Which hydraulic model to use for vertical flow constructed wetlands?

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Which Hydraulic Model to Use for Vertical Flow Constructed Wetlands?

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Abstract

Modelling water flow in a Vertical Flow Constructed Wetland (VFWC) is a prerequisite to model wastewater treatment using process based filtering models. The material used in VFCW is very susceptible to generate preferential flow. If this occurs, water will bypass most of the soil porous matrix in a largely unpredictable way. Even if it is possible to simulate water content variations within a VFCW, we cannot correctly model outflow with the standard van Genuchten-Mualem function if preferential flow occurs. 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 study and simulate the hydrodynamic behaviour and the solute transport through a simplified representation of a French VFCW by using both a classical equilibrium model and a non-equilibrium model (dual-porosity model: mobile-immobile water model, with water content mass transfer) included in the HYDRUS-1D software package. Modelling results were compared to a solute breakthrough curve obtained from a tracer experiment, carried out on an existing VFCW. Inlet concentrations were first corrected to take into account tracer loss and experimental uncertainties. Then, both the hydraulic parameters of the mobile and immobile regions (θ_r^m / θ_s^m and $\theta_r^{im} / \theta_s^{im}$) and the transfer coefficient (ω) were optimized to fit the tracer experimental breakthrough curve. The comparison between measured and simulated tracer breakthrough curves indicates that the non-equilibrium approach seem to be the most appropriate for simulating preferential flow paths.

1. 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. Irstea (formerly Cemagref) 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. Despite good treatment efficiencies, Molle et al. (2008) highlighted that treatment efficiency could be improved if the hydraulic behaviour 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 on the filter surface and the filter media turns into a matrix made of

gravels and organic matter. Water retention is mainly caused by organic matter in the filter. Consequently, both gravitational and capillary flows, due to gravel and the presence of organic matter, respectively, have to be considered (Maier et al., 2009). The macroporosity due to coarse material and the network of reed's stalks 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 the sludge dries fast and cracks become visible facilitating preferential flow paths through the sludge layer especially at the beginning of a feeding period (Molle et al., 2006). 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 (Gerke and van Genuchten, 1993; Köhne et al., 2009). Variably saturated water flow is then often modelled by the Richards equation assuming that water content and pressure head are at equilibrium at a given node. For simulating preferential flows in structured media, these equilibrium models cannot be applied (Gerke, 2006). Moreover, even if it is possible to simulate water content variations within a VFCW using equilibrium models, outflow cannot be correctly modelled with the standard van Genuchten-Mualem function (Morvannou et al, submitted). Therefore, a model representing a non-equilibrium water flow and solute transport would be more appropriate.

Regarding preferential flow models, none has been applied to the flow and transport in VFCW yet. However, lots of studies have been carried out concerning preferential flows in the field of hydrology for simulating water flow and/or solute transport in saturated and unsaturated porous soils through macropores (Šimůnek et al., 2001; Haws et al., 2005; Köhne et al., 2006; Maier et al., 2009). Šimunek et al., (2003, 2008) carried out extensive literature reviews of existing models. Most of them require the parallel consideration of two or more domains for the same porous medium. Four of them have been implemented in the HYDRUS software package (Šimůnek et al., 2006). 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 differ by the way flow and transport in ''fast" (macropore domain) and slow or stagnant pore space (matrix domain) are modelled. 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 hydrodynamic behaviour and the solute transport through a simplified representation of a VFCW by using both a classical equilibrium model and a non-equilibrium model included in the HYDRUS-1D software package. We used the dual-porosity model as the simplest non-equilibrium approach, with fewer parameters, while having both non-equilibrium flow and solute transport. Modelling results will be compared to a solute breakthrough curve obtained from a tracer experiment carried out on an existing VFCW to determine which approach is the most appropriate. Finally, using a more realistic approach we tried to calibrate the dual-porosity model.

2. Materials and methods

2.1. Tracer experiment

The Evieu wastewater treatment plant (200 p.e., Ain, France) is in operation since 2004. 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*.

A fluorescein infiltration experiment was carried out from 04/15/2010 to 04/19/2010, corresponding to the entire feeding period, on one of the VFCW of the first stage of the wastewater treatment plant. 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 $m^3/h/m^2$ 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 was 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 as expected; some remained in the pump sump (despite we emptied it after the tracer batch) and was consequently applied with the next batches. Unfortunately, the remaining concentration could not be determined. In addition, after the batch some fluorescein remains also on the top of the filter due to the low permeability and the heterogeneity of the sludge deposit. After the fluorescein application, its concentration was recorded at the VFCW outlet (online fluorimeter PELI 1300 Case, Peli Products, USA) along with the outflow rate (measured by a venture flume) at a time interval of 1 minute throughout the tracer experiment.

At the same time, water contents were recorded with TDR probes, but only during the first batch of the tracer experiment. TDR probes were inserted at three different depths of the filter (13, 31 and 47 cm below the VFCW top surface) and connected through multiplexers to a signal generator/analyzer (model TDR100, Campbell ScientificTM, Logan, UT). Results were recorded using a datalogger (model CR1000, Campbell ScientificTM Logan, UT). Measurements were made at 20 second time intervals.

2.2. 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 flows and to highlight how complexity is increased by additional parameters. According to Šimůnek et al. (2003), preferential flows have 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 (e.g. the van Genuchten relationship). This assumption does not hold anymore in case preferential flow occurs.

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. Figure 1 comparatively represents how macropores can be observed on the filter and how they are modelled at the REV scale.

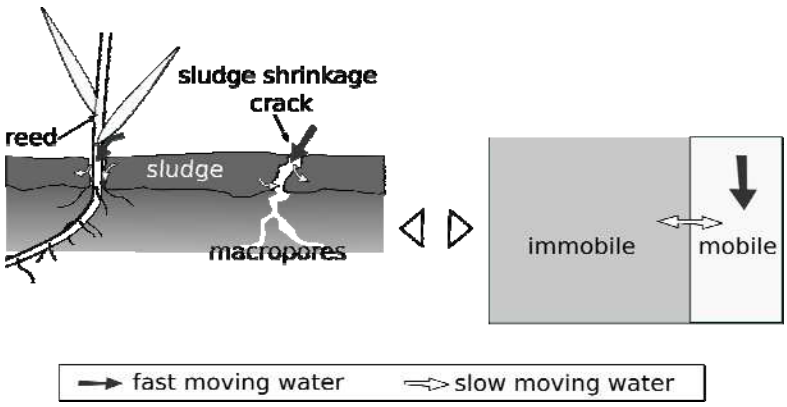

Figure 1. Schematic representation of macropores and preferential flow paths in a VFCW (left) and the corresponding conceptual physical non-equilibrium model for water flow and solute transport (right)

(1) In dual-porosity models, it is assumed that flow only takes place within the macropores (the mobile region), whereas the flow in the rest of the matrix is neglected. Water in the rest of the matrix constitutes the immobile region. 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 (θ_s^m) and the immobile (θ_s^{im}) 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. For sake of simplicity we considered residual water content to be null for both regions.

(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.

2.3. Model description

Based on the significant ponding occuring during feeding (~5 cm/m²), we assumed that water distribution is homogeneous. 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. As the number of parameters in the dual-porosity model is higher than in the equilibrium model, a simplified representation of the VFCW facilitates modelling and understanding of the non-equilibrium phenomenon.
The one-dimensional mesh used for simulations consisted of 101 equidistant nodes. The top boundary condition is a time-dependent atmospheric boundary condition with a threshold value for surface runoff set to 10 cm. Wastewater load duration and flow rate are specified, while evapotranspiration 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 10 cm, a value that was never observed in our case. The bottom boundary condition is a seepage face. Initial conditions are set to hydrostatic equilibrium.

2.4. Tested hydraulic models

Water flow and solute transport were simulated using two different modelling approaches: the generally-equilibrium model and the dual-porosity model (non-equilibrium model). Two dual-porosity models are available in HYDRUS-1D depending on if the mass transfer rate (Γ_w) 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 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.

$$\Gamma_w = \frac{\partial \theta_{im}}{\partial t} = \omega\left[S_e^m - S_e^{im}\right] = \omega\left[\frac{\theta^m - \theta_r^m}{\theta_s^m - \theta_r^m} - \frac{\theta^{im} - \theta_r^{im}}{\theta_s^{im} - \theta_r^{im}}\right] \quad (1)$$

Which, in our case, simplifies to: $\Gamma_w = \omega\left[\frac{\theta^m}{\theta_s^m} - \frac{\theta^{im}}{\theta_s^{im}}\right]$ (2)

where Γ_w is the mass transfer rate for water between the mobile and immobile regions, θ^m and θ^{im} are the mobile and immobile water content, respectively, θ_r^m and θ_r^{im} are the mobile and immobile residual water content, respectively, θ_s^m and θ_s^{im} are the mobile and immobile saturated water content, respectively, ω is a first-order rate coefficient (T^{-1}), and S_e^m and S_e^{im} are effective fluid saturations of the mobile and immobile regions, respectively.

Even if the second model provides a more realistic description of the exchange rate between the fracture and matrix regions (the difference in pressure heads is the actual driving force for mass transfer), the mass transfer term may be inherently more unstable numerically (Šimůnek et al., 2003).
For the equilibrium model, we used hydraulic parameters determined from a previous study (Morvannou, 2012) and for the dual-porosity model some hydraulic parameter values were adapted from Morvannou (2012) (θ_s^m, α_m, n_m, λ and θ_s^{im}) whereas others were arbitrarily fixed (θ_r^m, K_s, θ_r^{im} and ω) (Table 1).
The first aim of this study was to have a better insight into hydrodynamic and solute transport phenomena taking place inside a VFCW. In a first attempt we simulated the tracer application with only one pulse. Moreover, in order to evaluate if the observed multiple tracer peaks could be due to tracer kept in the sump or at the surface of the filter, we also tested a case with seven pulses of decreasing concentration. Modelling results from the equilibrium and non-equilibrium models were compared in terms of concentrations and cumulative fluxes computed at the outlet.

2.5. Calibration of the dual-porosity model

The second objective was to calibrate the dual-porosity model. In this part of the study, we divided the gravel-sludge layer in two layers in order to take into account the decreasing gradient of organic matter content versus depth and to compare the results with the water content measured by the TDR probes installed in the filter. The one-dimensional mesh, the top and bottom boundary conditions were the same as those used for the previous simulations. The setup of initial conditions necessitated a prior initialization step. We could not use measured water contents (TDR probes) 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 a batch simulation until pressure heads reach a pseudo-permanent state. We then selected the time for which water content profile matches the experimentally-measured initial water content. The corresponding water pressure profile was then considered as initial condition. Inlet tracer concentrations were adapted from the tracer concentrations measured at the outlet. Therefore, we applied four batches with decreasing tracer concentrations. Then, both the hydraulic parameters of the mobile and immobile regions (θ_r^m / θ_s^m and $\theta_r^{im} / \theta_s^{im}$) and the transfer coefficient (ω) were optimized to fit the tracer experimental breakthrough curve.

3. Results and discussion

3.1. Tracer experiment

Figure 2 presents the tracer concentration measured at the outlet of the VFCW and the cumulative percentage of the tracer recovery.

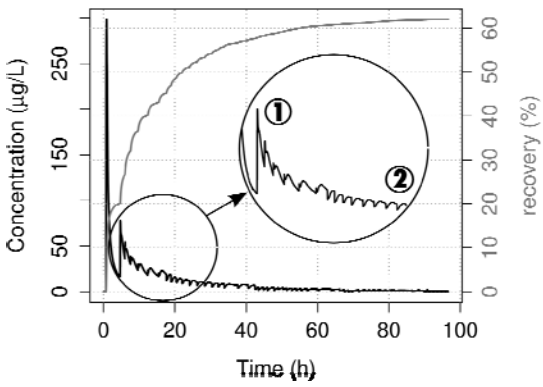

Figure 2. Tracer experimental breakthrough curve and cumulative tracer recovery percentage

The total tracer recovery is 62% and consequently reveals some fluorescein losses. They could be due to the ponding of water above the surface (photodegradation of the tracer), tracer retention on the organic matter (adsorption) and uncertainties of flow and concentration measurements.

Figure 2 highlights two main phenomena. (1) Not only one but several peaks are observed on the experimental breakthrough curve (Figure 2 (1)). Even if the tracer is mixed only once with the incoming wastewater, it seems like the tracer application was carried out in several times (remaining tracer in the sump and on filter surface). The tracer leaves the filter from the

first batch pointing out the presence of preferential flows in the filter. (2) The second phenomenon is a change of the breakthrough curve shape. After the seven first peaks, the tracer concentration decreases when a new batch arrives and then increases according with a logarithmic tendency towards an equilibrium value (Figure 2 (2)).

3.2. Modelling results

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

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

Equilibrium model						
Layer	θ_r [-]	θ_s [-]	α [1/cm]	n [-]	K_s [cm/s]	λ [-]
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									
Layer	θ_r^m [-]	θ_s^m [-]	α_m [1/cm]	n_m [-]	K_s [cm/s]	λ [-]	θ_r^{im} [-]	θ_s^{im} [-]	ω [1/s]
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

Figure 3 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.

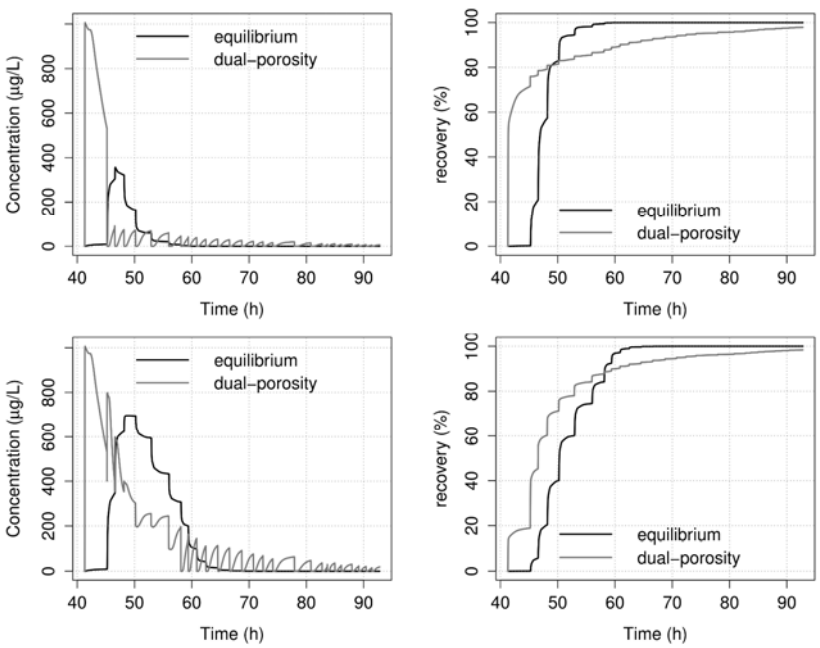

Figure 3. Simulated concentrations (left) and cumulative fluxes (right) for one pulse (top) or seven pulses (bottom) from the equilibrium and non-equilibrium models

When comparing the simulated tracer breakthrough curve obtained from the two models, we observe that the tracer leaves the filter faster with the dual-porosity model than with the equilibrium one. On the other end, we note that the equilibrium model is not able to reproduce the shape inversion observed with the experimental tracer breakthrough curve (Figure 2 (2)). 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.

Secondly, applying only one batch containing tracer does not allow simulating the multiple peaks of tracer observed in Figure 2. 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 cumulative tracer fluxes in the outlet of the filter we cannot see an important difference between the equilibrium and non-equilibrium results. Indeed, cumulative fluxes are not sensitive enough for comparing the modelling results whereas tracer concentrations provide information about non-equilibrium phenomenon which takes place in the filter.

The comparison between measured and simulated tracer breakthrough curves indicates that the non-equilibrium approach seem to be the most appropriate for simulating preferential flow paths.

3.3. Calibration results

Table 2 present the hydraulic parameter values for the dual-porosity model adapted from both the tracer concentrations obtained at the outlet of the filter and the water contents recorded in the VFCW.

Table 2. Parameter values used for the calibration of the dual-porosity model representing the VFCW behaviour in HYDRUS-1D

Layer	θ_r^m [-]	θ_s^m [-]	α_m [1/cm]	n_m [-]	K_s [cm/s]	λ [-]	θ_r^{im} [-]	θ_s^{im} [-]	ω [1/s]
1	0.00	0.01	0.12	1.80	5	0.50	0.70	0.83	0.040
2	0.00	0.02	0.50	3.20	25	0.50	0.38	0.39	0.005
3	0.00	0.05	0.50	3.20	25	0.50	0.34	0.36	0.005

Figure 4 presents the measured and simulated concentrations obtained from the tracer experiment and the dual-porosity model (with the parameter values presented in the Table 2), respectively. Figure 5 presents the measured and simulated water contents from the TDR probes and the dual-porosity model, respectively.

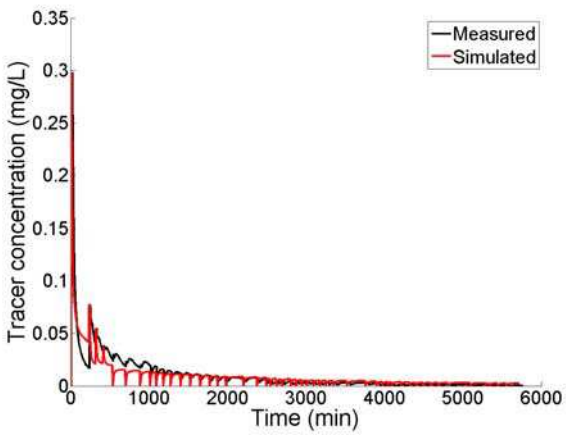

Figure 4. Measured (black line) and simulated (red line) concentrations from the tracer experiment and the dual-porosity model, respectively

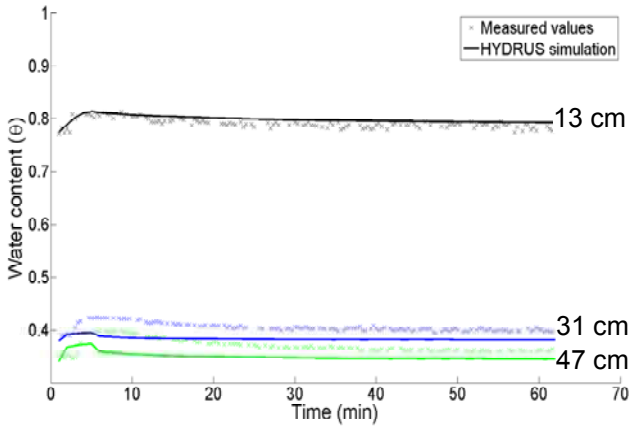

Figure 5. Measured (dots) and simulated (lines) water contents from the TDR probes and the dual-porosity model at different depths, respectively

After adapting hydraulic parameters, the simulation using the dual-porosity model (Figure 4) showed a good match with the measured data (RMSE = $1.47.10^{-5}$). We identified the four pulses corresponding to the four inlet concentrations at the beginning of the tracer experiment. After, these four batches, we observed the same tendency that we observed in the Figure 2 (2): the tracer concentration decreases right after the loading and then increases according with a logarithmic tendency towards an equilibrium value until a new batch.

First, we saw that the water retention and hence the water content decreases with depth, as organic matter content is lower deeper in the filter. Secondly, even if we only recorded water contents for the first tracer batch, Figure 5 showed that the simulation of water contents was good for the sludge layer (13 cm) where predicted water contents were close to observed water contents (RMSE = $9.1.10^{-3}$). The simulated water contents for the first (31 cm) and second (47 cm) gravel-sludge layers were moderately good (RMSE = 0.39, 0.43, respectively).

Therefore, the dual-porosity model is able to simulate both the tracer breakthrough and water contents at different depths of the VFCW.

4. Conclusions

A comparison was carried out between a classical equilibrium model and a non-equilibrium model (dual-porosity model) for simulating the hydrodynamic behaviour and the solute transport through a simplified representation of a French VFCW. The HYDRUS-1D software package was used for modelling flow and transport. Modelling results were compared to a solute breakthrough curve obtained from a tracer experiment carried out on an existing VFCW. This allows the determination of the most appropriate modelling approach.

The comparison between measured and simulated tracer breakthrough curves indicated that the tracer leaves the filter faster with the dual-porosity model than with the equilibrium one, which is consistent with the experimental tracer breakthrough. Moreover, the dual-porosity model provides the same shape inversion due to the tracer transfer into the immobile region

and its release after each batch. Moreover, in addition to simulate tracer breakthrough, the dual-porosity model succeeds to simulate the water content profiles at different depths of the filter. Therefore, the non-equilibrium approach seems to be the most appropriate for simulating preferential flow paths in a French-type VFCW.

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