Simulation of anaerobic processes in subsurface flow constructed wetlands

Introduction

Constructed wetlands (CWs) provide a natural way for simple, inexpensive, and robust wastewater treatment. In subsurface flow CWs no free water level is visible, and water flows either horizontally or vertically through the porous filter media. A large number of physical, chemical, and biological processes occur in parallel and influence each other: Detailed understanding of CW functioning is therefore difficult and CWs have long been seen as "black boxes" where wastewater enters and treated water leaves the system.

Numerical models that describe the transformation and elimination processes in CWs are a promising tool to get a better understanding of the processes in CWs. Until now, very few models to simulate removal processes in subsurface flow CWs have been developed (Langergraber, 2008). Of these models, several are applicable to horizontal flow (HF) CWs, as they only consider saturated water flow using e.g. a tanks-in-series approach. For modelling vertical flow CWs with intermittent loading, transient variably-saturated flow models are required. Due to the intermittent loading, these systems are highly dynamic, adding to the overall complexity of the system.

In HF CWs anaerobic processes play a major role and therefore have to be considered. Four model formulations have been developed ranging from a rather simple model to complex reaction schemes. The pros and cons of these model formulations shall be discussed and ways to a general model suitable for describing anaerobic processes and their competition with aerobic, anoxic and plant-uptake processes in CWs shall be formulated.

Available model formulations

Four models have been considered for discussion which are described briefly:

- **Rousseau (2005)**: Flow model based on tank-in-series approach; reaction model in matrix notation based on the mathematical formulation of the Activated Sludge Models (ASMs; Henze et al., 2000); includes the description of aerobic, anoxic and anaerobic processes for carbon and nitrogen removal. Figure 1 shows simulated and measured COD and ammonium concentrations using Rousseau's model.
- **Brovelli et al. (2007)**: Flow model based on MODFLOW; reaction model ASM formulation including aerobic and anoxic processes. Currently the model is being updated i) by introducing the Variably Saturated Flow (VSF) Process for MODFLOW (Thoms et al., 2006) and ii) by extending the biogeochemical reactions with anaerobic processes based on the model formulation by Maurer and Rittmann (2004).
- **Mena (2008)** proposed an extension of the CW2D model with anaerobic processes. The multi-component reactive transport module CW2D (Langergraber, 2001; Langergraber and Šimůnek, 2005) was developed to describe the biochemical transformation and degradation processes for organic matter, nitrogen and phosphorus in vertical flow CWs. Therefore no anaerobic processes have been included in the original model description. Figure 2 and 3 show simulation results for HF CWs using the original CW2D model formulation without anaerobic processes.
- **Ojeda et al. (2008)**: Processes affecting solids, organic matter, nitrogen and sulphur are considered based on a simple model described by Van Cappellen and Gaillard (1996). The model was developed primarily for HF CWs, but because of the underlying flow model, it is also capable of simulating vertical flow CWs. Figure 3 and Table 1 show simulation results using Ojeda's model.

Comparison and discussion

The experience showed that the inclusion of anaerobic processes in the model is only important for high loaded systems, i.e. the results shown in Figure 3 show that the measured data could be simulated without the consideration of anaerobic processes whereas Table 1 shows that anaerobic process play a big role for higher loaded HF CW systems.

Table 2 shows the comparison of the different biokinetic processes considered in the models described above. The model with the highest complexity is the model used by Brovelli et al. (2007).

Additionally, the processes relevant for HF CWs and that shall therefore be considered are given. As the main purpose of the proposed model is the prediction of effluent concentrations and not the prediction of gaseous emissions the authors suggest to skip the following processes:

- ***Iron reduction***: Usually very low concentrations of Fe in regular urban wastewater (less than 2 mg/L). Therefore it is supposed that these processes play a minor role when treating domestic wastewater. However, they can be easily added if necessary e.g. for industrial and mining wastewaters.
- ***All processes with hydrogen as electron donor***: It is assumed the hydrogen occurs only as intermediate product and is consumed rather quickly. The following points have to be considered:
  - If one does not consider CH_4 in the matrix, then the transformation H_2 to CH_4 is not important, it is just a sink, not affecting other components.
  - If CH_4 is put in the matrix, then methanogenesis is considered to occur via just one pathway, meaning that the stoichiometry has to be changed (100% of SF converted to 100% SA to 100% CH_4).
  - Both means that one process is ignored: in the first case SO_4 reduction with H_2, in the second case H_2 volatilisation, respectively.

The experience of the authors show that there is clear evidence that ***biological sulphide oxidation*** plays a role in some constructed wetland systems. Therefore it is proposed to include these processes (occurs under aerobic and anaerobic conditions) in the model.

The full model formulation of the biokinetic model shall be presented at the *11th IWA Specialized Group Conference on "Wetland Systems for Water Pollution Control"* (1-7 November 2008, Indore, India). The authors want to point out that there are a number of **other processes** that have **to be considered** for the formulation of a full model for constructed wetlands:

- The flow model describing water flow in the porous media is of utmost importance; finite element or finite difference models shall be used for describing water flow.
- Influence of plants (growth, decay, decomposition, nutrient uptake, root oxygen release, etc.)
- Transport of particles/suspended matter and the description of clogging processes
- Adsorption and desorption processes (in most finite element/difference software already present)
- Physical re-aeration

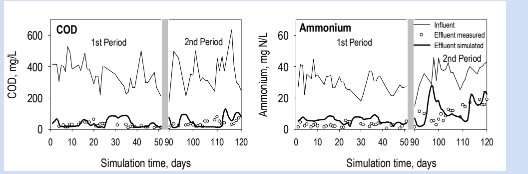

Fig.1: Simulated and measured COD and ammonium concentrations in a HF CW. (Garcia et al., 2007; between day 50 and 90 no measured data on the influent and effluent COD)

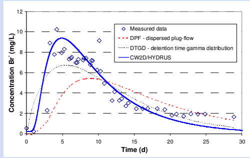

Fig. 2: Comparison of measured data from tracer experiments to simulation results using different models (acc. to Mena, 2008).

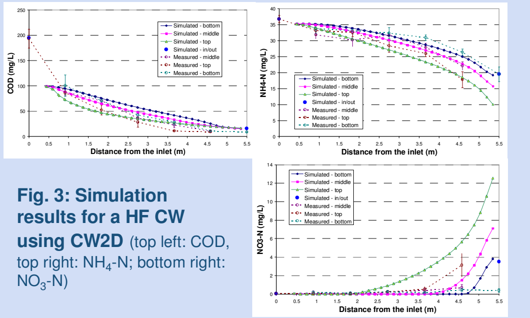

Fig. 3: Simulation results for a HF CW using CW2D (top left: COD, top right: NH_4-N; bottom right: NO_3-N)

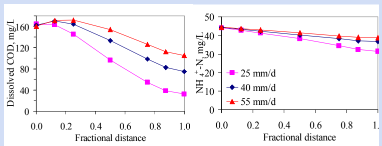

Fig. 4: Simulated dissolved COD (left) and ammonia (right) concentrations for different hydraulic loading rates. (Ojeda et al., 2007)

Table 1: Percentage of COD removal by different microbial reactions for different influent COD concentrations. (Ojeda et al., 2008, constant hydraulic loading)

Microbial reaction	Total COD			
	190 mg/L	225 mg/L	290 mg/L	375 mg/L
Aerobic respiration	19	19	19	19
Denitrification	22	18	13	11
Sulphate reduction	26	25	20	18
Methanogenesis	33	38	48	52

(a) Influent characteristics: NH_4^+ = 45 mg N/L, NO_3^- = 1.2 mg N/L, SO_4^{2-} = 73 mg/L.

Table 2: Comparison of the biokinetic processes included in the different models and processes that shall be included in the proposed model formulation

Process	Rousseau	Brovelli	Mena	Ojeda	Proposed
Biomass growths	X	X	X	-	X
Lysis of biomass	X	X	X	-	X
Hydrolysis (XS to SS)	X	X	X	X	X
Nitrification	X	X	X	X	X
Aerobic growth on SS	X	X	X	-	X
Aerobic growth on SA	X	X	X	X	X
Denitrification on SS	X	X	X	-	X
Denitrification on SA	X	X	X	X	X
Fermentation (SS to SA)	X	X	X	-	X
Iron reduction on SA and H_2	-	X	-	-	-
Sulfate reduction on SA	X	X	X	X	X
Sulfate reduction on H_2	X	X	-	-	-
Methanogenesis on SA	X	X	X	X	X
Methanogenesis on H_2	X	X	-	-	-
Biological sulphide oxidation	X	-	X	-	X

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