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Simulation of constructed wetlands treating combined sewer overflow using HYDRUS/CW2D☆,☆☆

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ABSTRACT

Constructed Wetland 2D (CW2D) is a biokinetic model describing microbial dynamics and transformation and degradation processes in subsurface flow constructed wetlands (CWs). The implementation of CW2D in HYDRUS (©PC Progress s.r.o.) was verified for application on CWs treating combined sewer overflow (CSO CWs). CSO CWs mitigate pollutant and hydraulic shock on receiving waters. Their loadings are stochastic in terms of periodicity, volume and quality. Their storage basin and outflow limitation causes cycles of saturated (intra-event) and unloaded (inter-event) states. The need for verification is due to this stochasticity. Key parameters to overcome the limitations identified by earlier studies were (1) biokinetic parameters, (2) fractionation of COD between readily and slowly biodegradable and inert forms and (3) adsorption of inert COD. With the new settings inoculation runs yielded stable biomass and domain conditions. These were successfully used as initial conditions for calibration and validation. Laboratory column experiments formed the basis of comparison, including single loads and a load series. The goodness of fit was quantified by an updated method. Good fit was reached to COD and NH_4-N. Fitting to NO_3-N was not a target; still, dynamics are discussed.

1. Introduction

1.1. Terminology and specificities of CSO CW

Combined sewer systems accommodate high flow rates of stormwater mixed with sewage during storm events. Therefore, these systems have to have integrated combined sewer overflow (CSO) mechanisms. On one hand these mechanisms prevent the overfilling of the sewer and surface flooding; on the other they limit flow rates to match the capacities of wastewater treatment plants. Peaks exceeding the hydraulic capacity of the plant are discharged as CSO (Meyer et al., 2013). If untreated, this flow is a significant pollution source (e.g. ammonium, organics) and hydraulic shock (e.g. streambed erosion and destruction of macroinvertebrate habitats) for receiving water bodies (Chocat et al., 1994).

Constructed wetlands (CWs) for CSO treatment are wide-spread or desired in several countries in Europe (Meyer et al., 2013). These systems differ in their loading characteristics from CWs treating sewage as CSOs have stochastic periodicity, volume and quality. CSO vertical flow CWs (here, CSO CWs) have a storage basin above the filter material. The high loading rates lead to saturated conditions of the media and generally to ponding above (intra-event state). Intra-event states last up to dozens of hours and are separated by periods up to dozens of days. In these, the filter media releases all gravitational water. The pores get filled with air and dry out to a various degree (inter-event state). The treatment processes can be attributed to either the intra-event or the inter-event environment based on their dominant occurrence. Filtration, adsorption and anaerobic degradation take place during the intra-event state. The porous media releases the water at a rate determined by an outflow throttle and aerobic processes, most importantly nitrification of the adsorbed ammonia dominate the inter-event state (Dittmer et al., 2005; Uhl and Dittmer, 2005;

☆ **Software**: HYDRUS 2D/3D 2.03.0350 and HYDRUS Wetland Module ©PC Progress s.r.o (hydrus@pc-progress.cz). Patch provided to (1) simulate outflow rate limitation and (2) to avoid hung occurring at *NH4N* depletion in the domain. For more details see http://www.pc-progress.com/en/Default.aspx?support.
☆☆ **Abbreviations**: model parameters, variables and components are written in *italic*.

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Meyer, 2011; Dittmer and Schmitt, 2011). Woźniak et al. (2007) reported however that aerobic processes may occur at both periods.

Constructed Wetland 2D (CW2D, Langergraber and Šimůnek, 2005) is a biokinetic model, implemented in the Wetland Module extension of the software HYDRUS (©PC Progress s.r.o). Referred to as HYDRUS/CW2D, it is designated to simulate CWs with continuous or frequent feeding patterns. Equations of water flow and reactive solute transport in HYDRUS are coupled with the aerobic and anoxic transformation and degradation processes and bacterial growth and decay of CW2D. The described pollutants are organic matter, nitrogen and phosphorus. Modelled bacterial groups are heterotrophs and two groups of nitrifiers (Langergraber and Šimůnek, 2011). For a more detailed process description, please refer to Langergraber and Šimůnek (2005, 2011).

The load pattern of CSO CWs is irregular leading to the stochastic alternation of intra- and inter-event phases. Still, HYDRUS/CW2D might be capable to simulate them because it has all sub-models of internal processes except the transport of particulates (filtration). The targeted pollutants in Germany and France, which are represented also in the tool, are COD and NH_4-N.

1.2. Previously identified limits of applying HYDRUS/CW2D on CSO CWs

One of our aims was to overcome previously identified limits, hence these limits are discussed here. The tool had been studied earlier to simulate CSO CWs. The simulations were based on laboratory column scale and pilot lysimeter scale experiments and had various successes (Henrichs et al., 2007, 2009; Meyer, 2011; Meyer et al., 2013). The previously applied calibration approach targeted stable biomass concentrations in CW2D. Loads and inter-event states were repeatedly simulated to reach biomass equilibrium. The outcome of such stabilization process can be used as initial conditions in order to see how the tool predicts the effluent concentrations after. This is a measure of the capability to simulate real series of CSO feedings using the HYDRUS/CW2D model package. The previously applied calibration approach included the following steps to reach stability:

1. Fitting flow and single solute transport using tracer test results.
2. Setting up sorption for *NH4N* and slowly biodegradable COD (*CS*).
3. Setting up COD fractionation.
4. Validation of the new parameters simulating other single events.
5. Validation via long-term simulations of consecutive events (reaching stability).

The calibration of the biokinetic parameters of CW2D was also listed in these works but it had been confused with setting up sorption, COD fractionation and manually setting bacteria initial conditions. Sorption is a submodel of the model package not related to CW2D; COD fractionation is about determining time-variable boundary concentrations manually and bacterium concentrations are variables of CW2D. The parameters of the biokinetic submodel were practically untouched and the limitations of HYDRUS/CW2D for simulating CSO CWs were drawn up like this.

Meyer (2011) was able to fit simulated and measured effluent concentrations of single loads. At first, initial bacterium concentrations were adjusted manually to match the vertical distribution of the measured DNA/RNA/ATP concentrations. Fitting this way was successful. Then, a similar biomass distribution was targeted via reaching biomass equilibrium. Fitting failed when using imported initial conditions from the stabilizing runs. Meyer (2011) (1) concluded the applicability of CW2D needs further simulation studies, (2) suggested an extension with particulate deposition and transport and (3) highlighted a gap in the knowledge about bacteria dynamics in the inter-event periods.

Henrichs et al. (2007, 2009) were successfully modelling ammonium dynamics and COD degradation when setting up adsorption for *CS*. A good fit was reached for single loads whilst long-term simulations failed for COD. Among the assumed causes were (a) COD fractionation of inflow between readily (*CR*) and slowly (*CS*) biodegradable and inert (*CI*) forms, (b) the concentration and distribution of heterotrophic biomass (*XH*) and (c) similarly to Meyer (2011), organic matter degradation and nitrification in inter-event periods.

CSO CWs differ in their loading and operation characteristic to normal CWs so the need of the calibration of the biokinetic parameters is anticipated. Issues (b) and (c) can theoretically be overcome adjusting biokinetic parameters which makes manual initial condition settings needless. Finding a balance between microbial growth and decay could put a cap on the limitless growth of *XH* as well and lead to realistic degradation rates in the inter-event periods. The calibration of a set of biokinetic parameters was targeted to obtain self-stabilized conditions, realistic biomass distribution and to provide a good match of simulated and measured effluent concentrations.

Our work targets to identify limits of the applicability of HYDRUS/CW2D on CSO CWs based on column experiment data and to bring closer full-scale applications. Using numerical models can give better insights to CSO CWs and understanding their limitations can promote model development itself (Meyer et al., 2015). Process-based models can be used to display detailed wetland functions but other necessities might need different approaches. In the case of CSO CWs, displaying long-term purification efficiencies was found highly important in a phenomenological model for design-support (Meyer and Dittmer, 2015).

2. Materials and methods

2.1. Experimental set-up

The laboratory columns and experimental data on loads (Woźniak, 2007, Woźniak et al., 2007) were selected from a long-term project series ('BOFI') carried out at the Institute of Urban Water Management, University of Kaiserslautern, Germany. The columns (Fig. 1) had outflow limitation and rapid loading pulses which resulted ponding above the sand filter media. Loads were wastewater diluted to concentrations which is typical for CSOs (Dittmer et al., 2005).

CW2D was used in the version 2.03 of HYDRUS with a patch enabling to simulate outflow limitation by setting up an upper threshold on the outflow rate. Another patch prevented the calculations to halt when ammonium-nitrogen in the model (*NH4N*) was depleted. To be able to compare the previous simulation study of Meyer (2011) to the present one an identical domain was created. It consisted of 3 × 105 (horizontal × vertical) finite elements as represented on Fig. 1. The storage volume above the filter media was substituted by a material with no residual water content ($Q_r = 0$); hundred per cent porosity ($Q_S = 1$) and a high hydraulic conductivity at saturation ($K_s = 104$ m/h) ('air layer'). The outflow was throttled to 0.01 or 0.03 L/s/m^2.

2.2. Used calibration and validation approach

The simulation study had three main work phases: (1) reproduction of the simulations of Dittmer et al. (2005) and Meyer (2011) (see also Section 1.2) with identical parameters to verify new software version and patches, (2) calibration of parameters to achieve biomass equilibrium and a good fit of a following single load, and (3) validation of the new biokinetic parameter set using other single loads and a load series of five loads. The targets of fitting were