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Model-based optimization of constructed wetlands treating combined sewer overflow

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ABSTRACT

The model-based Orage toolkit facilitates the design of constructed wetlands treating combined sewer overflow (CSO-CWs). It deals with the stochasticity of overflows and optimizes filter area and material site-specifically. Its automatic optimization approach, which is based on measured or simulated CSO series and simple input parameters, is a novelty. In the process, the iterative shell calls a single-output model repetitively, comparing effluent concentrations from different filter setups to legislative thresholds. The approach was confirmed with measured and simulated inflows. Parameters were fixed so that extremely small and large filters are avoided (decreases clogging risk and short-circuiting, respectively), and pollutant removal is optimized on a tighter range of filter areas. The iterative shell was verified using inflow data and area of a full-scale CSO-CW, with effluent thresholds between 4–10 mg/L NH_4-N. Zeolite-enriched media ensures NH_4-N removal at high hydraulic loads (possibly up to 250 m^3/m^2/year) where clogging is a possible risk.

1. Introduction

1.1. Constructed wetlands treating combined sewer overflow

1.1.1. Benefits

The urban stream syndrome is a generalized degradation of streams draining urban land compared to their natural state (Chocat et al., 1994; Walsh et al., 2005). These waters, which are ecosystems and natural resources, are negatively impacted by combined sewer overflows (CSOs). Storm events trigger high flow rates of stormwater mixed with sewage in the combined sewer networks. If this rate exceeds the intake capacity of the wastewater treatment plant, or what the pipe network can accommodate, the unwanted flow peak is discharged at CSO points (Meyer et al., 2013). These discharges are carrying organic, nutrient, heavy metal and bacteria pollution. In contrast, separate sewer outlet (SSO) is released end-of-pipe and has lower concentrations, but suspended solids, specific organic pollutants and heavy metals are still a concern. Both CSOs and SSOs[1] might cause flow peaks which erode and/or silt up stream habitat and change morphology.

Constructed wetlands for CSO treatment (CSO CWs) offer a solution to mitigate the impact of overflows. The term CSO CW is used here to refer to the state-of-the-art in France which is a vertical downflow arrangement. It was developed based on the retention soil filters in Germany (RSFs, *Retentionbodenfiltern*; Uhl and Dittmer, 2005; Dittmer et al., 2016), the "French" constructed wetlands for domestic wastewater treatment (Molle et al., 2005) and pilot scale research (Fournel, 2012).

1.1.2. Specific features of CSO CWs

The feeding significantly differs from CWs treating domestic wastewater because CSOs are stochastic in terms of volume, qual-

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Abbreviations: TSS, total suspended solids (water quality constituent); NH_4-N, ammonium nitrogen (water quality constituent); COD, chemical oxygen demand (water quality constituent); CSO, combined sewer overflow; SSO, separate sewer outlet; CW, constructed wetland; PE, population equivalent; *A_min*, lower end of the optimization range of candidate areas [m^2]; *A_max*, higher end of the optimization range of candidate areas [m^2]; *Peak_MA_cc*, measure of filter performance, [mg/L]. See also subchapter 2.1.4.1; *shortcut_limit*, maximum allowed ratio of short-circuiting time to total outflow time [%]; *h_max*, maximum ponding depth over the virtual area of the filter [m]; *V_design*, highest event volume which the wetland must treat effectively [m^3].

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[1] This paper and the modelling tool Orage focuses on CSO-CWs but SSO is touched as well as Orage comes with a hydraulic optimization (scaling) support for SSO wetlands.

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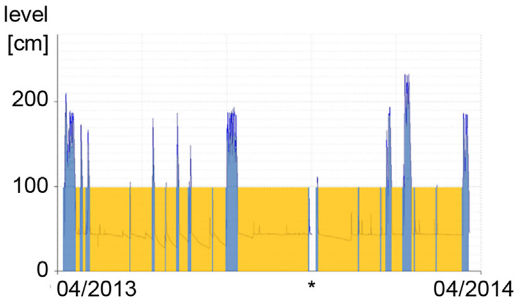

Fig. 1. Water levels over one year in the full-scale CSO CW at Marcy-L'Étoile (blue series). The ochre rectangle represents the porous media; water levels above it indicate ponding. Filter operation can be characterized by the stochastic alternation of intra-event (loaded; blue) and inter-event (unloaded, ochre) periods. The storage basin above the media is left uncoloured on this chart when unloaded just as the data gap (marked by *).

ity and return periods (Fig. 1). A detention basin over the filter is essential because feedings are flood-like. The basin is empty at the beginning of the events therefore Infiltration and subsequent percolation is limited to the inlet zone. This operational state is considered as short-circuiting and a drop of NH_4-N removal performances were reported (Pálfy et al., 2016a). However, pores saturate rapidly and ponding occurs, which is considered the normal operational state. The whole filter is water contacted and percolation is close to plug-flow (intra-event state). Performances are maximal. Low flow velocities are ensured by the mechanical outflow limitation (orifice) on the outlet structure.

Draining the detained water might take several hours. Once it is done, the pores get filled with air for several days (inter-event state), but stay wet, which favours the metabolism of aerobic bacteria. Dominant removal processes differ in the anaerobic intra-event and aerobic inter-event state. The system might be negatively impacted by long droughts due to stress on living organisms (Dittmer et al., 2005; Uhl and Dittmer, 2005; Dittmer and Schmitt 2011; Meyer 2011; Dittmer et al., 2016).

1.2. Design optimization and modelling of CSO CWs

Storms generate stochastic load events with different flow rates, volumes and concentrations. Events are alternated by inter-event periods with different length and temperature. The stochasticity and site-specificity needs a dynamic approach for design optimization, which demand can be met by numerical models (Meyer et al., 2015).

Pálfy et al. (2016b) enumerated existing models. Although HYDRUS/CW2D (Langergraber and Šimůnek, 2005) had been calibrated for column-scale CSO CWs (Pálfy et al., 2015), for engineering purposes, such as design, a less complex tool is required (Meyer et al., 2015). On the other hand, the simpler and design-oriented model, RSF_Sim (Meyer and Dittmer, 2015) simulates German retention soil filters (RSFs) accurately even at full-scale. This tool is incompatible with French standards due to the differences in technical implementation discussed in Meyer et al. (2013). HYDRUS/CW2D and RSF_Sim would demand the manual iteration of different designs, leaving room for a simple and automated toolkit.

For these reasons, a new design-support tool – Orage – has been developed. This tool targets engineers and offers automatic functions for design-optimization of CSO CWs, which is a novelty in the field. The core model (Pálfy et al., 2016b) has been inspired by RSF_Sim but is capable to simulate both single- and twin-bed (standards for SSOs and CSOs in France, respectively) filters and to account for performance decrease at starting loads (short-circuiting). Modelled pollutants are TSS, COD and NH_4-N. Although Orage was created for CSO CWs, it can help to scale filters treating SSO. This function is limited to a hydraulic optimization in practice, because concentrations of NH_4-N and COD in SSO are low anyway and TSS is filtered out with high efficiency regardless inflow concentrations.

The core model works with long inflow datasets (a couple of years). Certain parameters are selected automatically during the simulations to represent the impact of uncontrolled environmental factors on filter performance. These parameters are 1) seasonal temperature according to the regional climate and 2) the length of the last inter-event period. Furthermore, the core has been integrated into an automatic optimization algorithm (iterative shell) and a toolkit frame (user interface) to enhance practicability. After lunching the optimization, the iterative shell calls the core model repetitively and optimizes the filter area and material.

The software offers a second, decision-support function. The "applicability test" can be used if inflow series are unavailable. The user will rely on one of the 45 internal inflow series (5 climate regions and 9 surface imperviousness categories), which are scaled linearly to the entered catchment area (base: 50 ha) and the PE value (base: 2000 PE). This function reports only if a CSO CW is advisable or not.

In this paper, we 1) describe the iterative shell of Orage and use the tool with inflow data from the existing full-scale CSO CW of Marcy-L'Etoile; 2) analyse effluent NH_4-N concentrations in the function of the filter area and the hydraulics; and 3) fix key parameters of the iterative shell to keep future designs hydraulically fit.

2. Methods

2.1. Automatized optimization by the iterative shell

2.1.1. General outline

Orage is based on a single-output core model (Pálfy et al., 2016b) which simulates hydraulics (two tanks-in series in parallel) and pollutant removal (NH_4-N, COD and TSS). The core model is called repetitively by an optimization algorithm called the iterative shell. The target is a hydraulically sound design with the simplest material and smallest area (in order of priority). Limits on outflow rate and concentrations can be freely set for each project. The program performs optimization on hydraulics, NH_4-N and COD removal (in order of execution). For the French standards of constructed wetlands treating combined sewer overflow, the reader is advised to refer on cross-section figures in Pálfy et al. (2016a) or Meyer et al. (2013).

2.1.2. Hydraulics

The optimization of hydraulics precedes the optimization of pollutant removal. Its goal is to ensure the efficiency of the latter, by determining the range of filter areas [A_min; A_max] which will be tested for pollutant removal. The hydraulic optimization is based on 1) the necessary storage volume (user input); 2) the allowed maximum of outflow rate (user input) and 3) the short-circuiting duration, which correlate with filter area (calculated by the tool). The water authority provides data site-specifically which is entered to point 1) and 2), whilst 3) is limited by an internal parameter as discussed later.

In the case of the maximum area (A_max), user inputs set an initial limitation before optimization. These inputs are 1) the land area available for the filter and 2) the allowed maximum of outflow rate (because the release rate is linearly proportional to the area (Eq. (1)):

$$A\_max = \min\left(A\_land; F\_out\_max/F\_limit\_base\right) \qquad (1)$$

where A_max is the maximum filter area, A_land is the available land for the filter [m^2] (user input), F_out_max is the maximum