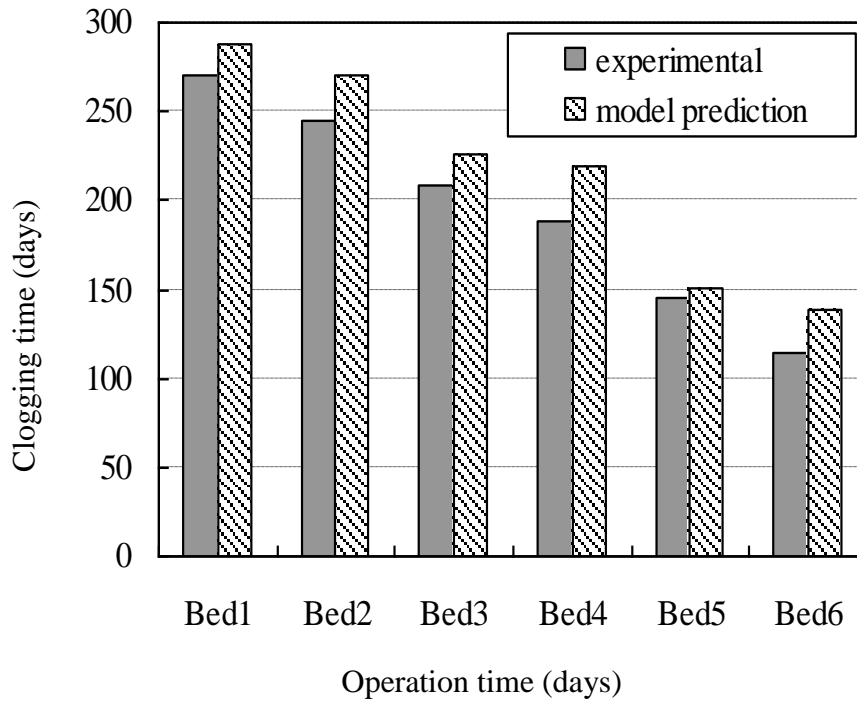
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584 Fig.4 Experimental and predicted clogging time



611 Fig.5 Experimental and predicted pore space volume reduction

