Orage: design-support model of vertical flow CSO-CWs

Orage : un outil d'aide au dimensionnement des filtres plantés à écoulement vertical pour le traitement des rejets urbains de temps de pluie

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RÉSUMÉ

Les filtres plantés à écoulement vertical pour le traitement des rejets urbains de temps de pluie sont variablement saturés et mettent en œuvre une limitation du débit de drainage. Ils peuvent être adaptés pour le traitement des surverses de déversoir d'orage ou des eaux pluviales strictes de manière à réduire l'impact des rejets en polluants et des débits de temps de pluie. Les débits et les concentrations reçus étant stochastiques, l'optimisation du dimensionnement nécessite une approche dynamique. Des modèles mécanistes étant difficiles d'utilisation, un modèle d'aide au dimensionnement, appelé Orage, a été développé. Il est basé sur une représentation simplifiée des processus et inclue une optimisation itérative et une interface. Il définit la taille optimale du filtre (surface profondeur) ainsi que le matériau le plus simple à mettre en œuvre, part un nombre limité de données et de débits. Le modèle simule l'hydraulique et les performances épuratoires en termes de DCO, MES et N-NH4. Il doit être fiable dans la détermination des niveaux de rejet. Sur la base de bilans masses, les premiers résultats montrent l'aptitude du modèle à simuler un évènement ou une série d'évènements. Une analyse de sensibilité a été réalisée montrant d'une part la robustesse du modèle et, d'autre part, les paramètres importants dans le calage du modèle.

ABSTRACT

In France, CSO-CWs are variably saturated vertical flow constructed wetlands with throttled outflow. These systems treat TSS, COD and NH_4-N and mitigate flow peaks. The received flows and concentrations are stochastic; as such, design optimization requires a dynamic approach. Process-based models would be difficult to handle and therefore, a new design support tool called Orage was developed. Orage is based on a simplified core model and has an iterative shell for optimization as well as a user interface. It interpolates the optimal dimensions and the simplest recommendable material site-specifically, using a low number of inputs and inflow data series. The core model simulates hydraulics and the removal of TSS, COD and NH_4-N and has to be reliable to base predictions on its output. First results with the core show a good fitting to a single load and a load series with closed material balance. The sensitivity analysis confirmed model robustness and warned that different parameters are important for a good performance in the case of the two operation modes.

KEYWORDS

Stormwater treatment, constructed wetland, design-support modelling, planted detentive filter, Orage, dynamic design

1 PLANTED DETENTIVE FILTERS AND THEIR MODELLING

The urban stream syndrome is a generalized ecological degradation of streams draining urban land (Walsh et al. 2005). Combined sewer overflow (CSO) is an important contributor with solids, organics, nutrients, heavy metals and bacteria as well as erosive peak flows. Constructed wetlands (CWs) offer a solution (e.g. Uhl and Dittmer 2005). Variable saturated vertical flow constructed wetlands with throttled outflow, referred here as CSO-CWs, are implemented in France. These target TSS, COD and NH_4-N and combine the results of Uhl and Dittmer (2005), Molle et al. (2005) and Fournel (2012) as 1) receive unsettled water to ease sludge management, 2) retain water at the bottom to mitigate drought effects, 3) have the aeration pipes in the process layer, 4) contain zeolite if enhanced ammonium removal is needed, 5) are covered with compost to facilitate reed development (Fig. 1).

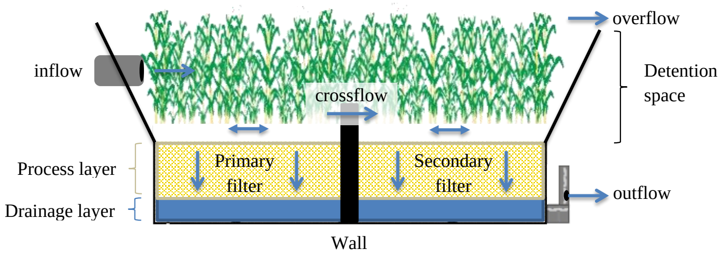

Figure 1: Schematic cross-section and flows in French CSO-CWs.

The loads arrive with stochastic periodicity, volume and quality. Ponding lasts for up to dozens of hours and is followed by periods up to dozens of days after all gravitational water is released. The pores get filled with air and might get dry in extreme cases. Dominant treatment processes in the intra-event state are filtration, adsorption and anaerobic degradation. Aerobic processes like nitrification of the adsorbed ammonia dominate the inter-event periods (Meyer 2011, Uhl and Dittmer 2005).

Design optimization requires a dynamic approach due to the stochasticity of flows. Process-based models are too complex for design (Meyer et al. 2015). On the other hand, RSF_Sim (Meyer and Dittmer 2015) is a design-oriented model which cannot be applied on a dual filter basin. Therefore, a new tool is developed called Orage. Orage optimizes scaling and filter material selection based on time series from sewer simulations or measurements. The core model is capable to simulate hydraulics and the removal of TSS, COD and NH_4-N in single- and dual-compartment filters. Several parameters are selected autonomously according to environmental factors like the climate region, the season or the length of the last inter-event period. Notably, single-compartment filters treat separate sewer outlet which has low concentration ranges of the modelled pollutants so optimization is expected to help hydraulic design only.

We introduce the structure and functionality of the core model of Orage. We demonstrate simulation results of the first CSO-CW at Marcy l'Etoile, France, with the objective to test the accuracy and the robustness and as such, to justify the integration with an optimization algorithm where many of the model parameters are fixed or selected from pre-defined tables.

2 THE CORE MODEL OF ORAGE AND EVALUATION METHODS

Hydraulics is represented by continuously stirred tank reactors (CSTRs) in series or in two parallel series as shown on Fig. 2.

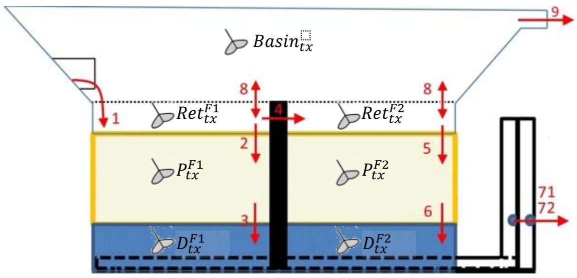

Figure 2: The seven CSTRs and flows in the core model of Orage. The tanks indexed by *F2* might have zero volume thus zero flows for single-sided filters..

The drainage layer (D_{tx}^{F1} and D_{tx}^{F2}) has a constant volume (saturated) but concentrations may vary. The process layer (P_{tx}^{F1} and P_{tx}^{F2}) holds volumes between the residual water and saturation. Removal processes are modelled here. The detention space is discretized into three tanks, Ret_{tx}^{F1}, Ret_{tx}^{F2} and $Basin_{tx}$.

COD and *TSS* concentrations are decreased when water leaves the process layer (flows 3 and 6), based on the same empirical equations. For *TSS*, these give a constant background value (Fournel 2012). In contrast, a true correlation was observed for COD and a three-stage approach is used as shown on Fig. 3 (left). Orage selects a curve from an internal table considering the number of days since the previous load as suggested by Meyer and Dittmer (2015) but also the season and the climate region. Hot days were assumed to lead quicker to a drop in the removal of dissolved COD.

NH4N removal is a two-step process and is based on Meyer and Dittmer (2015). First, adsorption is taking place during the intra-event period and second, the stored *NH4N* is subject to nitrification during the inter-event. The adsorption capacity of the filter material is described by a broken stick isotherm (Fig. 3, right). Instantaneous equilibrium is assumed between the liquid and solid phases. Adsorbed *NH4N* is nitrified in the inter-event period. The rate is dependent on the solid phase concentration and the temperature. Parameters will be calibrated to match field measurements.

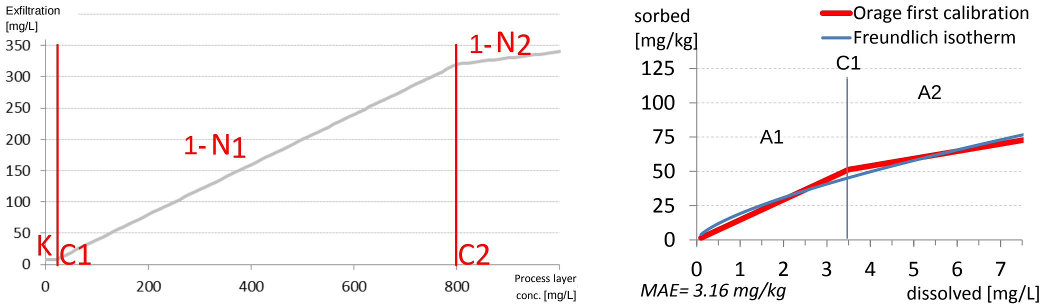

Figure 3: *COD* removal at exfiltration from the process layer (left, *K*: background conc., *N1*, *N2*: removal efficiency, *C1*, *C2*: thresholds) and *NH4N* adsorption isotherm (right, *A1*, *A2*: slopes of the isotherm; *C1*: threshold).

Stormwater contacts only a fraction of the filter media at commencing load (Fig. 4), which might last if the inflow rate is low. Calculations differ if the water level is below a constant called the shortcutting threshold water level *h_e*. This value is determined based on field measurements and process-based modelling. The area of infiltration is the function of the volume (2 and 5) using Darcy's law, and from the area the contact mass can be estimated.

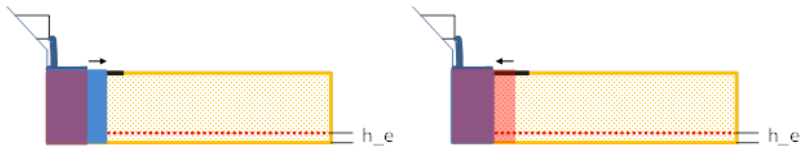

Figure 4: Shortcutting effect at commencing load. The contacted mass of media is re-calculated at each time step.

The first calibration of the model was done to a single event at a full-scale CSO-CW at Marcy l'Etoile, France. The load was extreme in terms of volumes and duration; furthermore, the extreme NH_4-N load (156 g/m^2) had caused breakthrough. After the model was fitted, the parameters were used to simulate a series of loads which consisted of four consecutive events. The single event was added after them to see if the preceding loads cause changes in the model predictions. Results were evaluated visually and statistically. The Morris method (Morris 1991) was used to test model sensitivity. It is a one factor at a time (OAT) screening technique and was applied with the improvements of Campolongo et al. (2007).

3 RESULTS AND OUTLOOK

The simulated single event fitted well measured hydraulics and outflow concentrations (Fig. 5). Using the same parameters for the event series gave good and intermediate fit for *COD* and *NH4N*, respectively. Statistical results are summarized by Tab. 1. The most critical of these values is the 6/24h Peak_MA_cc, a moving average of effluent concentrations returned for the iterative shell. It was underestimated by 26.9% for COD. This was caused by 1) the input concentrations for first and fourth event were from the settled detention space, and 2) the dry period before the first event was one month long but the impact was ignored. Omitting this event would have decreased the error to -9.5%.

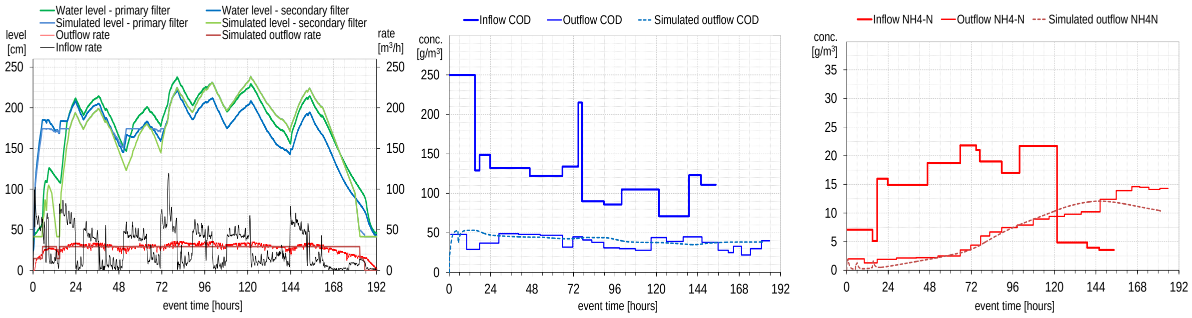

Figure 5: Calibration results for the single event. Hydraulics: left, *COD*: middle, *NH4N*: right.

For *NH4N*, the time weighted EMC of the effluent had a MAE of 33.5%. The effluent was at the low concentration range compared to the proposed 10 mg/L threshold so this error expressed in terms of concentrations is 1.4 mg/L which could be targeted by increasing background concentrations.

Table 1: Statistical evaluation of the simulation results of the event series compared to measured values

	COD:	***NH4N:***		***COD:***	***NH4N:***
Difference of mass removal performance:			**Error of nitrified mass**:		
± [%]:	*-0.4*	*4.8*	[%]:	*n/a*	*+15.8*
MAE [%]:	*10.6*	*9.6*			
Time weighted EMC of the effluent:			**Time shift to measured breakthrough (E14 only):**		
MAE [mg/L]:	*6.9*	*1.4*	[hours]:	*n/a*	*-0.1*
MAE [%]:	*8.8*	***33.5***			
Error of simulated 6/24h Peak_MA_cc:			**Goodness of fit (Ahnert et al. 2007):**		
[mg/L]:	*-18.9*	*-1.7*	E_j [-]:	*-0.64*	*-0.75*
± [%]:	***-26.9***	*-12.2*	$\overline{DEV}$ [mg/L]:	*8.4*	*1.5*

The sensitivity analysis identified the *COD* performance parameters *C2*, *N1* and *N2* (refer to Fig. 3) as the most influential. For *NH4N*, the analysis is to be repeated with different input ranges for the filter area to have results for shortcutting and normal operation separately. The results justify fixing a large number of model parameters and allow identifying those which are key to have a reliable prediction on the optimal filter area and the simplest material which is still satisfying in terms of *NH4-N* removal. Model calibration will improve with wider availability of monitoring data from CSO flows and -CW sites.

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