Simplified modelling of the hydraulic behaviour of vertical flow constructed stormwater wetlands

Modélisation simplifiée du fonctionnement hydraulique des filtres plantés de roseaux pour le traitement des eaux pluviales

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RÉSUMÉ

Dans le but de répondre aux problématiques de l'assainissement des eaux pluviales, notamment en milieu urbain, l'Agence National de la Recherche (ANR) finance le programme SEGTEUP (Système Extensif de Gestion et de Traitement des Eaux Urbaines de temps de Pluie) comptant pas moins de 8 partenaires.
Ce papier présente le travail effectué sur la modélisation simplifiée des filtres plantés de roseaux dédiés au traitement des eaux pluviales. Ce travail a abouti à la création de 2 modèles simplifiés "SEGTEUP" permettant de représenter le comportement hydraulique. Des tests de sensibilité et de robustesse ont ensuite été effectués sur ces derniers pour en tirer les paramètres les plus influents et pouvoir également retenir les premiers critères de dimensionnement. Nous avons ensuite testé les modèles en comparant leurs résultats aux résultats des modélisations plus mécanistes à l'aide du logiciel Hydrus-1D. Les modèles ont déjà été confrontés de façon satisfaisante aux résultats expérimentaux. A l'issu de ce travail, des premières grandeurs de dimensionnement ont pu être proposées.

ABSTRACT

The SEGTEUP (extensive systems for the management and treatment of urban stormwater) programme, funded by the French national research agency (ANR), aims to address the challenges of urban stormwater management. This paper presents a simplified approach to modelling planted filters for stormwater. The project aimed to create two simplified models, able to represent the hydraulic behaviour of the filters. The model robustness and sensitivity were tested in order to determine the most important parameters and thus those which should be considered in system design. The model was then compared with the more mechanistic and complex Hydrus 1D model, building on previous work showing the models were able to satifactory represent experimental data. We provide initial recommendations for sizing of planted filters, based on the results of this model study.

MOTS CLÉS

Eaux urbaines, Filtres plantés de roseaux, Modélisation hydraulique, Robustesse, Sensibilité

1 INTRODUCTION

In France, as in many places throughout the world, stormwater treatment is a priority, with Vertical flow Constructed Wetlands (VFCW) receiving increasing interest as a suitable treatment technique (Uhl and Dittmer, 2005). The behavior of such systems is, however, quite variable, in particular due to variable inflow (both in quantity and quality), making modeling of such systems challenging. Numerous models have been developed to describe and predict the performance of these systems (Daly et al., 2009; She and Pang, 2010), including the HYDRUS 1D model (Simunek et al., 1998), which solves the Richard's Equation, taking into account soil moisture throughout the filter substrate and drainage layer. While sophisticated approaches like this are useful, the use of simplified models has the advantage of being able to be rapidly applied to long time-series, and thus used for developing design and sizing curves. The aim of this paper is thus to present two simplified models for VFCWs, capable of predicting the hydraulic performance of such systems based on their design parameters. We briefly describe these models and (i) assess the robustness and sensitivity of the models, and (ii) compare the model against the more sophisticated HYDRUS. The models developed have their origin in those presented by eWater (2009) and were tested against data collected by Hatt et al. (2009) from a full-scale biofiltration system (similar in nature to a VFCW) by Ross et al. (2011).

2 DESCRIPTION OF THE SIMPLIFIED MODELS

The models were created assuming conservation of mass. The VFCW were modelled as a series of storages, with barriers used to describe flow restrictions. Darcy's Law was used to describe flow through the saturated medium, while the Mualem-Van Genuchten relation described flow through a partially saturated medium. Evapotranspiration is taken into account and the model is iterative. We tested two models, previously described by Ross et al. (2011), and which derive from the models originally developed by eWater (2009) in the software MUSIC v4. We call these models SEGTEUP III and SEGTEUP IV, as described briefly below (the SEGTEUP IV model is shown (Figure 1), with simplifications in SEGTEUP III noted).

- Three storages: Surface Pond, Filter Layer, and Drainage Layer (SEGTEUP III is further simplified, with only Surface Pond and Drainage Layer)
- The flow between the two first storages is governed by Darcy's law and between the Filter and Drainage by the Mualem-Van Genuchten relation (in SEGTEUP III, flow from pond to drainage layer is governed by Darcy's Law)
- Capillarity is taken into account to account for transfer of water from the Drainage Layer to Filter Layer under non-saturated conditions in the Filter.
- Evapotranspiration is taken into account from the Drainage. It is calculated thanks to a monthly factor also due to the macrophytes (in SEGTEUP III, an annual constant is used).

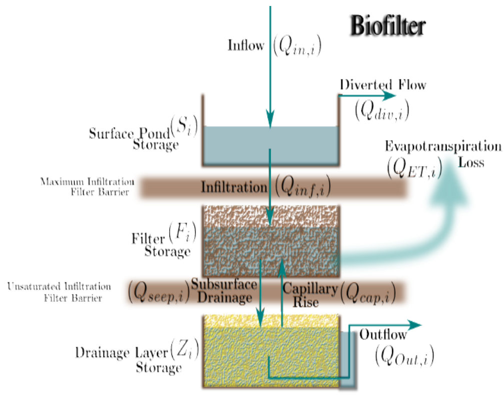

Figure 1: Conceptual representation of the model SEGTEUP IV

3 METHODOLOGY

3.1 Sensitivity and robustness

Our aim in this paper was to evaluate the hydraulic performance of these two previously developed models. We do so according to three criteria that describe the hydraulic and hydrologic behaviour of the system: (i) Percentage of inflow captured by the filter (ii) Outflow rate and (iii) Time ratio for which the Drainage Layer is dry. We tested the robustness and sensitivity of the model using the Sobol (1993) decomposition of functional variance approach, testing the three parameters which play the most important role in the model (Table 1)). The simulations were carried out using 1 year of real rainfall data from Yzeron (France), which has a connected impervious area of 3.3 ha. The bottom saturated layer depth of the system was assumed at 300 mm, as was the drainage layer depth.

Table 1: Parameters and their range (Area ratio = ratio of filter area to its active catchment area).

Parameter	Abbreviation	Range tested
Hydraulic conductivity	Kf (mm/h)	K_f =[5, 50, 100, 200, 500, 1000]
Depth of Filter Layer	Fmax (mm)	Fmax =[50, 100, 200, 400, 500, 800]
Area ratio	A (ad)	A =[0.5%, 1%, 2%, 3%, 4%, 5%]

3.2 Comparison with HYDRUS-1D

We compare both models with HYDRUS-1D in order to observe if our simplified models give the same results as a more sophisticated model. To undertake this comparison, we create a two-layer model in HYDRUS-1D (Fig. 2). The model is constructed a one-week event, with the three statistics described previously (Percentage of water captured; filter outflow rate and percentage of time drainage layer is dry). The comparison between the models is undertaken for the values given by each model and for the form of the temporal dynamic of each of the three statistics.

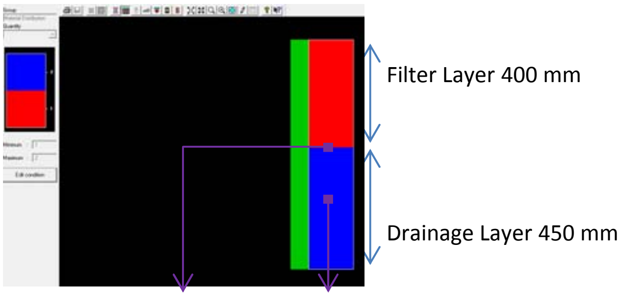

Figure 2: Representation of the VFCW in Hydrus-1D

4 RESULTS AND DISCUSSION

4.1 Sensitivity and robustness

Hydraulic conductivity is clearly the most important parameter influencing the captured flow and outflow rate (accounting for 69% of the variation; Figure 3). This is followed by the area ratio (accounting for up to 15% of the variation in model outputs), with Fmax having no significant influence. For the amount of time the Drainage Layer is dry, these results are less obvious, since the dry time percentage varies between only 0% (SEGTEUP IV) and 2.8% (SEGTEUP III). This confirms previous results that a saturated depth of around 300 mm suffices to protect the system from drying for periods of up to 5 weeks (for a system with filter Ks of 200 mm/hr and an area (A) of around 2% of the impervious catchment area (Zinger et al., 2007, 2012; Blecken et al., 2009).

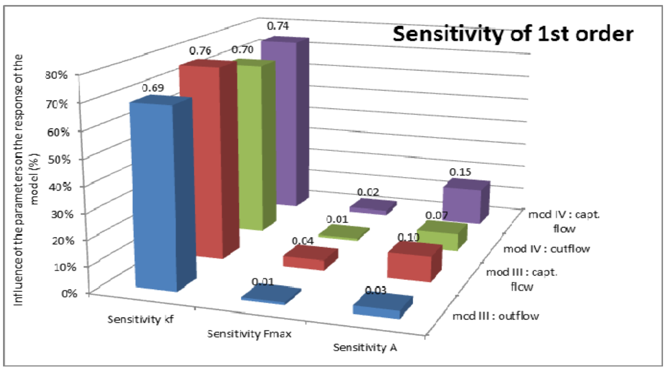

Figure 3: Sensitivity of SEGTEUP models to their parameters

The robustness assessment allowed us to define the suitable parameter ranges from these models. The results demonstrate that system performance is very sensitive to hydraulic conductivity values below 100 mm/hr, with decreases below this resulting in significant overflows. Similarly, reducing the area of the VFCW to less than 1% results in rapid decreases in performance. Correct specification of the filter hydraulic conductivity appears most critical, particularly because clogging over time may well result in the system conductivity reducing below this value.

4.2 Comparison with HYDRUS-1D

In general, we found that the model behaved very similarly to the HYDRUS-1D model for both ponding depth and outflow rate (Figure 4), suggesting that our simplified models are useful.

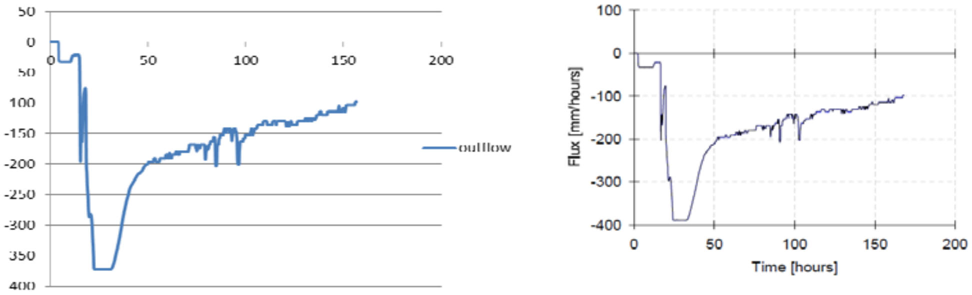

Figure 3: Outflow response. At left : SEGTEUP results; At right: Hydrus-1D results

5 CONCLUSIONS AND IMPLICATIONS FOR DESIGN

We demonstrate the potential for two simplified models to represent the dynamic behaviour of vertical flow constructed wetlands. The models, already demonstrated on real data, seem to be able to replicate the behaviour of the much more complex HYDRUD-1D model. The results of this study suggest that VFCWs in France should be constructed with filter media hydraulic conductivity of 100-500 mm/hr, with a ponding depth of 200-500 mm, and an area making up around 2% of the impervious catchment area. Future work is required to determine the range of values necessary for application in other climatic regions of France. In future work, we aim to integrate a variable time step into the model, and to account for clogging over time. In addition to this, we will use the model to develop design curves for VFCWs in France.

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