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An integrated model of substrate clogging in vertical flow constructed wetlands

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ABSTRACT

This paper presents an integrated model of substrate clogging in a vertical flow constructed wetland (VFCW). The model simulates the reduction of pore space in the wetland substrate due to combined influences of various physical, biogeochemical and plant-related processes. A series of experiments based on laboratory-scale VFCWs were conducted to examine and measure key parameters related to clogging of the wetland substrate during operation under different conditions. The model was then validated using data collected from the experiments. The results showed that the model was able to replicate the clogging phenomenon as observed in the experiments, in particular, the characteristic clogging time. The model also predicted well individual contributions to clogging by accumulated inert suspended solids, microbial biomass and plant root materials during the wetland operation. Although the validation was based on the laboratory data, the results indicated that the model describes well the processes underlying the clogging and has the potential to become a tool for assessing the performance of prototype CWs in relation to clogging at both the design and operation stages.

1. Introduction

Substrate clogging is a tangible risk for a subsurface-flow constructed wetland (SFCW), affecting seriously the wetland's function in wastewater treatment. Clogging is mainly influenced by loading rates of BOD, COD and suspended solids (SS) (Winter and Goetz, 2003). During the wetland operation, SS and particulate organic matters are removed from the treated water initially by means of physical processes such as sedimentation, entrapment and adsorption. Subsequently, the trapped SS and particulate organic matters are hydrolyzed and degraded by aerobic and/or anaerobic processes (García et al., 2010). Dissolved organic matters can be adsorbed to granular media, plant roots and detritus, and oxidized by resident microbial populations (Burgoon et al., 1995). The removal of these materials produces immobile solids that reduce and block the pore space. This in turn may lead to dramatic changes of the flow condition in the system, creating problems such as short-circuiting, reduction of hydraulic retention time, surface ponding of wastewater, odors, presence of insects and after all considerable reduction in the wetland's treatment efficiency (Platzer and Mauch, 1997). Under the worst-case scenarios, the life span of the wetland treatment system may be significantly shortened.

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 occurs. A simple theoretical clogging model was developed by Blazejewski and Murat-Blazejewska (1997) to calculate the clogging time based on a sandy CW system. In this model, a biosolid density was introduced to convert the wastewater load to porosity reduction. Langergraber et al. (2003) and Zhao et al. (2004) presented an approach for estimating the clogging time based on the concept of available void space in the substrate. While Langergraber et al. (2003) considered the degradable fraction of accumulated matters, Zhao et al. (2004) focused on accelerated solids mineralization during operation-break periods. 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 models did not take into account the biofilm growth, or the influence of vegetation and its contribution to the increase of recalcitrant detritus.

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On the other hand, Rousseau (2005) developed a mechanistic model that estimates the reduction of pore volume in CWs as a function of time. The model is able to predict the porosity change and thus can be a useful tool for studying the clogging phenomenon. However, this model contains 26 state variables associated with 26 mass balance equations, including in total 118 model parameters. With so many parameters involved, it is extremely difficult to calibrate the model in order to determine proper values of input parameters, especially those that are not measurable or cannot be measured easily. This would lead to great model uncertainty in applications (García et al., 2007). Moreover, this model did not include the macrophyte root biomass in the calculation of pore volume reduction. In theory, the clogging time estimation should consider the detached biofilm and plant detritus in the CWs.

Giraldi et al. (2010) developed a one-dimensional finite element analysis (FEA) model (named FITOVERT) for VF treatment wetlands to evaluate clogging due to biofilm and particulate matter accumulation. The coupling between clogging and hydraulics was achieved by relating the accumulation of clogging matter to loss of media porosity. Only the hydraulic module of the model was calibrated and validated. Furthermore, the contribution of the plant root's biomass to clogging was not considered either.

The aim of this study is to develop a clogging model to simulate key physical (such as physical filtration), biogeochemical and plant-related processes that are responsible for the pore space reduction during the operation of VFCWs. This model is based on a relatively small set of parameters that describe adequately the characteristics of wastewater (e.g., SS and COD concentration etc.), wetland medium/substrate and plant. In parallel to the model development, experiments were conducted within laboratory-scale VFCWs. Data collected from these experimental wetlands were used to calibrate and validate the model.

2. Model development

2.1. Background

It is well recognized that the treatment of wastewater in CWs results from various physical, biogeochemical and plant-related processes. SS in the wastewater is mainly removed near the inlet of the wetland, typically within 1/3 of the total depth from the surface, under normal operating conditions (Wynn and Liehr, 2001). Only at high flow rates, wash-out of solids proportional to the flow rate occurs (Rousseau, 2005). Although detachment of biofilm is a commonly acknowledged process, it is assumed that sloughed parts of the biofilm are retained and metabolized within the pores, unless they are washed out by a peak flow.

Aerobic and anoxic microbial carbon conversion processes in CWs are often simulated based on the Activated Sludge Model (ASM1; Henze et al., 2000) and Constructed Wetland Model 1 (CWM1 Langergraber et al., 2009). These modeling approaches were also adopted in the present study with improvements of the original models made to better represent CWs by incorporating the effects of vegetation. Following the method of Wynn and Liehr (2001), the plant growth and decay model was kept simple, with no explicit consideration of individual factors such as nutrient availability, air temperature, solar radiation and water level.

Clogging was evaluated based on pore volume reduction in the present model. Three contributors to pore volume reduction were: (1) biofilm due to bacteria growth, (2) solids retained and (3) plant detritus. The model computed the masses of these substances, which were then converted to volumes according to the mass densities to determine the pore volume reduction. If the amount of accumulated matters became so high that there was virtually no available void space inside the pores for further settlement of solid materials, the clogging occurred. At this point of time, the hydraulic conductivity of the CW substrate decreased significantly with a near-zero substrate porosity. The period of the CW operation up to this point of clogging occurrence was defined as the clogging time.

2.2. Model setup

The model development was based on the mass balance of involved materials in the CW, following the principle given below:

$$\frac{dM\_TS}{dt} = F_{in} - F_{out} + S \tag{1}$$

M_TS is the total solid mass (g) in the wetland system (the biomass of plant roots considered separately); t is the time (d); the F_{in} and F_{out} are the influx and efflux (g/d), respectively; S is the source/sink term (g/d) due to reaction/conversion.

As shown in Fig. 1, the source/sink terms in Equation (1) depend on the following processes and factors: (a) total inert suspended solids are absorbed and retained inside the substrate; (b) biodegradable organic matters are converted into biosolids; (c) biomass residues are transformed into inert solids through microbial endogenous respiration. Note that inert solids can also be derived from plant roots considered separately.

Calculations of the flux and source/sink terms are discussed in detail below:

(I) The influx of inert particulate matter (F_{in_IS}, g/d) associated with the influent to the CW, including organic and/or inorganic substance (M_{IS}), can be expressed as:

$$F_{in\_IS} = Q_{in} \times C_{in} \times (1 - f_v + f_v \times f_{nv}) \tag{2}$$

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 in the TSS (−); and f_{nv} is the proportion of the inert (non-biodegradable) matter in the organic TSS (−).

(II) The source of biosolids production (S_{BS}, g/d) due to the conversion of biodegradable organic matter can be expressed as:

$$S_{BS} = \frac{Q_{in} \times C_{BOD} \times Y_H}{1 + K_d \times \theta} \tag{3}$$

where C_{BOD} is the influent BOD (g/m^3) concentration; K_d is the heterotrophic microbial endogenous decay coefficient (d^{-1}); Y_H is the observed yield for heterotrophic biomass (−) and θ is the mean residence time (d) of biosolids in the CW.

(III) The source of inert matter production from conversion of biomass residues (S_{IS}, g/d) through microbial endogenous respiration can be described as:

$$S_{IS} = f_p \times K_d \times \theta \times S_{BS} \tag{4}$$

where f_p is the fraction of microbial biomass converted to inert matter (−).

Some fractions of inert solids and biomass solids would be washed off and discharged through the effluent. Thus, the mass balance equations for inert solids (M_IS, g) and biomass solids (M_BS, g) in the system are:

$$\frac{dM\_IS}{dt} = F_{in\_IS} - F_{out\_IS} + S_{IS} \tag{5}$$