Which Hydraulic Model To Use In Vertical Flow Constructed Wetlands?

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WHICH HYDRAULIC MODEL TO USE IN VERTICAL FLOW CONSTRUCTED WETLANDS?

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Abstract. Modeling water flow in a VFCW is a prerequisite to model wastewater treatment using process based filtering models. As for soils, when the vertical structure varies in different material types, it has a significant impact on water flow passing through it. The heterogeneous filtering material is composed of a mix of mineral porous material, and organic matter which makes its hydraulic characterization a difficult task. Indeed, the porosity may serve as preferential flow paths through which water can bypass most of the soil porous matrix in a largely unpredictable way. Consequently, non-equilibrium conditions in pressure heads are created between preferential flow paths and the soil matrix pore region. Preferential flows limit the applicability of standard models for water flow that are commonly based on Richards' equation. Even if it is possible to simulate water content variations within a VFCW, we can not correctly model outflow with the standard van Genuchten-Mualem function. A number of various model approaches have been proposed to overcome this problem. These models mostly try to separately describe flow and transport in preferred flow paths and slow or stagnant pore regions. The objective of this study was to compare the various existing models simulating the preferential flows within the French VFCWs. Moreover, by assuming that several layers hydraulically different compose the VFCW, we tested at which layer(s) it is necessary to apply the non-equilibrium models.
A tracer experiment was performed to evaluate the non-equilibrium degree. It was conducted on a 100 p.e. plant in operation since 2004. Monitoring consisted in measuring inlet and outlet flows, infiltration rates and water content at a time interval of 1 minute. We used the HYDRUS-1D software package containing various non-equilibrium flow modeling approaches. The physical non-equilibrium transport models were used to simulate outflow, the tracer breakthrough curve as well as water contents within a French-type VFCW. Physical non-equilibrium models include the dual-porosity model (mobile-immobile water model, with water content mass transfer or head mass transfer), and the dual-permeability model (matrix and fracture pore regions). We also applied a bimodal single-domain approach (Durner model) in order to see if it is actually necessary to use non-equilibrium models to effectively simulate VFCW outflow.
Performance of the various non-equilibrium models (accuracy and limitation) was assessed by comparing the simulated and measured tracer fluxes using the mean square relative error (MSRE) of prediction. The comparison between measured and simulated tracer breakthrough curves indicates that the non-equilibrium (dual-porosity or dual-permeability model) approach seem to be the most appropriate for simulating preferential flow paths. In addition, simulations reveal that all layers participate in the preferential flow path process. These preferential flow paths are mainly due to the sludge layer that has been developed on the surface of VFCW since its start-up (swelling/shrinking during the feeding/rest periods) and to the network of roots and rhizomes present in it.

Keywords. Dual-porosity, non-equilibrium model, preferential flow path, vertical flow constructed wetlands

INTRODUCTION

Constructed wetlands (CWs) are an attractive wastewater treatment technology for small communities (< 2000 people-equivalents; p.e.), as their simplicity of operation, low cost and reliable treatment efficiency often fit with the limited resources small communities can allocate to wastewater treatment (Kadlec, 2000). Irstea (National Research Institute of Science and Technology for Environment and Agriculture) developed an innovative type of first-stage for vertical flow constructed wetlands (VFCW), made of gravel instead of sand.

This first-stage type directly accepts raw wastewater, without the need for a preliminary settling tank. In a long-term operation, Molle et al. (2005) recorded on this first stage mean removal efficiencies of up to 80% for chemical oxygen demand (COD), 85% for total suspended solids (TSS), and 60% for total Kjeldahl nitrogen (TKN). However, despite recent optimization trials in terms of media depth and aeration, the first stage of this VFCW still lacks treatment efficiency, making it necessary to upgrade with a second vertical stage that increases the total surface area needed (1.2 m² $p.e^{-1}$ for the first stage and 0.8 m² $p.e^{-1}$ for the second stage). Molle et al. (2008) further highlighted that treatment efficiency could be improved if the hydraulic behavior of the VFCW would be better understood.

The French VFCW are initially entirely composed of gravel but after some years of operation a sludge layer develops at the filter surface and the filter media turns into a matrix of porous mineral material and organic matter. Consequently, both gravitational and capillary flows, due to gravel and the presence of organic matter, respectively, have to be considered. Water retention is due to the significant presence of organic matter in the filter (particularly between the sludge layer and the mix gravel/sludge directly below) (Maier et al., 2009). The porosity and the network of roots and rhizomes associated with reeds may serve as preferential flow paths through which water can bypass most of the porous matrix in a largely unpredictable way. Moreover, during the rest period (and this is even more pronounced during the summer, when temperatures are higher and rainfall lower) the physical action of reeds (reed movement with the wind) makes air and water flows within the filter easier. During this same period the sludge dries faster and the cracks are visible and significant and consequently preferential flow paths become more important (Molle et al., 2006). The fact that the sludge layer does not develop homogeneously over the filter surface (higher close to the feeding points than the filter sides) also leads to preferential flow paths. Consequently, non-equilibrium conditions in pressure heads are created between preferential flow paths and the matrix pore region. Up to now, VFCW is depicted as a porous medium with continuous properties (Morvannou, 2012; autres?). Variably saturated water flow through such a porous system is uniform and at local equilibrium, and is often described using the Richards equation. For simulating preferential flows in structured media, standard equilibrium models commonly-used cannot be applied for these VFCW systems because they assume homogeneity and local equilibrium conditions (Gerke, 2006). Moreover, even if it is possible to simulate water content variations within a VFCW, outflow cannot be correctly modeled with the standard van Genuchten-Mualem function. Therefore, a model representing a non-equilibrium water flow and solute transport would be more appropriate.

Regarding models representing preferential flows, none has been applied yet to the flow and transport in VFCW. However, lots of studies have been carried out concerning preferential flows in the field of hydrogeology for simulating water flow and/or solute transport in saturated and unsaturated porous soils through macropores (Šimůnek et al., 2001; Haws et al., 2005; Pot et al., 2005; Köhne et al., 2006; Maier et al., 2009). Many approaches for implementation of preferential flow in variably saturated porous media models have been described in recent years (Šimunek et al., 2003), and most of them require the parallel consideration of two or more domains for the same porous medium. The hydrodynamic of a VFCW can be analyzed by numerical models such as those implemented in the HYDRUS software package (Šimůnek et al., 2006). HYDRUS solves the governing flow and transport equations for partially-saturated porous media. Among the several approaches for modelling preferential flows, the HYDRUS software package provides four different and commonly-used conceptual physical non-equilibrium models: the Mobile-Immobile Water Model for non-equilibrium transport combined with standard equilibrium water flow (van Genuchten and Wierenga, 1976), Dual-Porosity Model for both water flow and solute transport (Šimůnek et al., 2003), Dual-Permeability Model assuming non-equilibrium flow and transport in both domains (Gerke and van Genuchten, 1993, 1996), and Dual-Permeability Model with Immobile Water. These models have in common that water flow is simulated using the Richards equation and solute transport using the convection-dispersion equation. In contrast, they distinguish between ‘‘fast” (macropore domain) and slow or stagnant pore space (matrix domain) and in which part of the porous medium (i.e., the matrix and/or macropore domain) water flow and solute transport take place. In addition they are coupled by kinetic mass transfer terms between the two pore domains. However, the disadvantage of these approaches is that the computational demand significantly increases as well as the number of additional parameters which are hard to estimate (Šimůnek and van Genuchten, 2008).

The purpose of this paper is to study and simulate the hydraulic behavior and the solute transport through a simplified representation of a VFCW (column) by using both a classical equilibrium model and a non-equilibrium model included in the HYDRUS-1D software package. In a first attempt we used the dual-porosity model as the simplest non-equilibrium approach, with fewer parameters, while having both non-equilibrium flow and solute transport. Modeling results will be compared to a solute breakthrough curve obtained from a tracer experiment to determine which approach is the most appropriate for representing preferential flows in a VFCW.

MATERIALS AND METHODS

Tracer experiment

The Evieu wastewater treatment plant (Ain, France) comprises a sequence of vertical and horizontal sub-surface flow constructed wetlands. The plant has been in operation since 2004. It was originally designed for 200 p.e., but as only 100 p.e. are currently connected, the filter surface has been divided in two to work at full capacity. The first stage is made up of three VFCWs receiving raw wastewater. The pump sump at the plant inlet only performs mechanical screening using a 5 cm mesh screen. Each filter is fed according to a feeding/rest regime of 3.5/7 days. Effluent from this first stage is then connected to a second pump sump and separated between the second stage’s vertical and horizontal flow constructed wetlands according to the experimental objectives (Molle et al., 2008). All beds are planted with *Phragmites australis* reeds.

A fluorescein infiltration experiment was carried out from 04/15/2010 to 04/19/2010 on one of the VFCW of the first stage of the wastewater treatment plant in order to visualize the heterogeneity of the tracer distribution pathways. The selected vertical filter (28 m², 2.9 m wide x 9.7 m long) is designed according to French recommendations. From the bottom to the top, it contains a 15 cm thick drainage layer (grain size of 30-60 mm), a 10 cm transition layer (grain size 15-25 mm) and a 60 cm gravel layer (d_{10} = 2.46 mm; UC = d_{60}/d_{10} = 1.39; average porosity of 40.4%). As the filter has been working at nominal load for 7 years, a sludge layer of about 20 cm has developed at the top of the filter. The VFCW is fed by raw wastewater in batches of 5 cm at a rate of 1.23 $m^3/h^1/m^2$ on average. During spells of dry weather, 8 separate batches are processed per day. Water is drained by a 160 mm diameter drainage pipe (0.42 m of pipe per m²), allowing passive aeration from the bottom as well.

For the tracer experiment, 1.98 g of fluorescein were diluted in a batch volume (1973 L) and applied to the filter. This is equal to 0.07 g/m² and the applied solution fluorescein concentration was 0.001 g/L. It should be noted that all the fluorescein was not applied in only one batch; it remained in the pump sump (some water remains in after each batch) and was applied with the next batches but the remaining concentration was not determined. In addition, after the batch some fluorescein remains also on the top of the filter. After the fluorescein application, its concentrations were recorded at the VFCW outlet along with the outflow data at a time interval of 1 minute end-to-end throughout the tracer experiment, including the 3.5 batch feeding days.

Commentaire [m1] : Parler de l'adsorption?

An introduction to dual-porosity models

The aim of this section is not to provide a full mathematical description of the dual-porosity models. For this purpose the reader may refer to Šimůnek et al. (2003, 2008). Our objectives are to emphasize how dual-porosity models represent preferential flow and to highlight how complexity is increased by additional parameters. According to Šimůnek et al. (2003), preferential flow has two main characteristics: (1) the ability to quickly propagate by "bypassing a large part of the matrix pore-space", and (2) the non-equilibrium between the water pressure head within the macropores and the water content in the rest of the matrix. Non-equilibrium is a key concept of preferential flow modelling. In the classical description of flow in variably saturated porous media based on the Richards equation, it is stated that the water pressure head and water content are always at equilibrium and linked by a water retention relationship (i.e., the van Genuchten relationship). This assumption does not hold anymore in case of preferential flow.

The dual-porosity model does not aim at physically representing the paths of quick flow (It would be very challenging to map every macropore at the scale of a VFCW) but rather to incorporate their effects in the representative elementary volume (REV) that serves as a basis for modelling. Fig. 1 comparatively represents how macropores can be observed on the filter and how they are modelled at the REV scale.

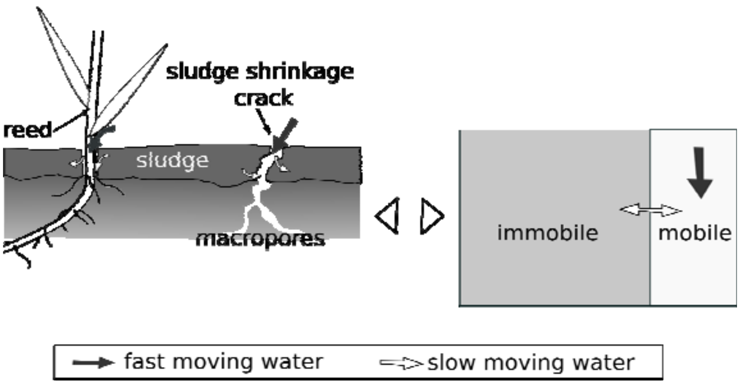

Figure 1. Schematic representation of macropores and preferential flow in a VFCW (left) and the corresponding conceptual physical non-equilibrium model for water flow and solute transport (right)

(1) In dual-porosity models, it is assumed that flow only takes place within the macropores (the mobile phase), whereas the flow in the rest of the matrix is neglected (water in the rest of the matrix constitutes the immobile phase). The hydrodynamic parameters (α, n and K_s) are

representative of the flow in macropores and therefore must be adapted, especially K_s, to produce quick outflow. The total porosity is divided between the mobile ($\theta_{s,m}$) and the immobile ($\theta_{s,im}$) regions (for sake of simplicity we considered residual water content to be null for both regions). This brings additional complexity to the model: for a given saturated hydraulic conductivity, the larger is the mobile region, the slower is the flow as illustrated on Fig 2.

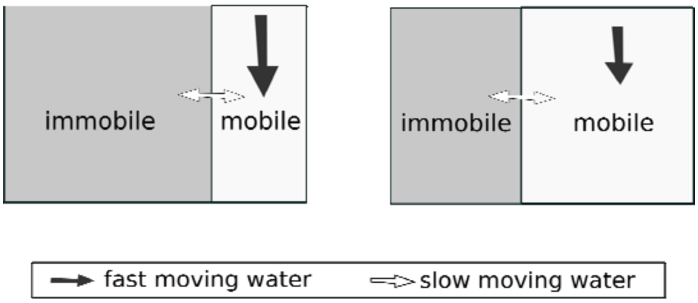

Figure 2. Conceptual physical non-equilibrium model for water flow and solute transport when the mobile region is small (left) or large (right)

(2) Non-equilibrium is modelled by adding a time-dependent parameter (ω) to the relationship between water content in the immobile region and water content in the mobile region that is linked to the water pressure head. This is a very important feature that allows water exchange at different time scale than the main gravitational drainage. This parameter also represents an increase in model complexity and needs to be calibrated for each material in the model.

Model description

Previous measurements carried out on the VFCW studied revealed that the water distribution is homogeneous, particularly due to the sludge layer and the water content profiles along the filter are noticeably identical (Forquet et al., 2011, Morvannou, 2012). Consequently, we modelled the water flow and the solute transport in one dimension with HYDRUS-1D. Moreover, in contrast to the previous study carried out on the same VFCW where we considered four layers (the sludge layer, the first gravel-sludge layer, the second gravel-sludge layer, and a final practically gravel-only layer), in this study we restrained the domain to only two layers: the sludge and the gravel-only layer only . In addition, as the number of parameters in the dual-porosity model is higher than the equilibrium model a simplified representation of the VFCW allows simplifying the modelling and understanding each non-equilibrium phenomenon.

The one-dimensional mesh used for simulations consisted of 101 nodes. The top boundary condition is a time-dependent atmospheric boundary condition with a threshold value for surface runoff set to 100 cm. Wastewater load duration and flow rate are specified, while evaporation is neglected. If the incoming flow rate exceeds infiltration capacity, the ponding of water above the surface is then taken into account until it reaches 100 cm, a value that never observed in our case. The bottom boundary condition is a seepage face. The setup of initial conditions necessitated a prior initialization step. We could not use observed water contents since they do not provide continuous pressure head profile at the initial time and cause the model not to converge (Radcliffe and Šimůnek, 2010). The prior initialization step consists in repeating the simulation until pressure heads reach a pseudo-permanent state starting from hydrostatic distribution. We then selected the time for which water content profile matches the experimentally-observed initial water content. The corresponding water pressure profile was then considered as initial condition.

Modelling trials

- We tested two different modeling approaches to simulate non-equilibrium water flow and solute transport: the generally-equilibrium model and the non-equilibrium one *via* the dual-porosity model. Two dual-porosity models are available in HYDRUS depending on if the mass transfer rate is proportional to the difference in effective water contents, or to the difference in effective pressure heads (Gerke and van Genuchten, 1993). We used the first model because it should provide a more realistic description of the exchange rate between the fracture and matrix regions and it requires significantly fewer parameters since one does not need to know the retention function for the matrix region explicitly, but only its residual and saturated water contents. For the equilibrium model, we used those determined from the previous study (Morvannou, 2012) and for the dual-porosity model some hydraulic parameter values were adapted from the previous study whereas others were arbitrarily fixed.

- In a first attempt we simulated the tracer application with only one pulse. But as the tracer was not applied in one batch during the tracer experiment and remained on the top of the filter after the first batch, we tested the application of many pulses. We fixed the number of pulses to seven.

- Modelling results from the equilibrium and non-equilibrium models will be compared in terms of concentrations and cumulative fluxes computed at the outlet of the column. In addition, modelling results will not be compared quantitatively to the tracer experiment results, but qualitatively. The aim of this study is not to calibrate the dual-porosity model but is to have a better insight into hydraulic and solute transport phenomena which take place inside a VFCW and consequently which hydraulic parameter plays a part on the dual-porosity model for simulating preferential flows.

RESULTS AND DISCUSSION

Tracer experiment

Fig 3 presents the tracer concentration measured at the outlet of the VFCW and the cumulative percentage of the tracer recovery.

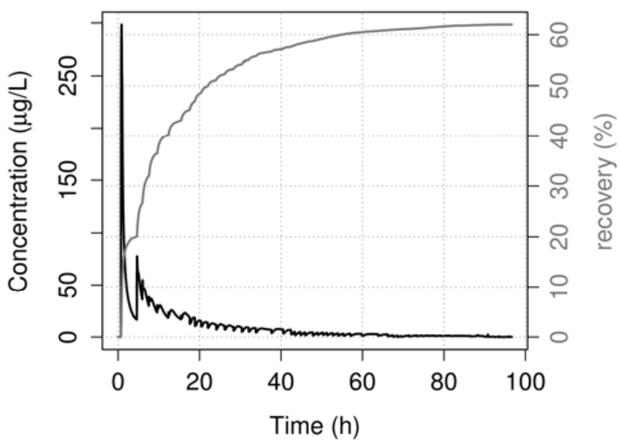

Figure 3. Tracer experimental breakthrough curve and cumulative tracer recovery percentage

The small tracer recovery percentage at the end of the tracer experiment reveals some fluorescein loss. They could be due to the ponding of water above the surface (photodegradation of the tracer), tracer retention on the organic matter, or some loss in pipes.

Fig 3 highlights two main phenomenons. On the one hand, not only one but several peaks are observed on the experimental breakthrough curve. Even if the tracer is mixed only once with the wastewater incoming in the treatment plant, the fact that all the tracer was not applied at once, a part of the tracer remained in the pump sump, it seems like the tracer application was carried out in several times. Therefore, seven peaks are observed after the tracer application. On the other hand, the second phenomenon is linked to the tracer transfer to the immobile phase. After the seven first peaks of tracer there is a shape inversion of the breakthrough curve: during each batch the tracer concentration decreases and after it increased. It looks like a release of the tracer.

Modelling results

Table 1 presents the hydraulic parameter values used for the equilibrium and non-equilibrium models.

Table 1. Parameter values of the hydraulic properties of the column representing the VFCW used in HYDRUS-1D

Layer	θ_r [-]	θ_s [-]	α [1/cm]	n [-]	K_s [cm/s]	λ [-]	θ_{r_im} [-]	θ_{s_im} [-]	ω [1/s]
Equilibrium model									
1	0.64	0.84	0.12	1.80	2.50	0.50			
2	0.00	0.44	0.50	3.20	100	0.50			
Dual-porosity model									
1	0.00	0.05	0.12	1.80	5	0.50	0.20	0.79	0.05
2	0.00	0.10	0.50	3.20	100	0.50	0.20	0.34	0.00

Fig 4 presents the simulated concentrations and fluxes obtained from the equilibrium and non-equilibrium models. It also shows the results obtained with only one tracer pulse and those with seven tracer pulses.

Conc equ vs non-equ – 1 pulse	Flux equ vs non-equ – 1 pulse
Conc equ vs non-equ – n pulse	Flux equ vs non-equ – n pulse

Figure 4. Simulated concentrations (left) and fluxes (right) for one pulse (top) or seven pulses (bottom) from the equilibrium and non-equilibrium models

When comparing the simulated tracer breakthrough curve obtained from the two models, we observe that the equilibrium model is not able to reproduce the shape inversion observed with the tracer experimental breakthrough curve (Fig 3). On the contrary, the dual-porosity provides the same shape inversion due to the tracer transfer into the immobile region and its release after each batch. Preferential flow effects modelled as mobile and immobile water are very important for matching fluorescein tracer transport characteristics for a VFCW.

Secondly, applying only one batch containing tracer does not allow simulating the multiple peaks of tracer observed in Fig 3. It is necessary to apply the tracer several times to reproduce the peaks of tracer observed at the beginning of the tracer experiment.

If we just compare the tracer fluxes in the outlet of the filter we cannot see any difference between the equilibrium and non-equilibrium results. Indeed, fluxes are not enough for comparing the modelling results whereas tracer concentrations provide information about non-equilibrium phenomenon which takes place in the filter.

CONCLUSIONS

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