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Filling hydraulics and nitrogen dynamics in constructed wetlands treating combined sewer overflows

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ABSTRACT

According to French standards, constructed wetlands for combined sewer overflow treatment (CSO CWs) are vertical flow filters with detention basin and outflow rate limitation. Their purpose is to treat rapid loads of wastewater with stochastic volumes, concentrations and periodicity. The first full-scale CSO CW has been monitored for three years, involving online equipment. This provided in-depth understanding of hydraulics and nitrogen dynamics. The saturation of the filter was visualized along a longitudinal section to follow hydraulics at filling. Tracer tests showed that short-circuiting effects, which are adverse, weaken during the process. This was confirmed by the decreasing NH_4-N concentrations in the outflow. As such, short-circuiting can be addressed by minimizing filling time. As for nitrogen dynamics, NH_4-N adsorption capacities were identical for the applied sand-zeolite mixture and pozzolana materials. To calculate inter-event nitrification of adsorbed masses, an equation was fitted to temperature and mass measurements. The rate doubled with every 5.7 °C. Finally, nitrate was found to get washed out by low hydraulic loads (median: 0.95 m^3/m^2), highlighting the possibility of developing a second filter stage for denitrification. The results helped to calibrate the design-support software Orage.

1. Introduction

1.1. CSO treatment with vertical flow systems

Constructed wetlands for combined sewer overflow treatment (CSO CWs) are vertical flow filters with detention basin and fixed outflow rate. Because feedings are triggered by intense precipitation events, loads are stochastic in terms of volumes, concentrations and return periods. Water arrives if sewer flows exceed what the wastewater treatment plant or the pipe itself can accommodate (Meyer et al., 2013). Treating this water instead of direct rejection protects natural waters against pollutants and disadvantageous changes of streambed morphology. As such, CSO CWs mitigate the so-called urban stream syndrome, which is the generalized degradation of stream habitats draining urban land (Chocat et al., 1994; Walsh et al., 2005).

The pattern of hydraulic operation differs from CWs treating sewage. As outlet flow limitation is lower than infiltration capacity, loads saturate the porous media from the bottom at first and then cause ponding in the detention basin above it. The ponding might reach significant depth at voluminous events (intra-event state). The infiltration and subsequent treatment of the detained water may take several hours, governed by the small-diameter orifice that limits outflow. The coarse filter material helps to avoid clogging and outflow limitation avoids hasty passage and short biofilm contact. When ponding is over, air penetrates the pores again. The filter layer gets gravity-drained and rests unloaded for several days (inter-event state). Then, aerobic processes dominate. Filter design should seek a way to avoid drought stress on wetland biota as beds might dry out in extremely long and warm inter-events. The regeneration in the unloaded period enables to treat the next load rapidly and efficiently.

CSO CWs target to remove water quality constituents TSS, COD and NH_4-N. The treatment starts with sedimentation and physical filtration by the top few centimetres of the filter media (Dittmer, 2006). The dominant treatment processes are filtration of organic and inorganic solids, anaerobic bacterial uptake of dissolved COD, and NH_4-N adsorption. In contrast, the still wet but air-filled media favours nitrification and the mineralization of organics in the inter-

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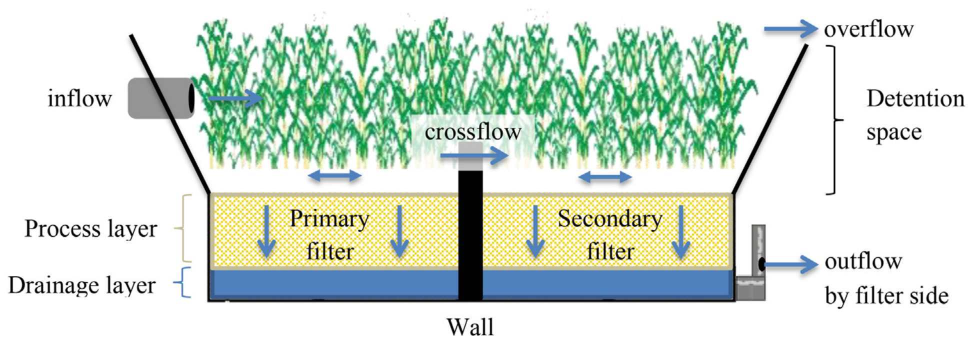

Fig. 1. CSO CWs in France have twin filter sides and permanently saturated drainage layer. The system is lined from its environment and the wall between the two sides is impervious, except of a cross-connection pipe ensuring crossflow.

Table 1
General characteristics of the CSO CW at Marcy-L'Etoile.

Parameter	Unit	Value
Catchment area	[ha]	98
Detention capacity	[m^3]	1160
Nominal hydraulic load	[m/year]	50
Filter surface	[m^2]	500
Target outflow rate	[l/s/m^2]	0.016
Population equivalent	p.e.	9200

event period (Dittmer et al., 2005, 2016; Uhl and Dittmer, 2005; Dittmer and Schmitt, 2011; Meyer, 2011).

1.2. The standard of CSO CWs in France

CSO treatment will be mandatory in France in accordance with goals set in the European Water Framework Directive (2000/60/EC). Vertical downflow arrangements (Fonder and Headley, 2013) were applied or desired in European countries as stand-alone stage or as an element of a treatment chain (Meyer et al., 2013). The first positive experiences came from the retention soil filters (RSFs or Retentionsbodenfiltern) in Germany (Uhl and Dittmer, 2005; Dittmer, 2006). We refer with the term CSO CW to the French state of the art (Fig. 1) unless otherwise specified.

Standards in France were based on experiences from Germany (Uhl and Dittmer, 2005; Frechen et al., 2006; Dittmer and Schmitt, 2011), from pilot-scale studies on a range of filter materials and filter depths (Fournel, 2012) and on "French-design" CWs which treat unsettled municipal wastewater (Molle et al., 2005). The traits of CSO CWs are:

i) Treating unsettled water facilitates sludge management. To protect the system against early clogging, feeding priority is alternated between the twin filter sides. The secondary side receives settled water from the primary side and at large events only. As such, longer inter-events and low solid loads favour sludge mineralization on the secondary side.
ii) the permanently saturated drainage layer on the bottom saves water for living organisms to any drought;
iii) aeration pipes are laid above the drainage layer. Placing them in the process layer is assumed to improve aeration;
iv) zeolite is added to the filter media if higher ammonium-removal is needed;
v) a thin compost cover facilitates reed establishment.

The first full-scale CSO CW site was built at Marcy-L'Etoile (France). Table 1 summarizes the general characteristics of the wetland. The combined sewer drains mostly residential area and the wetland was designed to accommodate flow volumes with one year return period. As an industrial release is present in the sewer, a weir

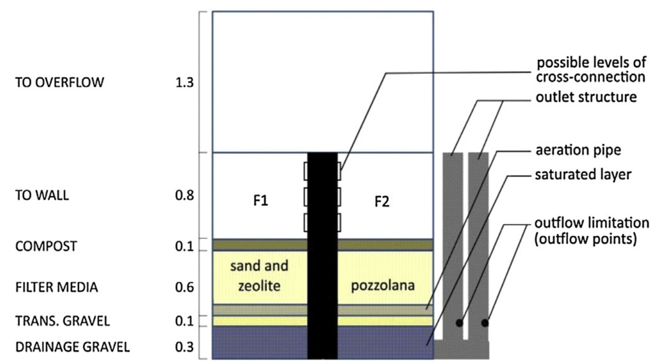

Fig. 2. Cross-section and internal structure of the CSO CW at Marcy-L'Etoile, France.

has been installed at the overflow point. The regular adjustment of this weir enabled to mimic the stochasticity of feedings without rain. Concentration ranges were comparable to unsettled CSO (Sztruhár et al., 2002; Fournel, 2012), with NH4-N concentrations at the upper end of the range (median EMC: 13.8 mg/L).

The filter layers are shown on Fig. 2. One filter side was filled with a mixture of 48 cm sand and 12 cm zeolite (4:1) whilst the other with pozzolana. The filter had about three years of startup operation before the nitrogen dynamic assessments.

The objective of this work is (1) to give insight into the functioning of CSO CWs, in terms of hydraulics at the early phase of the loads, and also into nitrogen dynamics, in terms of the fate of NH_4-N; and (2) to quantify related processes at full scale, in a way that results can contribute to the development and calibration of a model-based design-optimization software, Orage (Pálfy et al., 2016).

2. Materials and methods

2.1. Monitoring of flows and concentrations

Flow measurements and sampling were automatic. Inflow rates were registered based on an ultrasonic probe over a Venturi channel. At the outlet structure, the orifice allowed to use pressure probes and a calibrated correlation between the outflow rate and the pressure head.

Flow composite samples were taken at the inlet. The outlet was sampled time composite as orifice flows were stable. At least ten samples were collected in each bottle, so one composite represented a mean volume of 326 m^3 and 60 m^3 at the inlet and at the outlet, respectively. The reason for taking samples more frequently at the outlet was to catch any rapid change in the effluent concentrations for further analysis regarding system behaviour. The water was then analysed for TSS, total and filtered COD, NH_4-N,