Modelling of Treatment Wetlands

Modelling of the complex system constructed wetland requires a number of sub-models and input parameters which are strongly related to the type of the wetland and the objectives of the simulation study.

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Abstract

Due to the complexity of constructed wetland (CW) processes numerical models have to comprise a number of sub-models to describe all relevant processes. Only few tools based on process-based models are available for modelling the pollutant transport and degradation in subsurface flow CWs. The paper describes briefly the current background and status of CW modelling, experiences from applying existing simulation tools and limitations of existing tools, and some challenges identified. These challenges include the correct description of water flow, the incorporation of a model that allows predicting clogging, the determination of biokinetic model parameters, and the needs for developing a new design tool for CWs that is based on process based models. Finally, the results of the discussion in the session are summarised for the following points: modelling of water flow, data needed for a simulation study, and requirements of CW designers for a design tool.

Introduction

In constructed wetlands (CWs) a large number of physical, chemical, and biological processes are active in parallel and mutually influence each other (Kadlec and Wallace, 2009)). Therefore wetlands are complex systems and for a long time have been often considered as „black boxes“. When developing a wetland model a number of different processes have to be considered (Langergraber et al., 2009b):

- The flow model (describing water flow)
- The transport model (describing transport of constituents as well as adsorption and desorption processes)
- The biokinetic model (describing biochemical transformation and degradation processes)
- The influence of plants (growth, decay, decomposition, nutrient uptake, root oxygen release, etc.)
- The description of clogging processes
- Physical re-aeration

Still today most models for wetlands are using a „black box“ approach, i.e. they do not consider processes in wetlands in detail. Data from experiments are needed to derive model equations for „black box“ models. In process-based models the mathematical model equations are based on processes in wetlands and include balance equations for energy, mass, charge, etc. Data from experiments are used for calibration and validation of models. A better prediction should be possible using these models (Langergraber, 2008; Langergraber et al., 2009a).

Main outcome of the session:

- The amount and nature of data needed for the calibration depend on the CW type and the objectives of the simulation study.
  - Water flow: more data required for vertical flow CWs compared to horizontal flow CWs.
  - Pollutant concentrations: depends on biokinetic model parameters (influent fractionations) and dynamics in the influent of the system.
- Designers of CWs have the following requirements for a design tool:
  - Design tools need to be simple to use and predict reliable effluent concentrations.
  - It should be possible to change individual elements of design (e.g. grain size of filter media; order of beds in a multi stage system, etc.) and show the impact of these factors on effluent concentrations.
  - They should be able to predict failure of the system, e.g. which loads are acceptable over which time.

Current background / status

The available simulation tools describing transformation and degradation process in CWs are described by Langergraber (2011). Horizontal flow (HF) systems can be simulated when only water flow saturated conditions are considered. For modelling vertical flow (VF) CWs with intermittent loading, transient variably-saturated flow models are required. Due to the intermittent loading, these systems are highly dynamic, adding to the complexity needed to model the overall system. Available models can be grouped into the following categories (Langergraber, 2011):

- Reactive transport models for saturated flow conditions
  - applicable only for constant flow rates
  - with a tanks-in-series approach for water flow
  - applicable to variable flow rates (incl. changing water table level in the HF bed)
  - coupled to a complex groundwater flow model
- Reactive transport models for variably saturated flow conditions
  - with simplified approach for simulating the variably-saturated water flow
  - coupled with flow models that use the Richards equation to describe variably-saturated water flow.

Recent developments, especially toward implementation of the CWM1 biokinetic model (Langergraber et al., 2009b) include the works of Langergraber and Šimůnek (2012), Samsó and Garcia (2013), and Mburu et al. (2012). Table 1 compares the 3 tools regarding the considered sub-models required for a wetland model.

Experiences / examples

Experiences from applying existing simulation tools can be summaries as follows (Langergraber, 2011):

- Simulation results (effluent concentrations) match the measured data when the hydraulic behaviour of the system is well described, i.e. the influence of the parameters of the hydraulic properties of the filter material is much higher compared to the influence of the parameters of the biokinetic model.

  For water flow simulations in VF beds it is advised to measure:

  - at least the porosity and saturated hydraulic conductivity of the filter material, and
  - if possible the volumetric effluent flow rate between loadings
- not all measured data acquired from experiments are useful for simulation purposes (e.g. sampling frequency, analysed parameters, dynamic behaviour
- information gained from experiments and/or measurements can be of too much detail compared to the needs of the simulation tools and their underlying numerical methods
- modern biotechnological tools help to gain new insights in the functioning of CWs (e.g. data obtained from these experiments are usually not in a form and/or have the appropriate units to be used directly for modelling purposes)
- a common language and understanding is needed between modellers and specialists from other fields (e.g. microbiologists, plant physiologists, hydrologists, CW designers, etc.) to produce useful data for modelling purposes

Limitations of existing simulation tools are (Langergraber, 2011):

- One of the main obstacles for the simulation tools available is that they are rather complicated and difficult to run. Meyer (2011) developed a simplified but robust and reliable model for design purposes for CWs treating combined sewer overflow based on experiences from simulations with a complex simulation tool.

Table 1: Comparison of recent simulation tools for constructed wetlands.

Simulation tool Reference	**HYDRUS wetland module** Langergraber and Šimůnek (2012)	**BIO_PORE** Samsó and Garcia (2013)	**AQUASIM** Mburu et al. (2012)
Flow model	Richards equation (variably saturated flow)	Variable water table (saturated flow)	No flow considered
Transport model	Advection, dispersion, adsorption	Advection, dispersion, adsorption	No transport model
Biokinetic model	CW2D + CWM1	CWM1	CWM1
Influence of plants	Evapotranspiration, uptake and release of substances	Evapotranspiration, uptake and release of substances	Evapotranspiration, uptake and release of substances
Clogging model	Not considered	Included	Not considered
Re-aeration	Considered	Considered	Considered

- Additions required for a CW design tool - 2 simple models for pre- and post-treatment units would be needed :
  - a simple model for prediction of TSS and COD removal based on the design of the mechanical pre-treatment unit, and
  - a model for pre- and/or post-treatment of phosphorus with pre-precipitation in the mechanical pre-treatment unit and/or adsorption filters after the filter beds, respectively.

Challenges / opportunities

Correct description of water flow

Morvannou et al. (2012) showed that the porosity of the layer of a VF CW may serve as preferential flow paths through which water can bypass most of the soil porous matrix in a largely unpredictable way. This is especially true for the sludge layer in French-style VF CWs (Troesch and Esser, 2012). Water flow in such a system cannot be modelled with uniform flow models (such as the van Genuchten-Mualem function in HYDRUS, Šimůnek et al, 2011). The comparison between measured and simulated tracer breakthrough curves indicates that the non-equilibrium approach (i.e. using a model to separately describe flow and transport in preferred flow paths and slow or stagnant pore regions) seem to be the most appropriate for simulating preferential flow paths. Such a dual-porosity model therefore also need to be incorporated in the software tools for accurately describe water flow and solute transport in French VF CWs.

Clogging model

Clogging models need to be able to describe i) the transport and deposition of suspended particulate matter, and ii) the deposition of particulate matter, bacterial and plant growth that may reduce the hydraulic capacity/conductivity of the filter medium. This is of importance for the simulation of the long-term performance and to predict the potential failure of CWs due to clogging.

Values of the biokinetic model parameters

One of the basic assumptions of Langergraber (2001) was that bacteria in CWs are and behave similar to those in activated sludge systems. Therefore the parameters of the biokinetic models developed for activated sludge systems should be applicable also to describe processes in CWs.

This assumption has been confirmed as experience showed that a good match between measured and simulated concentrations can be achieved when the hydraulic behaviour of the system is well described (see above). Additionally, Morvannou et al. (2011) found good agreement between measured and calculated volumetric nitrification rates (Table 2)

We therefore advise not to change parameters of the biokinetic model unless for good reasons. However, parameters describing the inflow wastewater that are related to the biokinetic model chosen have high impact on the simulation results and need to be adapted for each simulation study. These parameters include i) the fractionation of influent COD (i.e. estimation of the different COD model fractions from measured total COD) and 2) the calculation of the organic N content of the different COD fractions.

Table 2: Comparison measured and calculated volumetric nitrification rates (adapted from Morvannou et al., 2011).

Method	Measured with solid respirometry	Calculated from simulation results *
Results [mg $O_2/L_{sample}/h$]	32-50 (mean = 41, SD = 9; 2 values)	30.5

* from simulations using parameters for the biokinetic model from activated sludge systems.

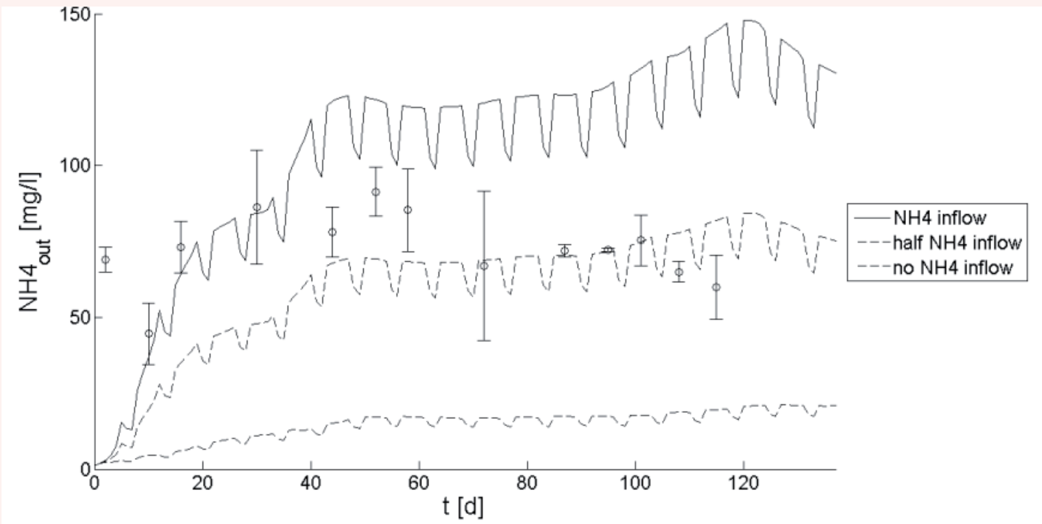

Figure 1: Influence of inflow NH_4-N concentrations on effluent NH_4-N concentrations.

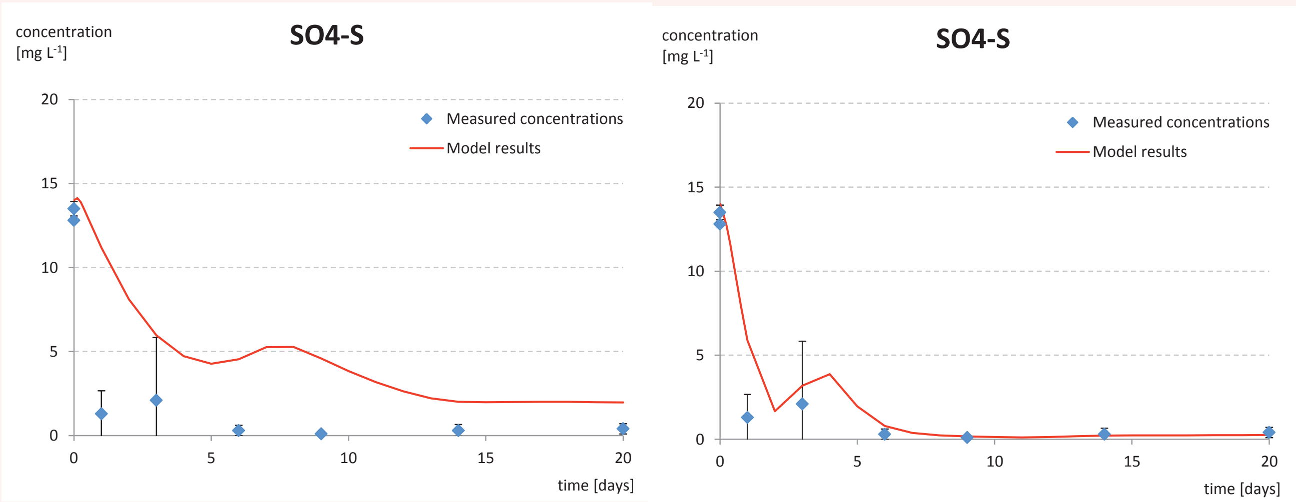

Figure 2: Measured and simulated sulphate concentrations for a batch-fed column at 24°C planted with Carex (left: using the standard parameter set of the biokinetic model; right: after adaptation of inhibition and half-saturation coefficients to allow anaerobic, anoxic and aerobic processes to occur in parallel; Pálfy, 2013)

Rizzo et al. (2013) describe the set-up of a model to simulate experimental data from a horizontal flow CWs fed with artificial wastewater. During the experiments the only nitrogen parameter measured was TKN. As simulation requires influent ammonia nitrogen concentrations, the organic N content of the different COD fractions had to be adapted from standard values for the type of artificial wastewater used. Figure 1 shows the effect of the different influent ammonia nitrogen concentrations on simulated effluent concentrations.

Pálfy (2013) simulated experimental results from batch-fed column experiments. He described the need to adjust some parameters of the biokinetic model to be able to simulate anaerobic, anoxic and aerobic processes to occur in parallel. These phenomena occurred in practice and can be explained by the local effect of root zone re-aeration. Figure 2 shows measured and simulated sulphate concentrations before and after adaptation of parameters of the biokinetic model. Batch experiments can be a way to calibrate biokinetic model parameters as there is no impact of water flow on the treatment performance.

Design tool for CWs

Langergraber (2011) concluded that to make numerical simulation a useful and applicable tool for CW design further developments of the existing models are needed. A simplified computer-based CW design tool based on process-based numerical models shall be developed that

- can be used with knowledge on CW design but do not require special knowledge on numerical modelling,
- allows designing CWs for different boundary conditions (such as climatic conditions, wastewater characterization, filter material, etc.), and
- makes the description of the dynamic behaviour of the designed CW possible thus allowing to show the higher robustness of CW treatment systems e.g. against fluctuating inflows and peak loads

Summary of the discussion

The discussion was organised according to the 4 topics listed in the previous chapter. The main points raised and discussed are summarized below.

<u>Application of models, water flow models</u>

- The models have been developed and mainly used for domestic wastewater right now. It should be however possible to use the models also for wastewaters with similar characteristics as domestic wastewater such as wastewaters from food industries. For synthetic wastewater recent experiences are available as well.
- Alain Petitjean (France) pointed out that the next step for the development of di-phasic flow models is to take into account the biofilm growth and its impact on water flow. Kela Weber (Canada) pointed out that they developed a model based on COMSOL that also considers biofilm growth and links that to changes of the flow pattern.
- Also for the HYDRUS wetland module it is planned to include preferential flow for bio-kinetic models. Assuming biofilm is an immobile part of the water, and to simulate this.

<u>Which data needed for a simulation study?</u>

- The data needed for the simulation study in general and for the calibration of the water flow model in particular depend a lot on the objectives of the simulation study. E.g. if nitrification and denitrification are occurring close together your hydraulic model has to be really, really accurate.

- Hydraulics of HF CWs:
  - Tracer studies
- Hydraulics of VF CWs:
  - Minimum requirement: porosity and saturated hydraulic conductivity of the filter material (allows, according to the experience, a moderate good fit of water flow simulations to measured data)
  - if possible: volumetric effluent flow rate between loadings (allows determination of parameters of the water flow model by inverse simulation)
  - additionally, if available: tracer studies and measurements of water content(s) and pressure potential(s) within the filter bed (will allow more accurate calibration of the water flow model)
- Concentrations:
  - Measured concentration according to the parameters of the biokinetic model used and that allow estimation of COD fractionation and organic N content of these fractions.
  - If the dynamic behaviour of the system should be modelled also the data need to show the dynamics, e.g. diurnal variations, and have to be collected in the respective frequency.

<u>Do companies need design tools for constructed wetlands? What are your requirements, what would companies like to have?</u>

- Models have to be applicable for people who have to design CWs.
  - For this objective the models need to predict outflow concentration with high accuracy. When designing CWs outflow concentration need to be guaranteed, models should also present uncertainties with results (e.g., 95% confidence interval).
  - Models also need to have a simplified interface, where an engineer can learn in a week's time how to use the model.
- Most companies that build CWs do have design tools, but they would like to have better design tools. They basically have two types of tools to design wetlands: rules of thumb (m2/PE, based on the collective experience in e.g. France, Austria or Germany), or using something like the P-k-C* model. But then it's important to remember that the k-rates in text books (e.g. Kadlec and Wallace, 2009) are lumped parameters. Those rates are affected by wastewater type, type and gravel size of media, plant and microbial community maturity – all those go a single lumped parameter.
- Where designers would like to go is to say: If we could change individual elements of design, how would that change the performance of the system? Examples are:
  - If there is experience with using 0 – 2 mm sand and then one has to use a 5 – 15 mm gravel because that's what's available, how does that affect design and in the end, the treatment performance of the system?
  - How much can I stress my system? That is a main topic including the forecast of the lifespan of the system. What is the maximum concentration/ load for certain periods that can be accepted? (knowing such concentrations/loads in the long term will kill the system).
  - For multi stage systems: How small can I make the first stage and make it still survive?

  None of the tools available now allows changing one element of design and tells the impacts on treatment performance. Moving beyond lumped parameters into discrete design elements, to look how changes in the physical design will change the effluent water quality.
- To enhance the prediction capability of models also data from stressed and failed systems are needed during calibration. However, CW designers usually present only working systems. For these experimental CW systems such as the LRB site can be of great help. However, even under controlled conditions sometime it is difficult to assess why systems collapsed.
- Resources are required for developing a design tool based on process-based models.
  - Who wants to pay for such a development? If an international project could be launched this goal could be reached sooner but still some year's development work would be needed.
  - For a small company it's not acceptable to wait for 3 or 4 years. They must have some information even if it is not the most accurate; to have something is better than nothing at all. Rough and approximate is good compared to having nothing at all (and waiting years and years for the perfect model).

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