Mechanistic understanding and prediction of bioclogging in sand filters and subsurface flow constructed wetlands

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INTRODUCTION

Clogging of the pore-space is the primary cause of efficiency reduction and aging of wastewater treatment devices such as sand filters and subsurface flow constructed wetlands (US EPA 2000; Langergraber et al., 2003; Kadlec and Wallace, 2009). Significant efforts have been undertaken to study and understand the mechanisms leading to clogging and to design solutions to alleviate its adverse effects. Clogging is the plugging of pores in the filtering medium and results in a decrease of the hydraulic conductivity of the substrate. It is normally more pronounced near the inlet. Physical, chemical and biological mechanisms may contribute synergistically to pore blockage. Examples of such mechanisms are the filtration of fines and colloidal particles suspended in the pore water, growth of biofilms and precipitation of minerals, such as calcite and apatite. While mineral precipitation is sensitive to the chemical composition of the wastewater and filtering material, biomass growth and deposition of suspended solids are ubiquitous processes and affect nearly every treatment device, although to a varying extent (e.g., Kadlec and Wallace, 2009). Empirical design criteria based on areal mass loading rates are currently used to minimize the rate of pore blockage, although with limited success (e.g., Austin et al., 2007). Therefore, more fundamental, process-based approaches could help in understanding and predicting the development of clogging as a function of the design parameters, such as the medium grain size distribution and the mass loading rate (e.g., Austin et al., 2007).

AIMS AND METHOD

The aim of this work was to improve the mechanistic understanding of clogging in wastewater filtering devices by analysing two of the main processes, namely biomass growth and deposition of fines. Mineral phase precipitation instead is not considered here. The insights gained were in turn used to evaluate alternative design options in order to provide more robust and physically sound design guidelines.

The work combined numerical modelling and experimental results taken from the literature. Overall, modelling results show a reasonably good agreement with the experimental data.

Simulations are performed using a previously developed variable-density, saturated flow reactive transport code able to simulate the porosity and hydraulic conductivity changes resulting from biological and geochemical transformations (Brovelli et al., 2009). This model can be used to simulate complex reaction networks, and an arbitrary number of components both biological and abiotic, all of which can potentially lead to porosity changes. The link between porosity and hydraulic conductivity was implemented using three alternative constitutive relationships. Attachment and detachment were also incorporated as rate-controlled processes, with the rate parameter as a nonlinear function of the flow velocity (Brovelli et al., 2009). The reaction network we adopted is based on a modified version of the CWM1 model (Langergraber et al., 2009), which accounts for both aerobic and anoxic reactions, and uses acetate, nitrates and sulphates as possible alternative electron acceptors. Variations in the hydraulic properties are due to growth and decay of four different microbial consortia, and to deposition and resuspension of particulate organic matter. The latter material in turn is composed of an inert and a biodegradable fraction.

RESULTS AND DISCUSSION

Modelling capabilities were illustrated using a simplified test case. We considered a horizontal sand filter, and we analysed the changes in hydraulic conductivity during its lifetime of four years.

The main properties of the simulated filtering device are listed in Table 1. The filter was operated for four years to treat municipal wastewater.

Figure 1 depicts modelling results. It shows the relative computed hydraulic conductivity, i.e. the actual hydraulic conductivity normalized by the corresponding starting value. The left panel reports the hydraulic conductivity profiles within the wetland after 1, 2 and 4 years of operation. Initially and up to about 2.5 years, the decrease in hydraulic conductivity is moderate (less than 25% reduction). Later, due to accumulation of inert solids and biomass growth, the hydraulic conductivity significantly drops near the inlet, with a final value of about 5% the starting hydraulic conductivity. The right panel shows the computed bulk hydraulic conductivity for the same system at the end of the simulated time, as a function of the organic carbon loading rate. While this example is synthetic, it illustrates that the model we adopt here is a useful design tool. For example, Fig. 1b could be easily used to identify the optimal system dimensioning required to avoid significant clogging, based on the average concentrations expected in the influent wastewater.

Table 1. Main properties of the sand filter used in the simulations presented here. Typical values for constructed wetlands treating domestic sewage (Austin et al., 2007)

Property	Value	Units
Model length	7	m
Starting hydraulic conductivity	5	m d^{-1}
Starting porosity	0.35	-
Longitudinal dispersivity	0.03	m
Average retention time	4.5	d
Influent BOD_5	150	mg l^{-1}

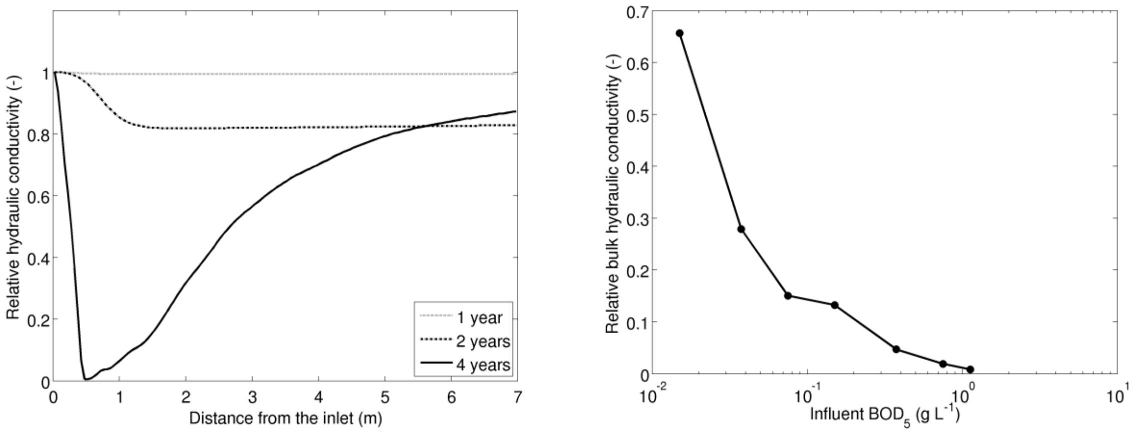

Fig. 1. Plots illustrating some of the model capabilities. The left panel depicts the simulated hydraulic conductivity profiles within the sand filter after 1, 2 and 4 years of operation. The right panel shows the simulated bulk hydraulic conductivity of the sand filter at the end of the 4th year of operation, as a function of the average loading rate.

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