

# Design-support and performance estimation using HYDRUS/CW2D: a horizontal flow constructed wetland for polishing SBR effluent

Tamás Gábor Pálffy, Zoltán Gribovszki and Günter Langergraber

## ABSTRACT

The 4,000 PE (700 m<sup>3</sup>/d) wastewater treatment plant at Balf, Hungary was based on sequencing batch reactor technology with phosphorus precipitation as the tertiary step. Its effluent met quality thresholds on average, with above-threshold peaks mainly in winter. The HYDRUS/CW2D model package (PC Progress s.r.o.) was used to simulate the treatment performance of a horizontal flow constructed wetland for polishing effluent. The goal of this study was to provide design-supportive information about the suitability of the proposed wetland and to prove the applicability of the computational tool used to gain that information. The simulations showed that the wetland with the proposed layout could not tackle peaks in NH<sub>4</sub>-N. Other effluent thresholds could be met, including chemical oxygen demand (COD), biochemical oxygen demand (BOD<sub>5</sub>), total nitrogen, total inorganic nitrogen and total phosphorus. The tool was unable to simulate COD and BOD<sub>5</sub> removal in periods when the electron acceptors were depleted because anaerobic processes are not modelled. Using a tool of such complexity for designing carries excessive work demands and involves many uncertainties. The simulation study highlighted that the model used could still facilitate the design of an effective system by showing the weaknesses of a test scenario as it was demonstrated.

**Key words** | constructed wetland, CW2D, design-support, polishing treatment, process-based model, sequencing batch reactor

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## INTRODUCTION

The wastewater treatment plant (WWTP) at Balf, Hungary was based on sequencing batch reactor (SBR) technology and designed for 4,000 PE (capacity 700 m<sup>3</sup>/d, average 180 m<sup>3</sup>/d). The plant was located in the basin of Lake Fertő/Lake Neusiedl, an important natural site, including areas protected by strict national and international laws. The advanced treatment chain included phosphorus precipitation after mechanical and biological treatment. The plant met the effluent quality thresholds set for concentrations of chemical oxygen demand (COD), biochemical oxygen demand (BOD<sub>5</sub>), total nitrogen (TN), total inorganic nitrogen (TIN), NH<sub>4</sub>-N and total phosphorus (TP) on a long-term average. However, the thresholds were breached for short periods due to the variability of the inflow rate and concentrations, and these periods of non-compliance were more frequent during winter (ÉDKTVF 2008; Gribovszki *et al.* 2009).

Extending the treatment chain by a horizontal flow (HF) constructed wetland (CW) was one of the possible solutions

for improving the effluent quality of Balf SBR. Other solutions considered were pumping either the treated or the untreated wastewater out of the watershed of the lake. An HF CW has advantages compared to these solutions, namely it would not negatively affect the water balance of the astatic steppe lake, because the water stays in the basin and it is a low-technology solution meaning low-maintenance costs and work demands (Gribovszki *et al.* 2009). It was assumed that an HF CW is the most robust solution that is capable of flattening occasionally occurring peaks to below legislative thresholds by the combined effect of hydraulic buffering (including a buffer pond), adsorption and biological degradation processes.

The applicability of HF CWs for the tertiary treatment of various types of wastewater has already been confirmed. These systems are capable of polishing treated effluents of domestic wastewater origin (Ayaz 2008, Vymazal 2009, Ghosh & Gopal 2010). The CW2D (Langergraber &

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Šimůnek 2005) biokinetic model implemented in the HYDRUS program package (Šimůnek *et al.* 2011; Langergraber & Šimůnek 2011) (HYDRUS/CW2D) is a tool that had already been used to simulate polishing treatment in pilot-scale wetlands. The results fitted well, measured COD and NO<sub>3</sub>-N, and were slightly above the measured NH<sub>4</sub>-N concentrations regardless of the low temperatures (Toscano *et al.* 2009).

The aim of our study was to show the applicability of a mechanistic computational tool, i.e., HYDRUS/CW2D to support the design of an HF CW. This was to be achieved by simulating the polishing treatment performance of an HF CW with fixed parameters, following practical design considerations. Simulations might help, not only the design, but also provide decision support.

## METHODS

Measured SBR effluent quantity and quality data (2007–2013) were obtained for simulations in HYDRUS/CW2D. Volumetric data were available for every day and water quality data were available from grab samples taken once a week. The measured water quality parameters were COD, BOD<sub>5</sub>, TN, TIN, NH<sub>4</sub>-N, NO<sub>3</sub>-N, NO<sub>2</sub>-N and TP. The concentrations were low because the outflow was the effluent after a tertiary treatment; however, all threshold values (there was no threshold for nitrate and nitrite) were breached at least once. For the numerical simulations, continuous data series for one winter were needed to look at performance in the most critical months. Days with only volumetric data were ignored because quality parameters were necessary for a continuous model input. Days with both quality and volumetric data were grouped by the month of the sampling, giving a realistic data series of an average 26 days for each month. This series is highly reliable compared to randomly assigning quality parameters for every 6 out of 7 days.

The measured quality parameters were slightly different from the input parameters required by CW2D. In the model, COD was defined as three different fractions: slowly (CS) and readily (CR) biodegradable, and inert (CI) COD (Langergraber & Šimůnek 2005). CR was estimated to be 26% of COD, which is the average proportion of BOD<sub>5</sub> and COD, CI was set to a constant value of 9 mg/L (Ghosh & Gopal 2010) and the rest of the COD was allocated as CS. TP was allocated between the organic phosphorus (org. P) and PO<sub>4</sub>-P components of the model, based on an estimated 0.1% P content of the organics after the amendment of

ferrous sulfate at the tertiary step. Organic nitrogen was not measured and the basic composition parameter setting (Langergraber & Šimůnek 2011) was used for calculations. No temperature series were recorded for the wastewater, its value was set to 9 °C for December and February and 8 °C for January based on single measurements made by the operator.

The selection of the filter material and the dimensioning were preliminarily based on literature data and on practical consideration, but it was necessary to set up simulations that can give more specific knowledge of whether the design could or should be improved. The parameters for the filter material were selected based on literature data from the work of Salvato *et al.* (2003):  $\phi$  0–4 mm sand, 86 m/d saturated hydraulic conductivity,  $\theta = 0.3$  for porosity. The adsorption parameters were taken from the literature and are summarized in Table 1. The values are representative for sand media and were set up for the model components CS, NH<sub>4</sub>-N and PO<sub>4</sub>-P.

The total volume of the filter material (1,350 m<sup>3</sup>) was selected based on the average daily hydraulic load and on a targeted nominal retention time of 2.25 days, which is typical for HF CWs (Kadlec & Wallace 2009). The depth of the domain was set to one meter to avoid soil frost, and no plant effects were considered. Eight rectangular beds of 15 × 11.25 m horizontal dimensions with an 0.075 m inclination would enable an optimal arrangement and they were in accordance with the length to width ratio proposed by Kadlec & Wallace (2009).

The water release from the SBR took only 1 hour, which exceeds the intake capacity of the filter beds limited by hydraulic conductivity. A levied buffer pond was added to the theoretical system, which stores the SBR effluent if too many high loadings arrive at the HF CW in a row. The pond has a capacity of 810 m<sup>3</sup> and an outflow limitation of 270 m<sup>3</sup>/d. The outflow limitation was selected near to the peak hydraulic intake capacity of the filters and limits the lowest possible retention time to 1.5 days. A complete

**Table 1** | Parameters used in the simulations to describe the adsorption capacity of the filter material

Component	Isotherm type	Isotherm parameters			
		Kd	Nu	Beta	Alpha
CS	Linear	0.575	0	1	2.4
NH <sub>4</sub> -N	Langmuir	0.9	0.003	1.2	2
PO <sub>4</sub> -P	Langmuir	9	0.044	0.77	1

The values were taken from the literature. CS: Mburu *et al.* (2012), NH<sub>4</sub>-N: Pálffy & Langergraber (2014), and PO<sub>4</sub>-P: Xu *et al.* (2006).

mixing calculated in the pond but any other potential quality-changing effects were ignored.

A 2D domain was simulated in HYDRUS/CW2D, representing the longitudinal section of one of the  $15 \times 1$  m filter beds with  $121 \times 20$  (length  $\times$  depth) finite elements. The first simulations were repeated six times with data from the November months, with a  $10^\circ\text{C}$  inflow in order to get an established bacterium distribution in the domain. The simulations continued, with the winter data for evaluation representing a 77-day period when the performance of the domain was expected to be lowest. The parameters of CW2D (Langergraber & Šimůnek 2011) were unchanged, except for the half-saturation coefficients for dissolved oxygen from the ammonia- and the nitrite-oxidizing bacteria. These were both decreased to 0.0026, based on the work of Pálffy & Langergraber (2014).

## RESULTS AND DISCUSSION

### General remarks

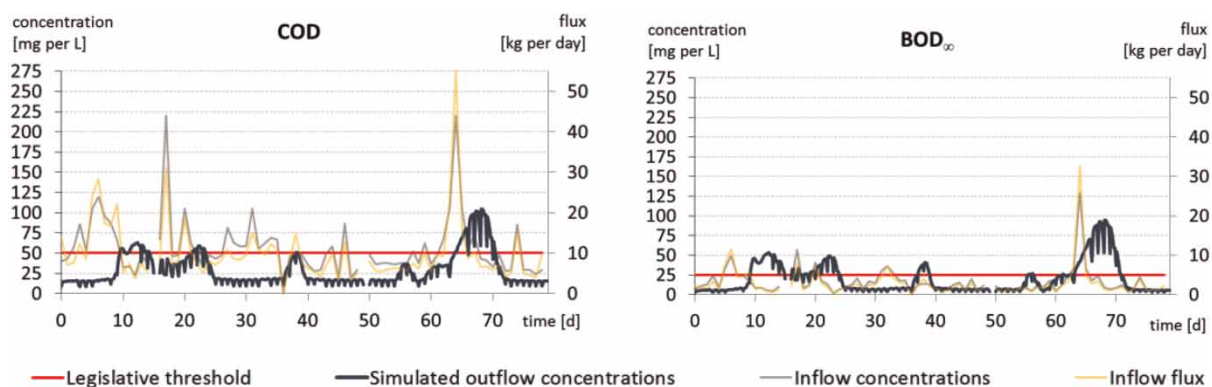
The simulation results predicted the performance of the conceptualized HF CWs for polishing the release of Balf SBR. The measured quality of the SBR effluent (hereafter referred to as 'influent') and the simulated wetland effluent (hereafter referred to as 'effluent') concentrations were compared by each pollutant.

The microbial concentration was at steady-state at the observation points during the simulations, despite the fact that, at the three inflow nodes, the propagation had not stopped and did not seem to converge to a constant value. The microbes have an optimal environment at these inlet points because the inflow contains enough nutrients and

also  $0.1\text{ mg/L}$  SO (dissolved oxygen). This induced an endless growth in CW2D, as described by Samsó & Garcia (2013) for CWM1. At this stage of growth, the bacterium concentrations were in a stable range in the other parts of the filter and concentrations were not detectably effected by the anomaly.

### COD and BOD<sub>5</sub>

The effluent concentrations exceeded the legislative threshold in a few instances. The ideal application field for CW2D is vertical flow CWs, which are aerobic systems; in addition, the CW2D was also listed for usage with low-loaded HF CWs (Langergraber & Šimůnek 2011). Even though the influent had low concentrations, it had peaks with  $225\text{ mg/L}$  COD. Figure 1 shows the quality thresholds for COD and BOD<sub>5</sub> and the effect of the simulated HF CW domain on effluent quality. CW2D does not consider anaerobic processes, so when the electron acceptors were depleted, the biological removal of COD ceased and the domain's only flattening effect was due to adsorption and mixing. Cross-checking the COD with the NO<sub>x</sub>-N values reveals that where the COD values are above the threshold, NO<sub>x</sub>-N was not present in the system. The domain turned anaerobic, and CW2D reached its limits because it lacks anaerobic degradation processes. Therefore, these concentration peaks have to be interpreted with care and they provide an example of why CW2D has to be applied with caution on any HF CWs. The concentrations only slightly exceeded the threshold, even without anaerobic degradation, and therefore these results were rather positive. The same is true for the BOD<sub>∞</sub> which added up as the sum of the readily biodegradable (CR) and slowly biodegradable (CS) COD in the effluent. BOD<sub>∞</sub> is a safe basis for



**Figure 1** | COD and BOD<sub>∞</sub> at the HF CW domain: legislative threshold on concentration, simulated outflow concentrations using HYDRUS/CW2D, and inflow concentrations and solute fluxes representing measured effluent data from Balf WWTP. The threshold on BOD is for BOD<sub>5</sub>. The gaps at days 16 and 50 separate the December, January and February data sets.

comparison to use with BOD<sub>5</sub> thresholds as it represents the total COD minus the non-biodegradable COD (9 mg/L).

## Nitrogen forms

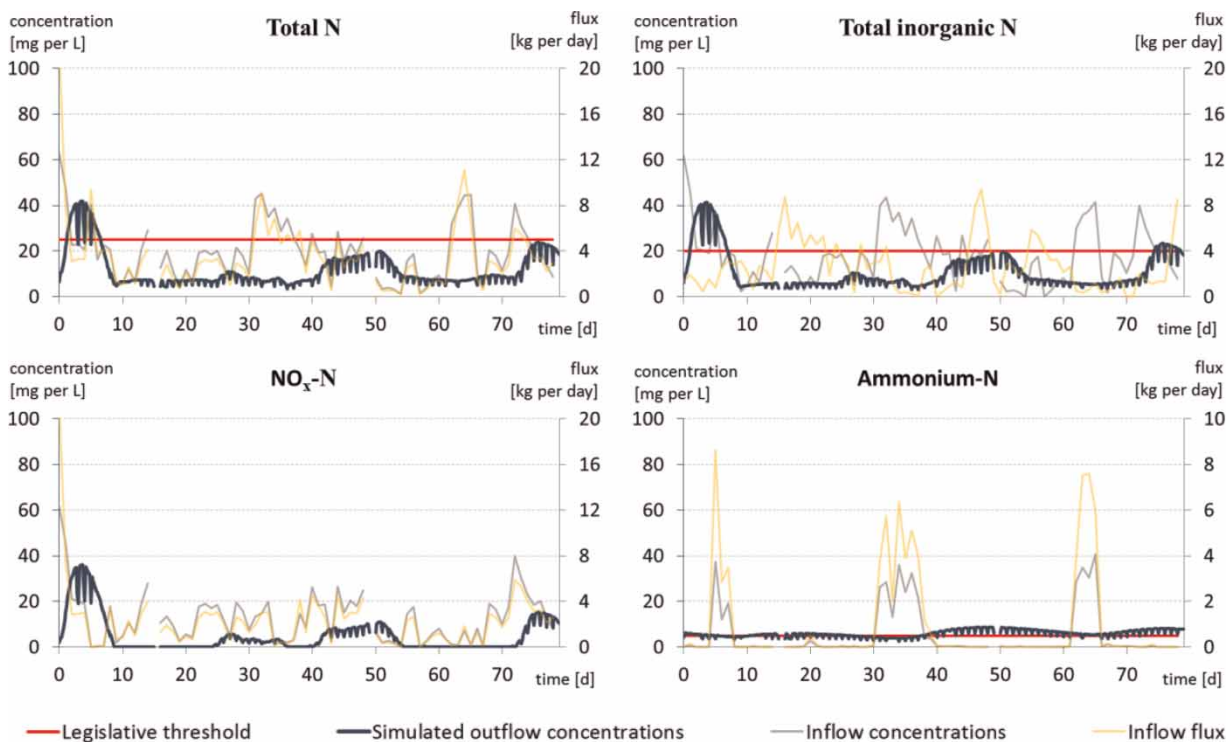
Figure 2 shows the quality thresholds for TN, TIN, NO<sub>x</sub>-N and NH<sub>4</sub>-N and the effect of the simulated HF CW domain on the effluent quality. TN, TIN and NO<sub>x</sub>-N concentrations followed a similar trend in the effluent. NO<sub>x</sub>-N was almost exclusively nitrate and was the main form of nitrogen in periods with increased nitrogen concentrations. TIN and TN breached thresholds after a load of about 60 mg/L nitrate at the beginning of the simulation period but it was predicted that the HF CW would cut all other peaks, keeping them below or at the legislative limits.

The case of ammonium nitrogen was different. The predictions showed a low overall removal rate for the cold period. The main effect of the CW was to rather flatten the peaks, which would be a significant improvement in an ecological sense but would be unsatisfying regarding the legislative limits. The issue could be targeted by mixing a material with high NH<sub>4</sub>-N adsorption capacity with the

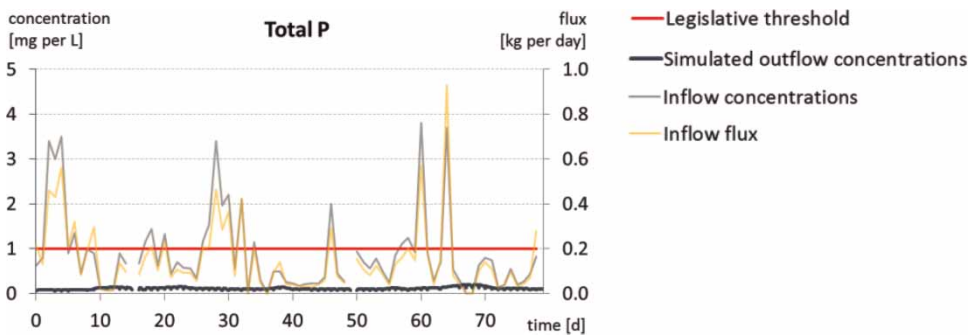
filter media such as, e.g., zeolite. Meyer *et al.* (2014) showed extremely high retention of ammonium in a CW with chabazite (a form of zeolite) mixed with the sand filter media. There was near-zero NH<sub>4</sub>-N present in the influent on days with average influent quality. The absorbed ammonium could be nitrified on such days when the circumstances are more favorable for autotrophs, e.g., warmer days.

## TP

Figure 3 shows the quality thresholds for TP and the effect of the simulated HF CW domain on the effluent quality. TP concentrations were predicted to be kept low by the adsorption capacity of the sand without adding any special media. Adsorption was the main – or only – removal process for phosphorus, and the adsorption sites became saturated with time (Kadlec & Wallace 2009). The presented performance represents the filter at an early stage, the concentration of the sorbed P ranged from 5 to 1 mg/kg dry matter (inlet and outlet zone, respectively). If the removal performance fails in the long term, the installation of a small filter bed filled with high adsorption



**Figure 2** | TN, TIN, nitrate plus nitrite nitrogen (NO<sub>x</sub>-N) and ammonium nitrogen at the HF CW domain: legislative thresholds on concentration, simulated outflow concentrations using HYDRUS/CW2D, and inflow concentrations and solute fluxes representing measured effluent data from Balf WWTP. There is no threshold for NO<sub>x</sub>-N. The gaps at days 16 and 50 separate the December, January and February data sets.



**Figure 3** | TP at the HF CW domain: legislative threshold on concentration, simulated outflow concentrations using HYDRUS/CW2D, and inflow concentrations and solute fluxes representing measured effluent data from Balf WWTP. This performance is representative for the first year of operation. The gaps at days 16 and 50 separate the December, January and February data sets.

capacity material such as furnace slag (Xu *et al.* 2006) might be necessary at the end of the treatment chain.

## CONCLUSIONS

HYDRUS/CW2D is a complex numerical tool and its use for design-support has excessive work demands. However, the present study pointed out that it is possible to use it to reveal the weak points of a preliminary design and, as such, to help to develop an optimized system for a specific site. This kind of application of CW2D and similar models can be rationalized in the case of large-scale projects, or for CW projects with special characteristics, such as the HF CW proposed for the polishing treatment of effluent from the SBR at Balf.

CW2D lacks anaerobic processes and, as such, it has to be used with care for modeling HF CWs. The suggested application fields of CW2D included HF systems if the loads are low. It should also be added that these domains should exclude inflow concentration peaks for pollutants that can cause anaerobic conditions in the wetland. If the simulated domain turns anaerobic, the processes responsible for organic and ammonium transformation cease. Anaerobic degradation would take over in real life and grow to strength as the microbial community adapts to the changes.

The conceptualized polishing treatment chain contained a buffer pond and eight HF CW beds in parallel, with sand filter media, a total surface area of 1,350 m<sup>2</sup> and a depth of one meter. The simulations have shown that adding this system to the existing treatment chain would be satisfying in terms of COD, BOD<sub>5</sub>, TN, TIN and TP removal. However, the wetland would probably fail to tackle the peaks of NH<sub>4</sub>-N of the SBR effluent and therefore a media with

higher NH<sub>4</sub>-N adsorption capacity should be considered. Phosphorus removal would be highly efficient until the media reaches its adsorption capacity in the long term. The results showed no need to mix special media to the filter material to keep TP below the legislative thresholds. However, as the simulations have been run with literature data only, it is advised to carry out laboratory experiments to derive exact data. The experiments would determine filter media properties, including adsorption capacity, prior to implementation to increase the reliability of the predicted treatment efficiency.

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