Environmental Modelling & Software 102 (2018) 49–72

Contents lists available at ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft

A single-output model for the dynamic design of constructed wetlands treating combined sewer overflow☆

T.G. Pálfy [a, b, c, *], D. Meyer [a, b], S. Troesch [b], R. Gourdon [c], L. Olivier [a], P. Molle [a]

[a] IRSTEA Lyon, Freshwater Systems, Ecology and Pollution Unit, 5 rue de la Doua, CS70077, 69626 Villeurbanne Cedex, France
[b] Epur Nature SAS, 153 av. Marechal Leclerc, 84510 Caumont sur Durance, France
[c] University of Lyon, INSA Lyon, DEEP Laboratory, 20 av. A. Einstein, 69621 Villeurbanne Cedex, France

A R T I C L E I N F O

Article history:
Received 23 September 2016
Received in revised form
24 July 2017
Accepted 26 December 2017

Keywords:
Combined sewer overflow
Constructed wetland
Design-support modelling
Dynamic design
Stormwater treatment
Orage

A B S T R A C T

Constructed wetlands treating combined sewer overflow (CSO CWs) are vertical flow filters in France, with outflow limitation and detention basin. Treating storm-generated flows reduces pollutants and flow peaks entering natural waters. Storm-generated flows are stochastic and therefore optimized CSO CW design requires a dynamic approach, i.e., a modelling software targeting engineers. Therefore a new tool, called Orage, was developed. Orage consists of a core model, an iterative shell and a user interface. It optimizes dimensions and materials of CSO CWs site-specifically, based on inflow series and a low number of input parameters. The core model simulates hydraulics and TSS, COD and NH_4-N removal. Manual fitting of the core showed good results with a single load. The same parameters gave satisfying accuracy when simulating load series with closed material balance. Sensitivity analysis confirmed model robustness and justified coupling with an automatic shell algorithm for automatic optimization, based on a single output.

Software availability

Name of software: Orage alpha 0.6
Developer: IRSTEA and MEGAO Informatique, France
Contact: Remy Arnaud (remi.arnaud@megao.com)
Availability: freeware, version 1.0 available online at epnac.irstea.fr from 2018

1. Introduction

1.1. CSO CWs and stormwater treatment

Urbanization impacts negatively the hydrology, physical-chemical properties and biota of surface- and groundwater. Preventive measures are often absent and as a consequence, waters suffer the effects of untreated urban runoffs. These are rejected with combined sewer overflows (CSO) or as separate sewer outlet (SSO). Urban stream syndrome is the generalized ecological degradation of streams draining urban land (Chocat et al., 1994; Walsh et al., 2005).

Combined sewers accommodate high flows of stormwater mixed with domestic sewage. Overflow mechanisms prevent overfilling of pipes and limit downpipe flow rates to the capacity of the wastewater treatment plant. Unwanted peaks discharge as CSO carry significant amount of organics, nutrients, heavy metals and bacteria. In contrast, SSO is released end-of-pipe and carry less organic matter and nutrient, but suspended solids, specific organic pollutants and heavy metals are a concern. Both CSO and SSO erode and/or silt up stream habitat and change streambed morphology (Meyer et al., 2013).

Constructed wetlands (CWs) for CSO treatment (CSO CWs) are implemented or are planned to be in several countries. In Europe, vertical downflow (VF) arrangements are promising (e.g. Meyer et al., 2013) after positive experiences with retention soil filters (RSFs, Dittmer et al., 2016; Uhl and Dittmer, 2005) in Germany. The European Water Framework Directive (2000/60/EC) calls for the good quality of natural waters and the limitation and/or treatment

Abbreviations: TSS, total suspended solids; NH_4-N, ammonium-nitrogen; COD, chemical oxygen demand.

☆ For a clearer understanding, model parameters, variables and components are written in *italic* fonts.

* Corresponding author. IRSTEA Lyon, Freshwater Systems, Ecology and Pollution Unit, 5 rue de la Doua, CS70077, 69626 Villeurbanne Cedex, France.

E-mail addresses: tamas-gabor.palfy@irstea.fr (T.G. Pálfy), meyer13@t-online.de (D. Meyer), stephane.troesch@epurnature.fr (S. Troesch), remy.gourdon@insa-lyon.fr (R. Gourdon), laurie.olivier@irstea.fr (L. Olivier), pascal.molle@irstea.fr (P. Molle).

https://doi.org/10.1016/j.envsoft.2017.12.023
1364-8152/

of CSO is needed to reach its goals. Different types of CWs exist (Fonder and Headley, 2013), but the solution in France for CSO treatment is a specific vertical downflow arrangement with outflow rate limitation. In this paper, CSO CW refers to this new state of the art, unless otherwise specified.

In France, stormwater is collected in about 25% of the lines by combined sewers (SoeS, 2011) and treatment of overflows started recently. The key specificity of CSO CWs is that in contrast to CWs treating domestic wastewater, inflows have stochastic periodicity, volume and quality. Furthermore, these systems have a detention basin above the filter material. Loadings saturate the porous media and cause ponding (intra-event state). Several hours might pass until the detained water is filtered, leaving through an orifice to limit outflow rate. After this, the pores get filled again with air, for several days (inter-event state), and might even dry out in extreme cases. Some treatment processes can be attributed by their dominant occurrence to the intra-event, others to the inter-event environment. Filtration, adsorption and anaerobic biodegradation take place during intra-event while aerobic bioprocesses, predominantly the nitrification of adsorbed ammonia and organic matter biodegradation dominate the inter-event phase (Dittmer et al. 2005, 2016; Dittmer and Schmitt, 2011; Meyer, 2011; Dittmer et al., 2005; Uhl and Dittmer, 2005).

1.2. Design-support modelling of CSO CWs

Due to the stochastic nature of storm-generated flows and the related existence of intra- and inter-event phases, design optimization needs a dynamic approach. This can be achieved through modelling. Numerical modelling of wetlands treating combined sewer overflows is a new direction of constructed wetland research and the range of publications dealing with the topic is therefore relatively limited.

Some existing models have a wider application domain but match the complexity of the task. Such is the process-based HYDRUS/CW2D (Langergraber and Šimůnek, 2005), validated for laboratory CSO CW columns recently. The works of Pálfy et al. (2015a), Meyer (2011), Henrichs et al. (2009, 2007) has progressively extended the scope of the software's “non-regular” application for CSO CWs, but has also pushed it to its limits.

Modelling tools with system-optimization purpose exist as well. These strive to be practical in terms of handling (see e.g. Meyer et al., 2015), targeting practitioners in order to facilitate the design of stormwater treatment systems. For watershed scale, a module of SUSTAIN (Lee et al., 2012) provides a generalized scheme of process-based simulation of flow and pollutant transport for a handful of structural best management practices (BMP). However, simulating CSO CW technology requires the representation of adsorption processes and an outflow rate limitation that governs system hydraulics.

Specifically for single-basin CSO CWs that pioneer in Germany (Retention Soil Filters or RSFs), RSF_Sim is a design-oriented model. It has a well-described development track (Meyer and Dittmer, 2015; Meyer, 2011; Schmitt and Dittmer, 2007; Dittmer, 2006). It simulates full-scale, variably saturated vertical flow constructed wetlands with good accuracy (Meyer and Dittmer, 2015; Tondera et al., 2013). But French systems have specificities in their technical implementation (Meyer et al., 2013).

In light of new knowledge and developments such as the appearance of dual-sided filters (in France and also in Germany), new models of CSO CWs need to satisfy four additional needs, namely to (1) be capable to simulate two-sided filters; (2) include processes that describe the behaviour of overscaled filters and predict their weak performance so that such constructions can be avoided in the future; (3) select certain removal parameters automatically, depending from climatic factors that can impact those; and (4) provide discrete output which is easy to compare with legislative thresholds on emission concentrations. Such model could serve automatic CSO CW optimization, which is a necessity due to (1) the stochastic nature of combined sewer overflows, (2) the limited land availability in urban areas and (3) the expectable costs of treatment at the high number of overflow points, to be implemented in light of the Water Framework Directive and related national legislations.

For these reasons, we have developed Orage, an engineering tool that proposes CSO CW dimensions and material based on multi-year series of combined sewer overflows and pollutant concentrations. It consists of a core model and an autonomous optimization algorithm it is integrated into. We present the core model in this paper. To know more about the optimization algorithm, the reader is advised to refer to Pálfy et al. (2017a).

The core model simulates hydraulics and total suspended solid (TSS), chemical oxygen demand (COD) and ammonium-nitrogen (NH_4-N) removal. It selects several parameters autonomously, according to environmental factors such as regional climate, season or the length of the last inter-event period. Apart of two-sided CSO CWs, the core can simulate single-basin wetlands. As these treat stormwater in France, we focus in this paper on two-sided CSO CW applications.

One of the two key objectives of our paper is to show that the new needs listed above can be addressed efficiently by a model that has simple process descriptions, and with good accuracy in terms of predicted effluent quality. To reach this objective, we introduce the functionality and the structure of the core model of Orage, and demonstrate its ability to simulate the operation of a real CSO CW built at Marcy l'Etoile (France) that has been monitored continuously. Secondly, we define the core model's parameter sensitivity to show how it can be integrated into an automatic optimization algorithm as it requires many parameters to be fixed or selected from pre-defined tables. This also sheds light on how the simplification of model output series into a single value could benefit a practice which works to satisfy discrete emission thresholds.

2. Materials and methods

2.1. The concept of CSO CWs in France

The current state of the art in France (Fig. 1) is inspired 1) by experiences from Germany (Dittmer and Schmitt, 2011; Frechen et al., 2006; Uhl and Dittmer, 2005), 2) by “French-design” CWs treating unsettled municipal wastewater (Molle et al., 2005) and 3) by pilot-scale research (Fournel, 2012). Key considerations in their design are the following:

i) Treating unsettled water facilitates sludge management. The twin filter sides allow sequential feeding. This means one side stays unloaded at regular events (small volumes). Both beds are simultaneously fed in the case of bigger loads only. The primary filter receives the inflow; the secondary filter receives settled water through the primary, if any. Alternation of filter priority allows longer inter-events in the secondary filter which favours mineralization of any previously accumulated sludge and organics. The purpose is to avoid clogging. Sludge mineralization is discussed in Pálfy et al. (2017b).