# Simulation of a subsurface vertical flow constructed wetland for CSO treatment

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**Abstract** Constructed wetlands (CWs) have proved to be a highly effective measure to reduce the ecological impact of combined sewer overflows (CSOs) on receiving waters. Due to the stochastic nature of the loading regime and the multitude of environmental influences, assessment of the performance of such plants requires detailed mathematical modelling. A multi-component reactive transport module (CW2D) was applied to simulate the flow, transport and degradation processes occurring in a CW for CSO treatment. CW2D was originally developed to simulate the treatment of municipal wastewater in subsurface flow CWs. Loading and operational conditions in CSO treatment differ fundamentally from the conditions occurring for wastewater treatment. Despite these differences, first results from the simulation of lab-scale experiments show, that the model is generally applicable to this type of plant. Modelling of adsorption, degradation processes, and influent fractionation, however, require further research.

**Keywords** Combined sewer overflow; CW2D; numerical simulation; stormwater treatment; subsurface flow constructed wetlands

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## Introduction

### Constructed wetlands for CSO treatment

Constructed wetlands (CWs) for the treatment of combined sewer overflows (CSO) are generally designed as vertical flow soil filters with a detention basin on top of the filter layer. In most cases sand is used as filter material. The sand layer is commonly planted with reed (*Phragmites australis*). A throttle in the outlet structure is used to control the filtration rate and the detention time in the system. The main treatment objectives for CSO are: (1) detention and reduction of peak flows, (2) reduction of suspended solids by filtration and (3) reduction of soluble and particulate pollutants by adsorption and subsequent biological degradation.

The filter layer is completely drained after every loading event to ensure maximum aeration and aerobic degradation during the dry period. To prevent clogging of the filter due to excessive loads of suspended solids (SS), pre-treatment is essential. This is generally done by sedimentation in a conventional storm water tank. Details of design, operation and performance of constructed wetlands for CSO treatment are described by Uhl and Dittmer (2005).

### Loading characteristics

Fundamental differences between wetlands for wastewater and for CSO treatment are the loading regime and the quality parameters of the inflow. In CSO treatment the succession of loading events and dry periods is characterized by the stochastic nature of rainfall and the runoff behavior of the catchment area. Extreme cases are permanent loading for weeks on one hand, and several months without any loading event on the other. Loading rates (inflow/filter area) show a high variability ranging from mean values of 0.02 mm/s for less intensive rain events, up to peak flows of 1 mm/s during intensive storm events.

Quality parameters of CSO show generally lower pollution than wastewater. Organic matter predominantly occurs in particulate form, which can mainly be attributed to remobilisation of sewer sediments. As this effect is strongly related to the flow rate, SS concentrations as well as solute/particulate ratio of pollutants are highly variable within the course of a rain event.



#### Aim of the study

The performance of CWs for CSO treatment depends on a multitude of influences such as temperature, loading rate, pollution and duration of the actual loading, previous dry period, hydraulic and quality characteristics of previous loading events (Dittmer *et al.*, 2004). All of these parameters vary stochastically. Thus determining the performance during a specific loading event requires mathematical modelling. This applies particularly when influences of changes in design and operation need to be evaluated.

The assessment of emissions from CSOs is generally based on long-term simulations of the entire sewer system. The overall goal of modelling CWs for CSO treatment is the development of a simulation tool that allows long-term simulation and that therefore can be combined with pollution load models for sewer systems. Within this framework, the specific aim of this study is to investigated if a detailed model that was developed for the simulation of CWs for wastewater treatment can also be applied for CSO treatment. Further on the processes which can be basically transferred and which require substantial modifications should be derived from these results.

### Materials and methods

#### Simulation of subsurface flow constructed wetlands

The multi-component reactive transport module (CW2D, Langergraber, 2001) that is implemented into HYDRUS-2D (Simunek *et al.*, 1999) is applied to simulate the flow, transport and degradation processes occurring in a constructed wetland for the treatment of CSOs. CW2D was developed to model transport and reactions of the main constituents of municipal wastewater in subsurface flow constructed wetlands. It is able to describe the biochemical elimination and transformation processes for organic matter, nitrogen and phosphorus.

#### Lab-scale columns

Loading and environmental conditions of full-scale plants can be neither predicted nor controlled. Thus, lab-scale columns (Ø 200 mm) were used to test the simulation tool under defined conditions. Figure 1 shows the layout of the filter columns that corresponds directly to the layering of a full-scale CW.

The main filter layer consists of sand (grain size 0/2 mm, effective size 0.1 mm, coefficient of uniformity 2.8). The upper gravel layer serves to prevent erosion, while the gravel layer below the filter represents the drainage system. The test rig consists of 6 columns that are all fed identically. The filtration rate of columns 1 to 4 is manually controlled by a throttle in the outlet; Columns 5 and 6 have a free drainage (see Table 1). The identical operation of pairs ensures the reproducibility of results and helps in separating systematically from random effects.

In the first period the columns were loaded regularly once a week with 15.7 litre of synthetic sewer, which corresponds to a loading rate of 0.5 m/event. The synthetic sewer is based on the OECD guideline 303A (OECD, 1981), but is diluted to obtain concentrations within the range of CSO quality parameters. The constituents are given in

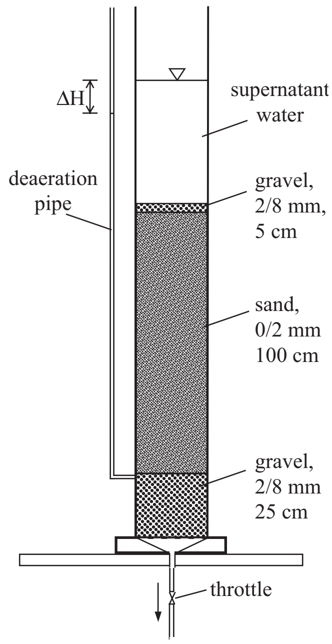


**Figure 1** Lab-scale filter column

**Table 1** Drainage regime of the filter columns

| | C1/2 | C3/4 | C5/6 |
|---|---|---|---|
| Drainage | throttled | throttled | free |
| Limited filtration rate (m/h) | 0.036 | 0.180 | – |

Table 2. In a second phase loading intervals and concentrations of pollutants were varied systematically.

The entire loading volume is applied within about 3 minutes. During infiltration the level of the supernatant water, the water level in the de-aeration pipe and the effluent flow rate are measured (variable time steps 30 sec to 30 min). If necessary, the setting of the throttles is adjusted. The difference between water levels in the column and in the de-aeration pipe allows for observing the hydraulic conductivity in columns 1 to 4. All columns show a constant conductivity without any tendency for clogging (C1/2 = 90 cm/h, C2/4 = 100 cm/h). Lower conductivity of columns 1 and 2 can be explained by the higher amount of biomass due to longer contact time with nutrients. This observation corresponds to the significantly higher purification efficiency of these columns.

Tracer experiments using potassium bromide (KBr) were carried out, to calibrate the transport model. To obtain breakthrough curves, the loading procedure was divided into

**Table 2** Composition of synthetic sewer (mg/l)

| | |
|---|---|
| Peptone | 96 |
| Meat extract | 66 |
| Urea | 18 |
| $K_2HPO_4$ | 16.8 |
| NaCl | 4.2 |
| $CaCl_2 \cdot 2H_2O$ | 2.4 |
| $Mg_2SO_4 \cdot 7H_2O$ | 1.2 |

three steps. The columns were first loaded with 9.5 litres to obtain saturated conditions. After this volume had infiltrated, another 2.5 litres were applied containing 10 mg/l $Br^-$. After the tracer has infiltrated, the last 3.5 litres are loaded. $Br^-$ concentrations in the effluent were measured with an ion-selective electrode. As the tracer was not washed out completely, measurements were continued during the next regular loading. For verification of the flow and transport model the same tracer concentration was added to the synthetic sewer and applied under regular loading conditions to columns 2 and 4.



#### Model of the lab-scale plant

For the simulations of the columns a 2D finite element mesh (105 rows and 3 columns) was used. On top of the upper gravel layer an atmospheric boundary condition was applied, at the bottom a free drainage boundary condition was used.

The supernatant water level decreases from about 40 to 45 cm immediately after the loading with a rate of 2.5 cm per minute. The model is not able to simulate this variable pressure head. To simulate the behaviour of the supernatant water level a "virtual" layer with a pore volume of 100% was used. As the lab-scale columns were not planted, the influence of vegetation was not considered in the model.

### Simulation results and discussion

It has been shown that a good calibration of the flow model is a prerequisite to obtain good simulation results for multi-component reactive transport simulations (Langergraber, 2003).

Up to now CW2D has successfully been applied to model wetlands for wastewater treatment with free drainage. CWs for CSO treatment are generally operated with a controlled effluent flow rate. As loading rates and intervals are determined by rainfall, operation of the effluent throttle is the only way to influence the performance of the plant. It is therefore essential that the model gives correct results for a wide span of possible effluent flow rates. Hence, the flow model was calibrated on the basis of data obtained from operation with free drainage to obtain the parameters to describe unsaturated flow. The calibrated model was than applied to the columns with controlled effluent rates.

#### Calibration of the flow and single-solute transport model

Volumetric water content and hydraulic conductivity for unsaturated conditions were modelled using the van Genuchten–Mualem equations implemented in HYDRUS-2D (Simunek *et al.*, 1999). Hysteresis was not considered. The corresponding soil hydraulic properties are described by the van Genuchten parameters. Values for the sandy main layer are given in Table 3. $\alpha$ and $n$ are empirical coefficients that influence the shape of the functions $\Theta(h)$ and $K(h)$. The virtual layer for supernatant water was simulated with $\Theta_r = 0$ and $\Theta_s = 1$ and $K_s = 10^6$ cm/h. With these values, head loss and retardation within the additional layer are negligible. Values for the gravel layers were taken from literature (Schneider, 2003).

**Table 3** Soil hydraulic parameters of the main layer for the van Genuchten model

| Parameter | Residual water content $\Theta_r$ | Saturated water content $\Theta_s$ | Saturated hydraulic conductivity $K_s$ | Empirical parameters | |
|---|---|---|---|---|---|
| | | | | $\alpha$ | $n$ |
| Unit | ($dm_w^3/dm_s^3$) | ($dm_w^3/dm_s^3$) | (m/h) | ($dm_s^{-1}$) | (–) |
| Value | 0.050 | 0.304 | 0.65 | 0.02 | 3 |

Estimating the van Genuchten parameters of the sand layer by inverse simulation (implemented in HYDRUS-2D) did not give reasonable results. To calibrate the flow model, these parameters were fitted by matching the curves of simulated and measured effluent rates as functions of time. Best results were obtained with the values given in Table 3. The values for α and n are close to those given by Schaap *et al.* (1998). $\Theta_s$ is also within the range of values given in the literature. $K_s$ is significantly lower than the values determined in columns 1 to 4. However, a rough estimation using the Hazen approach (e.g. Vukovic and Soro, 1992)

$$K_s[\text{m/s}] = 0.0116 \cdot d_{10}^2[\text{mm}] \quad (1)$$

gives an even lower conductivity of $K_s = 0.40\,\text{m/h}$.

Figure 2 shows the corresponding simulated effluent flow rate compared with several measured curves from column 6 (free drainage). Despite virtually identical conditions of all loading events, measured effluent curves show significant variations. This confirms that the infiltration process under the given combination of basic conditions (free drainage, extremely high loading rate and pressure head of supernatant water) is extremely sensitive to the slightest variations of environmental conditions. Considering these uncertainties simulated and measured data show a good match.

Figure 3 shows the measured and simulated breakthrough curves of the tracer experiment using the basis of the soil parameters given in Table 3 and roughly estimated values for the dispersivity ($D_L = 0.3\,\text{dm}$, $D_T = 1\,\text{dm}$). The simulated curve fits the measured data well.

#### Simulation with controlled flow rate

As the calibration of the flow and single-solute transport model was successful for free drainage, the simulation should also produce correct results when the effluent rate is controlled by a throttle. Figure 4 shows measured and simulated breakthrough curves for columns 2 and 4, respectively, under regular loading conditions. As the change in the boundary condition does not affect the transport model, simulated curves for both columns are identical. This theoretical assumption is confirmed by measured data as the data for both columns show only slight variations. The simulation results match the measured data well.

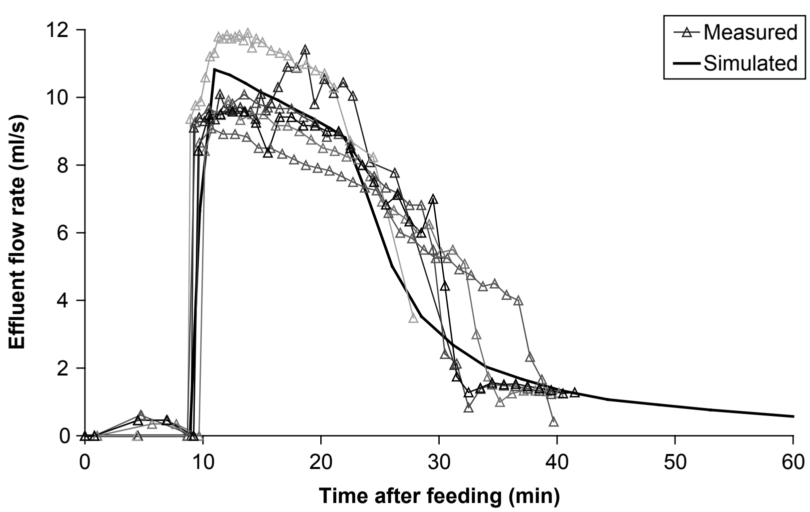


**Figure 2** Measured and simulated effluent flow rate for free drainage

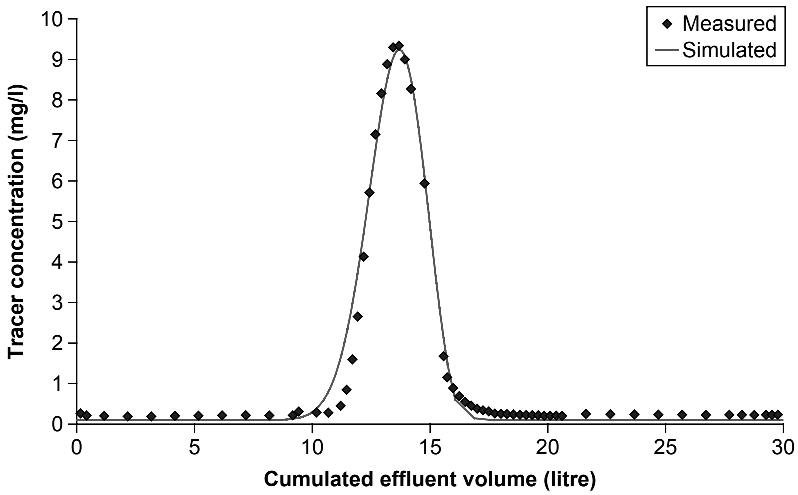


**Figure 3** Measured and simulated breakthrough curves of column 6

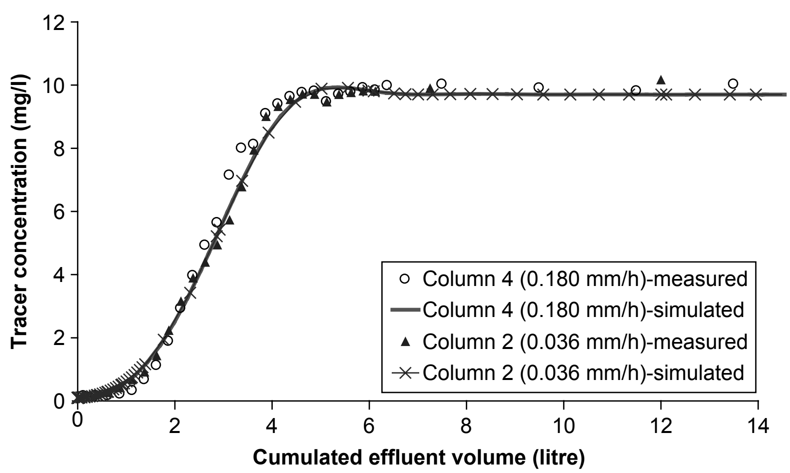


**Figure 4** Measured and simulated breakthrough curves for controlled effluent flow rate

#### Reactive transport model

The multi-component reactive transport model CW2D was tested for the column with free drainage. The standard parameter set as given by Langergraber (2001) was used except for the nitrogen content of COD. Adsorption was only considered for ammonia and inorganic phosphorus.

The model requires three fractions of organic matter (COD): inert, readily and slowly biodegradable organic matter (CI, CR and CS, respectively). As commonly applied for municipal wastewater CI was set to 80% of the mean effluent concentration of COD. The CR to CS ratio of the remaining COD was estimated to be about 2:1. Measured inflow concentrations of organic nitrogen were around 26.5 mg/l, with 8.5 mg/l originating from urea. Assuming instantaneous hydrolysis of urea, this fraction was considered as ammonia nitrogen. The remaining fraction of 18 mg/l is contained in proteins. Thus, the nitrogen content of COD was set to 0.10 $g_N/g_{COD}$ for all COD fractions.

After about 20 weeks the simulated system reached a steady state, i.e. the mean effluent concentrations of each loading remained constant. Table 4 gives influent and steady-state mean effluent concentrations.

**Table 4** Measured influent and effluent concentrations and simulation results

| Component<br>Unit | CR<br>$mg_{COD}/l$ | CS<br>$mg_{COD}/l$ | CI<br>$mg_{COD}/l$ | COD<br>mg/l | $NH_4$-N<br>mg/l | $NO_2$-N<br>mg/l | $NO_3$-N<br>mg/l | Norg<br>mg/l |
|---|---|---|---|---|---|---|---|---|
| Influent | (95) | (45) | (40) | 180 | 8.5 | 0.030 | 0.9 | 26.5 (18) |
| Effl. measured | – | – | – | 51 | 0.44 | 0.025 | 17.8 | 9.5 |
| Effl. simulated | 12.8 | 6.5 | 40.5 | 59.8 | 1.19 | 0.065 | 9.2 | 6.0 |

() … estimated composition of organic matter (COD) for the simulation

COD elimination in reality occurs by adsorption and subsequent degradation of organic matter. As adsorption of COD is not considered in the model, degradation is limited to the detention time within the active sand layer. Further investigations are still required regarding the correct influent fractionation of COD mainly due to the use of the synthetic sewer in particular and for CSO in general.

Like degradation of organic matter, nitrification also takes place during the dry periods, resulting in high effluent concentrations of nitrate nitrogen. Due to the complete aeration between the events generally only little denitrification occurs. The simulation gives an effluent concentration of total nitrogen of 16.4 mg/l, while measurements show a concentration of 27.7 mg/l. This difference can be partly explained by the high content of organic nitrogen in the synthetic sewer and by the lack of knowledge about the details of the adsorption process that plays a major role in the nitrogen transformation processes.

## Conclusions and outlook

The results show, that CW2D is generally applicable for the simulation of CWs for CSO treatment. Flow and single-solute transport simulations give plausible results for free drainage as well as for controlled flow filtration rates. This is essential in the field of CSO treatment, as the effluent throttle is the only way to influence the performance of a full-scale plant during operation. The measurements and simulation results show that unsaturated flow is extremely sensitive against slight variations of experimental conditions.

The laboratory experiments were not originally designed to be the basis for a model calibration. Several adjustments in the operation are therefore required to obtain more realistic conditions. Using a synthetic sewer ensures constant influent composition and reproducible results. On the other hand, adsorption and degradation characteristics of the constituents differ from those of a real sewer. Further investigations are also required for the COD fractionating for CSO that differs significantly from wastewater during dry weather conditions. Therefore in future experiments the filter columns will be loaded with real sewer.

As degradation predominantly occurs in the dry period between the loadings, adsorption of solute compounds is fundamental for the performance of the CW. Additional experiments will be carried out to analyze sorption processes in detail and determine influences of environmental conditions. An adequate model (linear, Freundlich or Langmuir isotherms) should be determined and calibrated.

Soil analyses of a full-scale plant have shown pronounced gradients of biological activity in vertical and horizontal direction. In the vertical direction, adsorption and degradation are almost limited to the upper 10 cm of the sandy main layer. Even higher activity is found in the sediment layer accumulating on top of the filter. This sediment layer preferentially develops close to the inlet. The same goes for the development of the biocoenosis in the main layer.

The laboratory experiments are basically 1D flow processes, while a detailed simulation of the full-scale plant requires a 2D model, considering the variations of hydraulic and adsorption parameters of the soil in both dimensions. Calibration based on measured data has to demonstrate how far the system can be simplified without decreasing the significance of the results.

As the loading occurs stochastically, biological processes within a full-scale plant do generally not reach a steady state. Further simulations will show if the model is able to assess the performance of a wetland during permanent inundation as well as the effect of long dry periods.



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