Modelling CWs for CSO treatment – reasonable balancing between detailed description and practicable handling

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ABSTRACT

Simulation models are an important tool in planning urban drainage systems, so enhanced treatment devices need to be implemented in the computing procedures. In combined sewer systems an enhanced treatment of combined sewer overflow (CSO) is required when augmented water quality requirements are demanded or conventional CSO treatment does not meet environmental quality standards. Constructed wetlands (CWs) have become the most common method to provide enhanced treatment of CSO in Germany.

Balancing between detailed description and practicable handling in modelling CWs for CSO treatment, also known as retention soil filters (RSFs), depends on modelling aims. To calculate average emissions of these CWs simple approaches like a RSF module in long-term pollution-load model KOSMO are adequate (Kaufmann & Schmitt, 2005). To describe and investigate operational conditions complex biokinetic reaction models like CW2D (Langergraber & Šimůnek, 2005) can be used, but they are not applicable as optimization tools in practical use.

To optimise operation and design the model RSF_Sim has been developed. Within the model a reasonable balance between detailed description and practicable handling has to be found. First versions of the new model are able to describe basic processes appropriately. Simulation results for single events show a good match of hydraulic conditions and effluent concentration curves (Meyer et al., 2008). Long-term simulation runs show proper results calculating average emissions, but also indicate needs of more detailed descriptions within the black box under varying operational conditions. Within the paper requirements, methods and prospects of modeling RSFs for practical use are given and discussed.

Keywords

CWs for CSO treatment; detailed simulations; CW2D; modelling for operation and design

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INTRODUCTION

During rain events discharges in combined sewer systems often exceed the capacity of WWTPs. A part of rainfall runoffs can be stored in storm water tanks but in case of hard or long rain events combined sewer overflows (CSOs) can not be avoided. To reduce the ecological impact of these overflows on receiving waters reed planted vertical flow constructed wetlands (CWs) for treatment of CSOs, also known as retention soil filters (RSFs), are widely applied in Germany.

Constructed wetlands for CSO treatment are generally designed as vertical flow filters with a detention basin on top of the filter layer. Middle sand (0/2 mm) has proved to be the most efficient filter material for this kind of treatment. The filter itself is planted with reed (phragmites australis). Fig. 1 shows a cross section of a wetland plant. During operation particulate substances are retained at the filter surface. They build up an additional sediment layer on top of the original sand filter. The filtration rate is controlled by a throttle in the outlet structure. RSF are operated under constant filtration rates. Recommended values are 0.2 or 0.1 l/(s*m²) depending on the filter material.

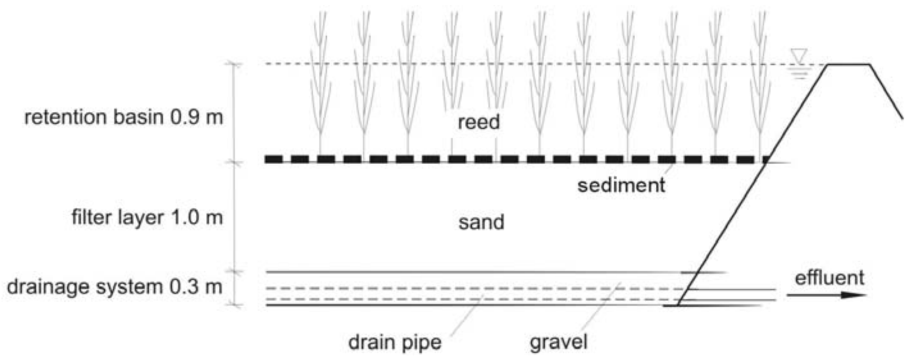

Fig 1: Schematic cross section of a constructed wetland for CSO treatment

The filter layer is completely drained after every rain event to ensure maximum aeration and aerobic degradation. Field studies have shown that dry periods between the loading events are also essential to prevent clogging (Uhl & Dittmer, 2005). To reduce frequency and duration of loading events upstream storm water tanks are applied. The inflow of this type of CW therefore consists in the CSO from conventional storm water tanks (figure 2). The loading regime of the CW depends on local rainfall characteristics and on the volume of the upstream storm water tank.

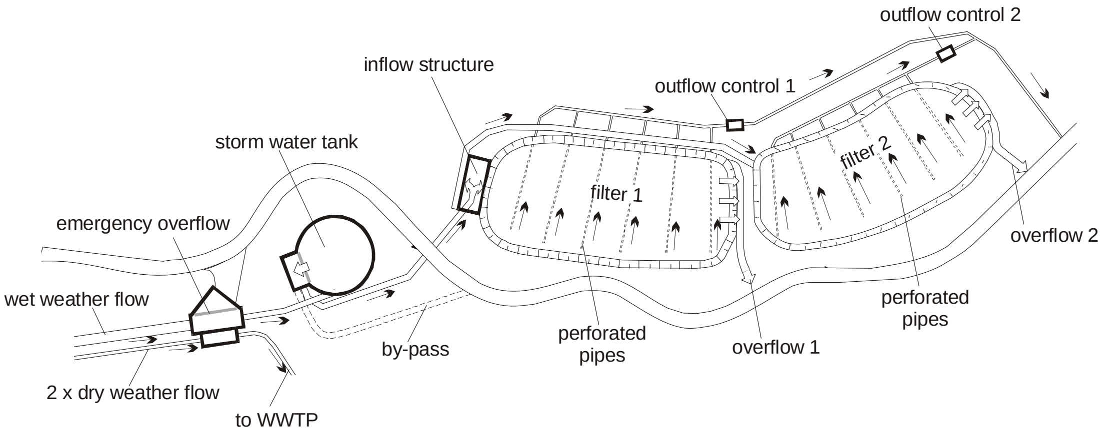

Fig. 2 Scheme of the full scale plant

Typical overflow frequencies of storm water tanks in Germany are 40 to 60 events per year with an accumulated duration of 200 to 300 hours per year (long term mean values). Runoff volume and pollution loads vary within a wide range. Flow rates and pollutant concentrations also vary in the course of each event (e.g. first flush effects). Dry periods can last up to several months.

Dimensioning of CW for CSO treatment is based on long term rainfall-runoff simulation. The main criterion is the annual hydraulic load [m³/a] per filter area [m²]. The long term average shall not exceed 40 m³/(m²*a).

PROCESSES IN RSFS

The main processes within the filters are (1) detention and reduction of peak flows, (2) reduction of suspended solids, (3) retention of soluble and particulate pollutants by adsorption and (4) subsequent biological degradation (especially of ammonium nitrogen). The processes in CWs for CSO treatment have been analysed in several research project including field studies and lab scale experiments. The main results of these activities are summarized below.

Hydraulic processes

The hydraulic processes within the filter are determined by the characteristics of the filter material (middle sand) and by the operational conditions (mostly inflow >> outflow). Both favour saturated flow, as soon as the retained water volume exceeds the effective pore volume of the filter. In case of smaller loading rates and/or durations the filter works under unsaturated or partly saturated conditions. The filter layer is completely drained after loading rain events. A more detailed description of the hydraulic processes is given in Meyer et al. (2008).

Retention and degradation processes for pollutants

The elimination of ammonium is based on a two-step process: during infiltration ammonium is absorbed by biofilms within the filter layer. Concentrations are reduced to a background level. Nitrification of the retained nitrogen mainly takes place during the following dry period. Nitrification activity is highest immediately after the draining and re-aeration of the filter layer. Nitrification of the retained ammonia regenerates the sorption capacity.

Long term loading and high ammonia loads can lead to a breakthrough of the inflow concentration. Adsorption capacity is highest in the sediment layer and in the upper parts of the sand filter. A high number of small loading events can also lead to an inhomogeneous horizontal distribution with higher sorption capacity close to the inflow structure. Biofilm growth in new-built RSFs takes several months, but established biofilm can keep its sorption capacity over dry periods up to a year.

As one result of nitrification NO_3-N concentrations in the filter layer rise during dry periods. This leads to nitrate wash-outs at the beginning of the next events. The adsorption

capacity for ammonium usually is regenerated completely within a few days.
Organic carbonates – represented by COD – show a different behaviour. Most part of the particulate fraction (size > 0.5 µm) is retained at the surface of the filter layer and oxidized during dry periods. For soluble COD compounds the filter shows an almost constant removal rate. Oxygen consumption during infiltration indicates immediate degradation. Ammonification of organic nitrogen during dry periods shows that there is also delayed degradation of organic substances that have previously been retained by absorption.

MODELLING PROCESSES IN RSFS

Simulation studies using CW2D

To simulate the performance of lab-scale filter columns in detail the multi-component reactive transport model CW2D (Langergraber & Šimůnek, 2005) was used. CW2D originally was developed to simulate the treatment of municipal wastewater in subsurface flow constructed wetlands. It is applied to simulate the saturated/unsaturated flow, transport and degradation processes occurring in a constructed wetland for the treatment of CSOs. Simulation results showed that the biokinetic reaction model CW2D is generally applicable for the simulation of RSFs (Dittmer et al., 2005), but additional components have to be implemented. Especially the filtration process has to be taken into account, because filtrated organic solids are the source of nutrient uptake for microorganisms after degradation of sorbed nutrients (Meyer et al., 2006).
The description of purification processes in CW2D is more detailed than the actual knowledge on RSF processes. For using the model several assumptions have to be made, that can not be experimentally verified (e.g. influent COD fractionation, concentration and distribution of microorganisms, organic matter degradation and nitrification). This applies especially to the description of COD degradation in dry periods between the loading events (Henrichs et al, 2007)

Simple model for long-term pollution-load simulation

Pollution-load simulations are generally used to describe the long term impact of urban drainage systems on receiving waters. Essential parameters are annual loads of COD and suspended solids. For ammonia the focus lies on the frequency of critical concentrations.
Based on the results of a field study a simple module for balancing constructed wetlands has been developed and implemented in the pollution load simulation model KOSMO (Kaufmann & Schmitt, 2005). Figure 3 shows a functional diagram of the module.

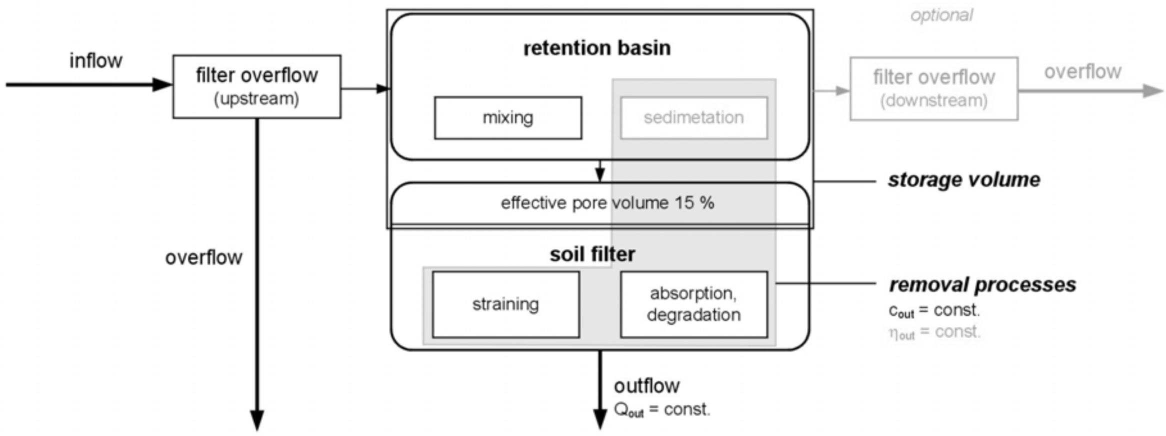

Fig. 3: Functional diagram of the modelling module for RSFs.

Constructed wetlands are represented in the model as a control structure with a defined storage volume and a default removal efficiency of pollution loads. The storage volume consists of the detention basin on top of the filter layer and the volume of the effective pores within the soil filter (15 %). The module calculates the removal processes in a simplified way: either a constant outflow concentration of pollutants or a constant removal rate (η) can be chosen. These values should represent annual mean values. Descriptions of specific processes for suspended solids (SS), filterable COD (COD_X), dissolved COD (COD_S), ammonium and nitrate are given in table 1. In the case of ammonia the constant concentration (first phase) and constant removal rate (last phase) are combined.

Table 1: Description of specific processes in KOSMO

Parameter	Process	Equations
SS	constant c_eff	c_eff = 3 mg/l
COD_X	constant c_eff	c_eff = 3 mg/l
COD_S	constant η	ηCSB_S = 50 %
NH4-N	sorption capacity (available at the beginning of every loading event) phase 1: constant c_eff phase 2: linear transition ph.1 to ph. 3 over 36 h after exhausting sorption capacity phase 3: constant η	sorpNH4 = 4 g/m2 c_eff = 0.1 mg/l c_eff = 0.1 + c·(1-η)·tS-end/36 tS-end < 36 h; c_eff = 0,1 + CRBF·(1-η) ηNH4-N = 10 %

c_in = inflow concentration; c = concentration in detention basin; c_eff: effluent concentration

Discharges and pollutant loads from filter overflow and outflow of the constructed wetland are balanced as emitted volume and load respectively. Further simplifications and presumptions of the model are:

- draining starts instantaneously with the beginning of the loading of the filter,
- the conditions of the soil (e.g. saturation) are not considered,
- only pore volume of sand layer is included as additional detention volume,
- interdependencies/interactions between different pollutants are disregarded,
- presumption of complete degradation of retained substances during dry periods.

For these simulations the CW has been modelled with constant effluent concentrations or pollutant retention efficiencies.
This model only describes the emissions from RSFs. The internal processes are not modelled. As sorption and degradation kinetics are not considered it is only applicable for a constant reaction time. Assuming predominantly saturated flow, reaction time is kept constant by the control of the filtration rate. Thus the model is not able to predict the effect of variations in operation mode or plant layout.

Development of new model RSF_Sim and discussion of further improvements

In spite of a good approximation on annual balances the KOSMO approach seemed to be inefficient to reach the aim as an optimisation tool for design and operation due to the multitude of influencing factors. In contrast to the previously described approach the new model RSF_Sim (Retention Soil Filter Simulation) is not embedded into the KOSMO simulation program. It is an independent tool which can be used for manual data input as well as for dealing with input data from KOSMO via a software interface. For easy handling a graphical user interface has been implemented for data input.

Further improvements compared to the internal KOSMO approach are more detailed mathematical process descriptions for each kind of pollutants. The new model RSF_Sim should be accurate enough to describe the performance under different conditions. On the other hand handling should be as easy as possible (Langergraber et al., 2008). Proper complex descriptions and simplifications have to be discussed for hydraulic conditions and typical pollutants.

Hydraulic model: In a first step of model development RSFs are described as a sequence of three stirred reactors with one-dimensional water flow and variable water contents. According to the real layer structure the whole filter is divided into retention space, filtration layer and drainage space. Duration of water passage through the filter layer has been implemented to take the hydraulic retention time into account. First simulation studies show proper results. Detailed model descriptions and first simulation results are given in Meyer et al. (2008).
In more detailed development steps the filter layer itself is divided into horizontal and/or vertical sub-layers to implement some of the following discussed improvements of pollutant retaining processes. Calculating processes in horizontal sub-layers are identical to the main layer, in the same way a sediment layer can be defined. For vertical sub-layers the filter space is described as parallel parts which are feed after each other according to water contents in the single retention layer. Water exchange between different parallel parts is not considered due to the prediction of part width >> part heights. Effluent concentrations are stirred in the drainage layer.

Suspended solids: SS have to be mainly taken into account to calculate RSF emissions. To calculate retention of SS the original KOSMO approach is taken over due to high quality of simulation results. Accumulation of SS could indicate the risk of occurring mechanical clogging effects. Therefore the main value had to be fractioned into different particle sizes. Up to now investigation of clogging processes do not give proper data bases to estimate general effects. Detailed descriptions would also lead to a number of estimated input values and computation steps compared to the simple flow model. Therefore detailed mathematical descriptions should be tried first in models like CW2D using Finite-Element-Meshes and differential equations.

Organic carbonates: The enormous number of organic carbonates is represented by COD. In research programs on CWs measurements of solute COD compounds are accomplished additionally to total COD. In this way filterable COD can be calculated so that databases are given for two different fractions. Usually long-term pollution-load models also consider this distinction. Due to these facts calculations of two different COD fractions as input values have been implemented in the first model version of RSF_Sim.

COD_X: In contrast to KOSMO simulations RSF_Sim does not calculate filtration processes with constant effluent values as background concentrations. Exact measurements of low COD_X concentrations (< 5mg/l) are not practicable in practice of RSF investigations, so low measurement values only indicate very high filtration rates and can be calculated in that way. To be able to consider accumulation processes RSF_Sim deals with two different filtration rates. Between retention and filtration layer a surface filtration is described as accumulative process by addition of retained masses. Smaller particles can reach deeper regions of the filter layer. They are supposed to be filtrated and accumulated in the filter layer space only as a small part of the total filtration process. The addition of both filtrations leads to a total removal rate close to 100 %. Accumulation is described as the addition of retained masses.
Descriptions of accumulation processes give options to calculate COD_X degradation in later model versions. The distinction of COD_X retention on the surface and in filter space is needed to consider processes in the sediment and filtration layer separately. The surface filtration is supposed to be the basic process for establishing a sediment layer. Accumulation of particles is usually more intensive close to the inflow structure, so vertical sub-layers can be used to take distribution into account. Degradation of small particles within the filter layer will have an influence on the amounts of COD_S and ammonium as source term. Due to the lack of knowledge of processes within the sediment simulation results have to prove practicability.

COD_S: In the current model version recurring processes for COD_S are immediate high-rate degradation as well as absorption and delayed degradation only in the dry period. In that way simulated outflow curves could be calibrated on measured single events with different outflow limitation rates, but validation on long-term measurements has failed. In a next step long-term results have been slightly improved by assuming lower filter performances corresponding to durations of dry periods and describing degradation rates with temperature dependency.
Future model versions will consider the reduction of oxygen demand corresponding to available oxygen. Measurements of dissolved oxygen distribution within the filter layer (Wozniak et al., 2007) indicate proper estimations of degrading conditions. In that way RSF_Sim could be able to describe critical COD overloads. Instead of describing the filter performance depending only on the duration of dry periods a description of slow degradation processes for all filtrated organic particles will be used as an indication for current filter performances. The more degradable organic compounds are available in long dry periods the more nutrients for microorganisms are available and the higher the filter performances should be on following loading events.

Ammonium nitrogen: Ammonium is supposed to be adsorbed during passage of the filter layer and degraded after drainage. To calculate sorption processes different mathematical descriptions were tested. The use of Freundlich-isotherms with empirical parameters k and n (Csorbed = k * Cdissolved ^ n) is not adequate to the simple character of RSF_Sim because iteration computation is required. Calculation over linear isotherms (Csorbed = k * Cdissolved) is not able to describe breakthroughs of inflow concentrations. Either beginning breakthroughs right after the beginning of outflows (small k-values) or overestimated sorption capacities (high k-values) have to be chosen. Therefore a calculation method with two linear isotherms valid over two different concentration ranges in combination with degradation was developed (Meyer et al., 2008).
Compared to the KOSMO model the new approach is able to calculate mass variations in the solid phase depending on dissolved concentrations. This allows finding actual concentrations in the liquid and solid phase for

different sub-layers as well as model calibration on outflow curve measurements. Detailed investigations of sorption processes showed that sorption capacities can be set as equal over all filter depths (Meyer et al., 2006), so the number of input values does not increase corresponding to the description of sub-layers.

Nitrate nitrogen: Due to the fact that anoxic conditions within the filter are defined as critical operational conditions description of denitrification processes is not a goal of modelling RSFs. Wash-out of degraded ammonium is described as strictly convective in addition to the passage of inflow concentrations. A comparison of simulation results with measured effluent nitrate values as mass balances indicates ammonification processes and can be used for calibration.

CONCLUSIONS AND OUTLOOK

Modelling CWs for CSO treatment as optimisation tool operation and design in practical use needs to come up to long-term pollution-load model requirements. Uncertainties calculating sewer systems and preliminary treatment in stormwater tanks within pollution-load models are not considered in this study. The new model RSF_Sim is also practicable for manual data input and has been used first in this way.

Reasonable balancing between detailed description and practicable handling in modelling CWs for CSO depends on modelling aims. To calculate average emissions of RSFs the KOSMO approach is adequate, but in this way operational conditions within the filter under varying conditions can not be described. Therefore it has been combined with simplified ideas of complex descriptions within the biokinetic reaction model CW2D to RSF_Sim. First simulation studies on lab-scale CWs showed proper results (Meyer et al., 2008), but also indicate needs of more detailed descriptions within the black box CW. Detailed knowledge of occurring processes can lead to improvements as well as further simulation studies with extended mathematical descriptions within CW2D.

Current aims of model development are more detailed descriptions of filter operation during dry periods. To consider sediment influences accumulated CSB_X is calculated as partly degradable as well as absorbed COD_S. Both fractions have influence of nutrients available for microorganisms during dry periods. Current status of degradation is used as indication for filter performance for the next loading event. To consider influence distributions of sediment the filter layer is divided horizontally into sub-layers for sediment and filter sand. In vertical direction higher accumulation of sediment close to the inflow structure can be taken into account. Due to the lack of knowledge of long-term internal processes (esp. within the sediment) simulation results will show practicability to calibrate input values on long-term measurements of effluent concentrations. For single events results of soil investigations during filter operation (Dittmer, 2006 / Wozniak, 2007 / Meyer et al., 2006 / Schwarz et al., 2001) are used. Availabilities, numbers and sensitivities of input parameters have to be analysed to keep RSF_Sim applicable as a practical tool.

As a next step of model development critical operation conditions will be considered. Therefore coherences of COD and available oxygen will be described approximately. For single events lab-scale results of oxygen distribution during water-saturated operational conditions (Wozniak et al., 2007) will be used for calibration.

Up to now RSF_Sim is able to calculate average emissions of enhanced CSO treatment. Further developments will show effectiveness on optimisation of operation and design by validating calibrated simulation results under specific conditions on more (given) investigation results. The main question will be the investigation and the description of recurring processes during dry periods.

ACKNOWLEDGMENT

The development and use of simulation models for CWs for CSO treatment is funded by a PhD-scholarship of the German Friedrich-Ebert-Stiftung.

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