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Short communication

Modelling the response of laboratory horizontal flow constructed wetlands to unsteady organic loads with HYDRUS-CWM1

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ABSTRACT

Although horizontal flow constructed wetlands (HF CWs) are usually subjected to unsteady loads in real application, the modelling of HF CW response to time-variable loads has been scarcely studied in literature yet. The aim of this study is to test the capability of HYDRUS-CWM1 to simulate the behavior of HF CWs subjected to unsteady loads. Hence, we applied HYDRUS-CWM1 to simulate laboratory results of HF CWs subjected to variable COD inflows. The modelling results adequately fit the experimental data, with an almost perfect agreement in global COD removal efficiencies (67 and 68% from laboratory experiments and simulations, respectively), and mean percent error equal to 20 and 31% for effluent COD and NH_4^+ concentrations, respectively. The obtained results suggest that HYDRUS-CWM1 can be a powerful tool to simulate the response of HF CWs under time-variable loads. Additionally, more detailed data are shown to be crucial in order to better exploit process-based model tools.

1. Introduction

Constructed wetlands (CWs) are a wastewater treatment technology that exploits the physical, chemical, and biological processes occurring in soils to improve water quality (Kadlec and Wallace, 2009). The low operation and maintenance costs allow for a widespread use of CWs, especially for treating wastewater from small communities (Haberl et al., 2003; Kadlec and Wallace, 2009).

Horizontal subsurface flow (HF) is a common CW type to treat organic loads (Kadlec and Wallace, 2009; Abou-Elela et al., 2013). In HF CWs, wastewater flows horizontally beneath the soil surface and from the inlet to the outlet of a gravel bed planted with wetland vegetation (Haberl et al., 2003; Kadlec and Wallace, 2009). Due to the reductive state developed, HF CWs are usually preferred to other CW types when anaerobic processes for treating wastewater are sufficient (Kadlec and Wallace, 2009). Moreover, HF CWs are also preferred to surface flow CWs for concerns about human contact with untreated wastewater, mosquito and odor control, and minimization of wildlife interactions within the wetland (Kadlec and Wallace, 2009).

Process-based models are powerful tool to investigate the behavior of HF CWs, since they are able to separately simulate the effect of the different organic removal processes (Langergraber, 2008). However, process-based models were typically used to investigate HF CWs subjected to steady state loads (e.g., Llorens et al., 2011; Samso and Garcia, 2013a) and only recently they were started to be used for unsteady long-term simulations (e.g., Samso and Garcia, 2013b). Generally, little is known about the ability of process-based model to simulate the performance of HF CWs under unsteady loads.

The aim of the work is to test the capability of HYDRUS-CWM1 (Langergraber and Šimůnek, 20012) to model the HF CW response to time-varying loads simulating the laboratory data collected by Galvão and Matos (2012).

2. Methods

In this section the main features of experimental dataset and of the used process-based model are briefly exposed. For more details about data from laboratory HF CWs see Galvão and Matos (2012), while about HYDRUS-CWM1 see Langergraber et al. (2009), Šimůnek et al. (2011a), and Langergraber and Šimůnek (2012).

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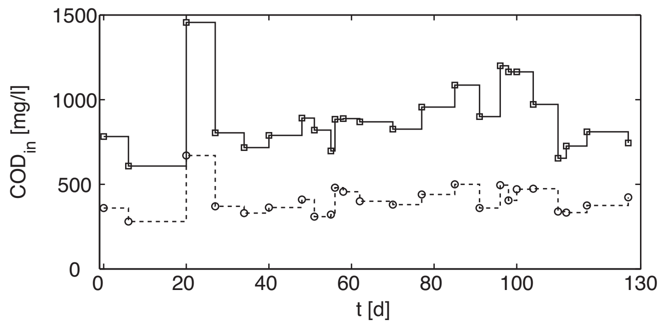

Fig. 1. Unsteady COD inflow concentrations. The squares and circles represent the measured data from Galvão and Matos (2012) for group A and B, respectively. The continuous and dashed lines figure the inflow trend assumed in simulations for A and B, respectively.

2.1. Experimental data

The data used to test the HYDRUS-CWM1 model were collected from laboratory experiments on six HF CWs set up at the Technical University of Lisbon in 2010 (Galvão and Matos, 2012). Each HF CW consisted of a gravel bed with length 1.1 m, width 0.76 m, and height 0.3 m. HF CWs were fed with an average hydraulic load of 10 l/d as follows: from Tuesday to Thursday 10 l/d; on Mondays and Fridays 20 l/d, to mimic the weekends (no feeding during Saturday and Sunday). A concentrated synthetic wastewater (i.e., no bacteria and no solids) was used with theoretical concentrations of COD and total nitrogen (TN) equal to 39 and 6 g/l, respectively. The synthetic wasterwater was composed with a mixture of urea, acetate, peptone, starch, powdered milk, and soy oil (for concentrations see Galvão and Matos (2012)). This solution was diluted to obtain the desired concentration to feed each bed. After an inoculation period, the six beds were divided in two groups, A and B, fed for 127 days with higher (A) and lower (B) average COD concentrations, respectively, as shown in Fig. 1. Each group was composed of three beds with different vegetation configurations: no plants, *P. australis*, and *Scirpus*. Water level was constantly maintained 5 cm below the surface. Since the HF CWs were situated inside laboratory, the resulting evaporation rates were very low (see Galvão and Matos (2012)) and are neglected in the present analysis.

The results from Galvão and Matos (2012) have shown no significant role of plants, therefore the data from the three different beds per group are averaged in the present work. In this way, we obtain a single effluent value of COD and NH_4^+ with corresponding standard deviation per group, which is compared with results from modelling simulations.

2.2. HYDRUS-CWM1

The HYDRUS Wetland Module is an extension of the HYDRUS family codes, which allows for a detailed simulation of subsurface flow CWs (Langergraber and Šimůnek, 20012). HYDRUS solves systems of partial differential equations in three dimensions in order to simulate (Šimůnek et al., 2011a): (i) variably-saturated water flow (Richards' equation); (ii) transport of constituents (mass balance equations); (iii) influence of plants (water and nutrient uptake, radial oxygen loss) and (iv) water temperature (heat transport equation). On this framework, the HYDRUS Wetland Module adds two different biokinetic models: CW2D for aerobic and anoxic processes, and CWM1 for aerobic, anoxic, and anaerobic transformations. Since HF CWs are principally anaerobic systems (Kadlec and Wallace, 2009), CWM1 was adopted in our simulations. For sake of simplicity, we refer to this option of HYDRUS Wetland Module as HYDRUS-CWM1.

The biokinetic model CWM1 (Langergraber et al., 2009) simulates the transformation of organic matter (expressed as chemical oxygen demand – COD), nitrogen (N), and sulfur (S) via biochemical transformation under aerobic, anoxic, and anaerobic conditions. The organic matter is considered via both soluble and particulate COD fractions, while microorganisms are considered as fixed particulate components. The soluble and particulate groups are referred as S_x and X_x, respectively, where x states the component acronym. A list of the components included in CWM1 and of the seventeen biogeochemical transformations considered in CWM1 are reported in Supplementary online material.

2.3. Model set-up

The HF CWs studied by Galvão and Matos (2012) are modeled via a vertical 2D rectangular domain 1.1 m long, and 0.30 m high. In the soil hydraulic model, the van Genuchten–Mualem formulation is assumed for soil water retention and hydraulic conductivity (Šimůnek et al., 2011a). For the solute transport model, the Millington and Quirck formulation is set for soil tortuosity, while a Langmuir law is considered for NH_4^+ adsorption (Šimůnek et al., 2011a).

Since the experiments of Galvão and Matos (2012) did not show relevant difference between vegetated and unvegetated CWs, the plant effects (i.e. water and nutrient root uptake, radial oxygen loss) are not considered. The scarce role of plant can be explained in term of evapotraspiration rate. Differently from outdoor locations in which evapotranspiration plays an important role (Pedescoll et al., 2013), very low evapotranspiration rates are reported for the indoor laboratory HF CWs studied by Galvão and Matos (2012). This confirms the scarce role of root water uptake in the hydrodynamics of Galvão and Matos (2012)'s HF CWs. An additionally explanation can be related to root development. Indeed, Galvão and Matos (2012) have also mentioned no significant removal rates inside each group related to root compartment. This probably because the plants were very young, so the root system was not expected to be fully developed. For sake of simplicity, the influent O_2 is set equal to zero, in accordance with other studies dealing with modelling HF CWs (e.g., Samso and Garcia, 2013a,b). The sulfur cycle is not modelled for lack of measured data.

Since the influent wastewater is synthetic, typical COD fractionations for domestic wastewater proposed in literature (e.g., Henze et al., 2000) are not usable. Hence, the COD inflow concentration is fractionated in accordance with influent load composition as follows: 62% for S_F, 10% for S_A, 3% for S_I, 20% for X_S, and 5% for X_I. Since NH_4^+ inflow was not monitored, an average ratio between NH_4^+ and COD inflow, $NH_4^+/COD = 0.02$, is used to estimate NH_4^+ inflow concentration.

Initial conditions are obtained simulating 10 days of inoculation, with low initial component concentration and COD inflow concentrations equal to 1108 and 510 mg/l for group A and B, respectively.

The adopted boundary conditions have the following features: the inflow is modeled as distributed on the whole water depth; outflow is located in a single node at 1 cm from the bottom and set as constant pressure head in order to maintain the water table 5 cm below the top; the upper boundary is not covered, therefore the atmospheric O_2 is allowed to diffuse within CW; all other boundaries are assumed impermeable and with no solute fluxes. A graphical representation of boundary conditions is reported in Supplemental online material.

Only few parameters are modified from the default values reported in Langergraber et al. (2009); their values are reported together with other set parameters in Table 1. Note that the fractions of organic nitrogen are calibrated in order to guarantee the

Table 1
List of the parameters set to simulate experimental HF CWs of Galvão and Matos (2012).

CWM1 biokinetic model parameters	
Rate of constant X_{FB} lysis	0.5[a]
Fraction of X_I generated in biomass lysis	0.01[a]
N content of S_F	0.137[b]
N content of S_I	0.117[b]
N content of X_S	0.147[b]
N content of X_I	0.137[b]
Soil hydraulic model parameters	
Porosity	0.3[c]
Saturated hydraulic conductivity	72 m/d[a]
Residual soil water content (gravel–sand)	0.045[d]
Parameter α in the soil water retention function (gravel–sand)	14.5 m^{-1} [d]
Parameter n in the soil water retention function	4[a]
Tortuosity parameter in the conductivity function (gravel–sand)	0.5[d]
Adsorption isotherm model parameters for S_{NH}	
Langmuir coefficient k_s (gravel)	0.411 m^3/g[e]
Langmuir coefficient ν (gravel)	5.35×10^{-4} m^3/g[e]
Inflow composition parameter	
Average inflow NH_4^+ on COD ratio	0.02[a]

[a] Fit parameter.
[b] Inflow total nitrogen balance guaranteed.
[c] Galvão and Matos (2012).
[d] Šimůnek et al. (2011b).
[e] Zhu et al. (2011).

total nitrogen balance in the inflow. The simulation are run assuming a constant temperature of 20 °C.

The domain is discretized via triangular mesh elements with catheti parallel to the HF CW length and height. The triangular mesh elements are 1 cm high and 1–5 cm in length to have a finer mesh near the inflow. The maximum time step is set equal to 0.001 d. A modification of the HYDRUS time step adjustment which takes into account model component concentrations was implemented in order to avoid numerical problems. More in detail, HYDRUS code is now implemented with an automatically reduction of the time step in case of a high error in total mass balance of any simulated chemical compounds (e.g., when the O_2 oxygen consumption is too fast). This new feature will be added into future HYDRUS version.

3. Results

The simulated COD effluent concentrations are reported in Fig. 2 (left panels). The simulations follow very well the experimental results in term of global removal efficiency. Indeed, the average global removal efficiencies of simulated COD effluent (68 and 69% for group A and B, respectively) result strongly similar to the values reported in Galvão and Matos (2012)'s experiments (69 and 66% for group A and B, respectively), with a maximum discrepancy of only 3%. Also the simulated behavior of daily COD effluent concentrations adequately follows the measured data, with a mean percent error (MPE – $\left[(COD_m - COD_s)/COD_m\right] \times 100$ – subscript m and s represent measured and simulated, respectively) equal to 22.0 and 17.5% for group A and B, respectively. The trend shows a weekly pattern with sudden effluent decreases driven by the absence of loads during Saturday and Sunday.

Simulated NH_4^+ effluent concentration are reported in Fig. 2, (right panels), showing also in this case a good fit with experimental data. MPE is satisfactorily low even if slightly higher than COD effluent (37.0 and 24.3% for group A and B, respectively), justified by higher uncertainty in NH_4^+ inflow concentration driven by the need to assume a constant NH_4^+/COD during the whole simulations.

In order to test if the water temperature variations are responsible to differences between simulated results and experimental data, additional simulations were run using the temperature data recorded by Galvão and Matos (2012). The results indicate that including temperature variations does not lead to appreciable change in simulated effluent concentrations from Galvão and Matos (2012)'s HF CWs (data not shown).

4. Discussion

The MPE on COD effluent of 20% can be viewed as a good starting point in the study of unsteady COD effluent from HF CWs, since up to now the validation of process-based model results is usually concentrated only on the bulk system response (e.g., Llorens et al., 2011), or via a qualitative check with graphs similar to Fig. 2 (e.g., Samso and Garcia, 2013b).

The good simulation results are obtained with a relatively simple manual calibration, changing only few parameters from the default values. A more refined calibration (e.g., based on optimization algorithms) would not be very useful due to the lack of more detailed input data, e.g. influent NH_4^+ concentrations, tracer experiments (e.g., Ranieri et al., 2013). Despite this lack of information, HYDRUS-CWM1 shows a satisfactory flexibility in calibration of HF CWs with scarcely detailed data.

The great advantage of process-based models is the possibility to isolate the effect of single processes on the whole behavior of the system. An example is given by the simulated COD effluent fractionation exposed in Fig. 3, in which acetate (S_A) results the

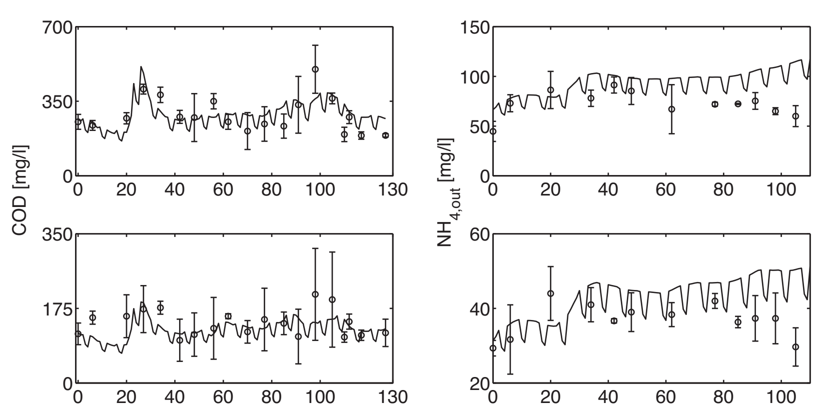

Fig. 2. Comparison between COD (left panels) and NH_4^+ (right panels) effluent concentrations simulated (continuous line) and measured (circle with standard deviation bar) for group A (upper panels) and B (lower panels).

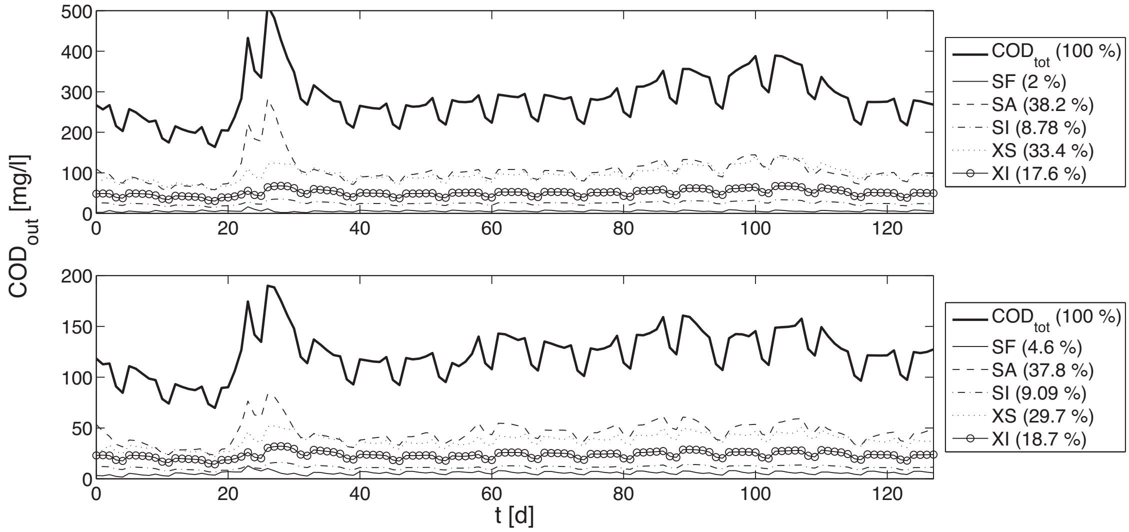

Fig. 3. Simulated fractionation of COD effluent concentration for group A (upper panel) and B (lower panel): total COD (thick continuous line); fermentable, readily biodegradable soluble COD (S_F – thin continuous line); fermentation products as acetate(S_A – dashed line); inert soluble COD (S_I – dash-dotted line); slowly biodegradable particulate COD (X_S – dotted line); inert particulate COD (X_I – continuous line with circles). In the legend are reported the contribution of each component to the total effluent COD expressed in percentages.

most abundant component. This theoretical result is in accordance with other modelling (Samso and Garcia, 2013b) and experimental (Huang et al., 2005) studies. Fig. 3 also shows that the highest COD effluent peak (around 20*th* and 30*th* days) is principally due to S_A, suggesting a lower ability of acetotrophic methanogenic bacteria (X_{AMB}) to degrade S_A at suddenly high COD concentration. However, available experimental data are suitable to verify only the capability of the model to simulate the global performance, i.e. COD concentrations, and not detailed COD effluent fractionation. In the future, more accurate experiments (e.g., measurement of methane emissions (Corbella and Puigagut, 2013)) will be needed in order to test the ability of process-based model to simulate all the included processes and not only the global response of CWs. Generally, more detailed data would strengthen the usefulness of process-based models, confirming theoretical results and allowing to build more detailed models.

5. Conclusions

HYDRUS-CWM1 models very well the global response of Galvão and Matos (2012)'s HF CWs to variable loads, with an average global removal efficiency of simulated COD effluent (68%) similar to the value registered in the experiments (67%). Moreover, modelling results show that HYDRUS-CWM1 adequately simulates also HF CW response to unsteady loads at daily scale, with an acceptable error of 20% on COD effluent concentrations. Even the daily NH_4^+ effluent concentrations are satisfactory captured under more uncertain NH_4^+ inflow information, with a MPE of 31%.

The results of this study suggest that HYDRUS-CWM1 can be used to study HF CWs under unsteady flows, opening new possible future applications. Among these, the stochastic behavior of HF CW outflows is of great interest. Indeed, the randomness of HF CW effluent is generally neglected during the typical design procedure, and the HF CW size should be highly overestimated to face real outflow variability (Kadlec and Wallace, 2009). In this context, HYDRUS-CWM1 can be a powerful tool to better investigate HF CW effluent stochasticity. A future improvement could be the modelling of stochastic influent loads modeled as noisy signals (Ridolfi et al., 2011). In this way, we could investigate if the randomness of effluent loads is driven by the variability of inflow loads. Consequently, we would provide new insights to improve the HF CW design procedure.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecoleng.2014.03.073.

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