Effect of substrate heterogeneity on flow in constructed wetlands and sand filters

Otoniel Carranza-Díaz, Alessandro Brovelli, Luca Rossi, D. A. Barry

Ecological Engineering Laboratory, Institut d' ingénierie de l'environnement, Ecole Polytechnique Fédérale de Lausanne, Bâtiment GR, Station 2, 1015 Lausanne, SWITZERLAND (otoniel.carranzadiaz@epfl.ch – alessandro.brovelli@epfl.ch – luca.rossi@epfl.ch – andrew.barry@epfl.ch)

INTRODUCTION

Horizontal flow constructed wetlands (HCWs) are engineered systems that can eliminate a wide range of pollutants from the aquatic environment (Vymazal, 2008). In their simplest form, they are large sand filters for biodegradation of through-flow waters. Their suitability to remove the organic and nutrient load from municipal and agricultural wastewaters has been largely demonstrated. But, additional research is necessary to understand the different biogeochemical processes, their mutual interactions and feedbacks and ultimately to identify the optimal conditions to treat anthropogenic recalcitrant pollutants, such as hydrocarbons, pharmaceuticals and personal care products (Vymazal and Kröpfelová, 2008; Imfeld et al., 2009).

With respect to biodegradation, for example, optimal pollutant elimination is achieved only if within the porous substrate the contact time between microbial biomass and contaminated water is sufficiently long. The contact time depends primarily on the hydrodynamic properties of the system and hydraulic residence time distribution (HRTD). Numerous studies (e.g., Persson, 1999; Suliman, 2005) with conservative tracers have however observed that poor hydrodynamic behaviour is common, and results from flow dominated by preferential pathways. The formation of highly conductive zones has been attributed to heterogeneous distribution of the porous material during the construction of the filter, physical and biological clogging, and presence of plant roots (Persson et al., 1999; Suliman et al., 2005). Then, the pollutant removal efficiency can be significantly reduced, potentially leading to the failure of the system. The aim of this work is to analyse the effect of the heterogeneous distribution of the hydraulic properties of the porous substrate on the HRTD and treatment efficiency. The observations made and conclusions reached will be used to develop improved design guidelines to reduce the risk of system failure resulting from a poor hydrodynamic behaviour.

METHOD

Numerical modelling was used to evaluate the effect of substrate heterogeneity on the breakthrough curves of both a conservative tracer and a reactive organic compound. We considered a 3D geometry representing a horizontal subsurface flow constructed wetland with typical design parameters for a system treating industrial sewage. Benzene was chosen as a test organic molecule because (i) constructed wetlands proved effective in removing BTEX from wastewaters (Imfeld et al., 2009) and (ii) the biodegradation process is well understood. Numerical simulations have been conducted using a modified version of PHWAT (Mao et al., 2006), a saturated flow and reactive transport code. Random, spatially correlated hydraulic conductivity fields following a log-normal distribution were generated using the turning band method, as implemented in TBSIM (Emery and Lantuéjoul, 2006). In order to vary the spatial structure and the extent of heterogeneity, we run 18 sets of simulations using the same mean hydraulic conductivity, and modifying the variance and the spatial correlation in each direction. Each set of simulations consisted of 10 runs with different but statistically equivalent random hydraulic conductivity fields.

A design residence time was selected in order to achieve sufficient benzene degradation, i.e., to obtain a concentration of benzene in the effluent within the water quality standards. For each random field, the model was run first to simulate the transport of a conservative tracer. The resulting breakthrough curve was used to characterize the HRTD of the system, and in turn to identify the optimal flow rate to achieve the design residence time. The flow rate was subsequently used in the simulations with benzene degradation, and the effluent concentration was compared to the corresponding target value. Statistical analysis in each set of numerical simulations was used to compute the probability of failure, and further to identify the conditions were system failure was likely.

RESULTS AND DISCUSSION

Extensive results were generated and analyzed; here some examples are provided. Figure 1 compares the spatial and temporal evolution of a tracer between the homogeneous and heterogeneous hydraulic conductivity cases. The upper panels (i) and (ii) depict the spatial concentration at a selected time. Panel (ii) contains a preferential flow path, enabling a rapid route to the outlet, while in the homogeneous case (i) the tracer is present only in the first half of the wetland.

A similar conclusion can be reached from the breakthrough curves reported in the lower panels of Figure 1 (Curves A and B). The two graphics report the flux-weighted average breakthrough curves for homogeneous and heterogeneous media (each with the same average residence time) across two different cross-sections of the wetland. The first cross-section (A) is 2.5 downgradient from the inlet, while the (B) is 7.5 m distant. Clearly, heterogeneous conditions result in a larger breakthrough curve spreading, and therefore a broader HRTD. Furthermore, we observed that in nearly all cases, the spreading of the breakthrough curves increases with the distance from the inlet. This indicates a scale-dependent behaviour, and is consistent with the experimental findings of Suliman (2005).

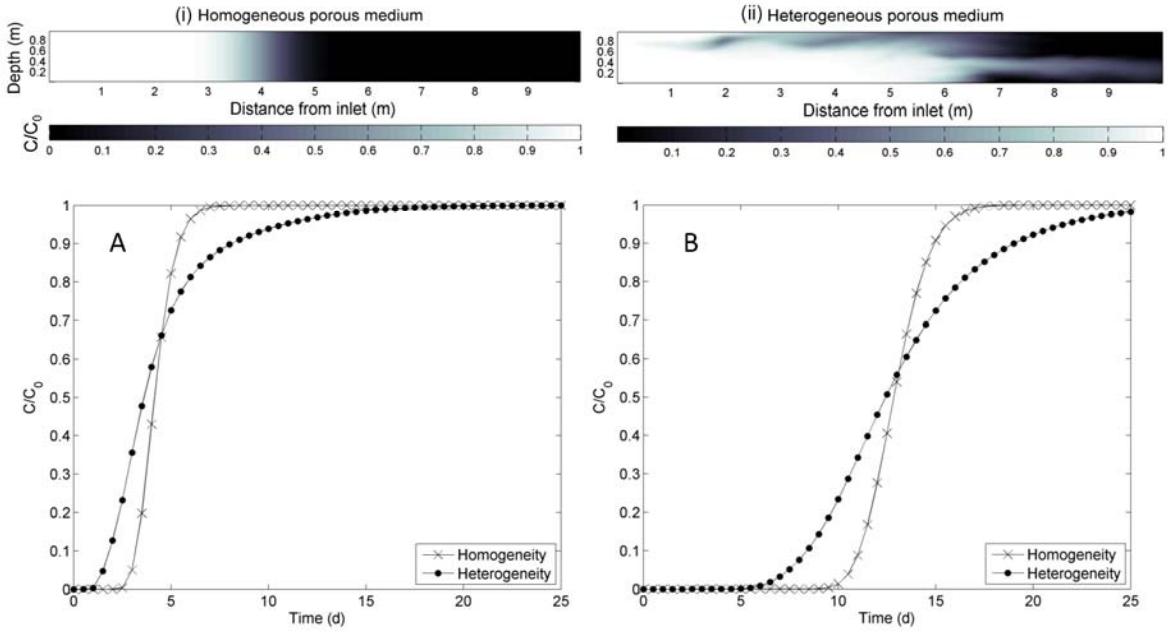

Fig. 1. Evolution of the conservative tracer with homogeneous and heterogeneous hydraulic conductivity. The maps in the upper part of the figure (i and ii) show the spatial distribution of the tracer, while the breakthrough curves depict the HRTD. The two graphs in the lower part of the figure (A and B) are relevant to different distances from the inlet: (A) 2.5m and (B) 7.5m. These results clearly illustrate that heterogeneity induces preferential paths and therefore contaminated water is discharged faster.

REFERENCES

Imfeld, G., Braeckvelt, M., Kuschk, P. and Richnow, H. (2009). Monitoring and assessing processes of organic chemicals removal in constructed wetlands. *Chemosphere*, 74(3): 349-362.

Vymazal, J. and Kröpfelová, L. (2008). Wastewater treatment in constructed wetlands with horizontal sub-surface flow. *Springer*, Czech Republic. 566 p.

Emery, X. and Lantuéjoul, C. (2006). TBSIM: A computer program for conditional simulation of three-dimensional Gaussian random fields via the turning bands method. *Comp. Geosci.*, 32(10): 1615-1628.

Mao, X., Prommer, H., Barry, D.A., Langevin, C. and Panteleit, B. (2006). Three-dimensional model for multi-component reactive transport with variable density groundwater flow. *Environ. Model. Soft.*, 21(5):615-628.

Suliman, F., French, H., Haugen, L.E., Kløve, B. and Jenssen, P. (2005). The effect of the scale of horizontal subsurface flow constructed wetlands on flow and transport parameters. *Water Sci. Technol.*, 51(9): 259-266.

Persson, J., Somes, N.L.G. and Wong, T.H.F. (1999). Hydraulics efficiency of constructed wetlands and ponds. *Water Sci. Technol.*, 40(3): 291-300.