Influence of design parameters on the treatment performance of VF wetlands – a simulation study

Bernhard Pucher and Guenter Langergraber

ABSTRACT

The main approach for designing vertical flow (VF) treatment wetlands is based on areal requirements ranging from 2 to 4 m² per person equivalent (PE). Other design parameters are the granularity of the filter material, filter depth, hydraulic and organic loading rates, loading intervals, amount of single doses as well as the number of openings in the distribution pipes. The influence of these parameters is investigated by running simulations using the HYDRUS Wetland Module for three VF wetlands with different granularity of the filter material (0.06–4 mm, 1–4 mm, and 4–8 mm, respectively). For each VF wetland, simulations are carried out at different temperatures for different organic loading rates, loading intervals and number of distribution points. Using coarser filter material results in reduced removal of pollutants and higher effluent concentrations if VF wetlands are operated under the same conditions. However, the treatment efficiency can be increased by applying more loadings and/or a higher density of the distribution network. For finer filter material, longer loading intervals are suggested to guarantee sufficient aeration of the VF filter between successive loadings.

Key words | Design, HYDRUS Wetland Module, temperature dependencies, vertical flow wetlands

INTRODUCTION

Within the last decades, treatment wetlands (TWs) have proven to be a sustainable, robust, low cost technology for the treatment of all sorts of polluted waters, including domestic wastewater, combined sewer overflow (CSO), stormwater and all sorts of industrial wastewaters (Stefanakis 2018). When nitrification is required, vertical flow (VF) wetlands are the most appropriate wetland type (Brix & Arias 2005; Dotro et al. 2017).

Several different design approaches exist for TWs; namely, the rule-of-thumb, regression equations, plug-flow models, loading charts and the P-k-C* model. For VF wetlands, the rule-of-thumb approach is often used in national guidelines defining areal loading rates (e.g. Brix & Johansen 2004; Brix & Arias 2005, for Denmark; ÖNORM B 2503 2009, for Austria; and DWA-A 262E 2017; Nivala et al. 2018, for Germany). Other design parameters included in those guidelines are the granularity of the filter material used for the main layer, filter depth (depth of the main layer), hydraulic and organic loading rates (HLR and OLR, respectively), loading intervals, amount of single doses, as well as the distribution onto the surface through pipes. Those parameters vary between the guidelines as well as the required effluent concentrations in different countries. This makes a general comparison of their impact on treatment efficiencies difficult.

While the interest in process-based models that are describing the occurring processes mathematically (Langergraber 2017) over simple or black-box models is increasing, only a few approaches have been made to actually support the design process. According to Stefanakis & Tsihrintzis (2012) the main factors affecting the treatment performance of VF wetlands are as follows:

- Filter material of main layer (grain size of material, filter depth)
- Loading: loading interval, volume of single doses, resting periods
- Loading rate: hydraulic and organic loading rates
- Distribution pipes: number of holes in distribution pipes.
The main goal of this study is to use a process-based numerical model – that is, HYDRUS Wetland Module (Langergraber & Šimůnek 2012) – to investigate the influence of different design parameters on the treatment performance of VF wetlands. The effect of selected design parameters on the treatment performance for domestic wastewater is shown for identical VF wetland systems with a 50 cm main layer comprising three different filter materials: sand 0.06–4 mm, coarse sand 1–4 mm, and gravel 4–8 mm.

MATERIALS AND METHODS

For this simulation study, the HYDRUS Wetland Module – an extension of the HYDRUS software package – with the CW2D biokinetic model has been used (Langergraber & Šimůnek 2012). The CW2D biokinetic model is based on the IWA Activated Sludge Model ASM1 (Henze et al. 2000) and incorporates aerobic and anoxic processes, namely hydrolysis, growth of heterotrophic bacteria (XH) describing mineralization of organic matter as well as denitrification on nitrate and lysis for XH, nitrification as a two-step process describing the growth and lysis of autotrophic bacteria, namely ammonium oxidation by Nitrosomonas spp. (XANs) and nitrite oxidation by Nitrobacter spp. (XANb).

The soil hydraulic model involves solving the highly nonlinear Richards equation, which characterizes the relationships between the water content, capillary pressure head, and unsaturated hydraulic conductivity (Twarakavi et al. 2008). Up to now, only the van Genuchten-Mualem model (van Genuchten 1980) has been coupled with the HYDRUS Wetland Module, which is working well with fine filter media, up to 0.06–4 mm, but leads to an overestimation of the hydraulic retention time (HRT) and unsaturation during simulations for the following operational settings were run for:

- organic loading rates (OLRs) of 20, 40 and 80 g COD m\(^{-2}\).d\(^{-1}\);
- loading intervals of 1, 3, 6 and 12 hours;
- number of holes per m\(^2\) in distribution pipes: 0.5, 1, 2, 4; and
- water temperature: 5, 10, 15 and 20 °C.

Thus, for each filter material, 192 simulations were run (in total 576 simulations for all three filter materials). Figure 1 illustrates the overall simulation approach.

Experimental data used for calibrating the wetland model were as follows: measured volumetric effluent flow rates for calibration of the water flow model as well as measured influent and effluent concentrations of chemical oxygen demand (COD) and NH\(_4\)-N for calibration of the pollutant transport and degradation model. For the VF wetlands with filter materials 0.06–4 mm and 1–4 mm, the wetland models have been calibrated on data described by Canet Martí et al. (2018) and Pucher & Langergraber (2018), respectively. For theVF wetlands system with 4–8 mm gravel, volumetric effluent flow measurements were carried out at BOKU University Vienna, whereas concentration data came from the system described by Nivala et al. (2019). Table 1 summarises the main operational parameters of the VF wetlands for which the wetland models were calibrated.

For each of the calibrated wetland models (i.e. filter materials), simulations for the following operational settings were run for:

Table 1 | Main VF wetland operational parameters of the data sets used for calibration

<table>
<thead>
<tr>
<th>Filter material</th>
<th>Loading interval (h)</th>
<th>Organic loading rate (g COD m(^{-2}).d(^{-1}))</th>
<th>Number of openings per m(^2)</th>
<th>Data for calibration</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.06–4 mm</td>
<td>6</td>
<td>20</td>
<td>0.5</td>
<td>Water flow and concentration: Canet Martí et al. (2018)</td>
</tr>
<tr>
<td>1–4 mm</td>
<td>3</td>
<td>80</td>
<td>1</td>
<td>Water flow and concentration: Pucher &amp; Langergraber (2018)</td>
</tr>
<tr>
<td>4–8 mm</td>
<td>1</td>
<td>80</td>
<td>1</td>
<td>Water flow: measurements at BOKU University Vienna; concentrations: Nivala et al. (2019)</td>
</tr>
</tbody>
</table>

Figure 1 | Illustration of the simulation approach.
Each simulation covered about 200 days simulation time. Results are presented as median and maximum values of effluent concentrations over the last 5 days of each simulation. The same influent concentrations have been used for all simulations and all VF wetlands (Table 2). The higher OLRs have been simulated by applying higher hydraulic loads; that is, larger volumes of single doses.

For the specific wastewater composition used (Langergraber et al. 2010), the COD fractionation was as follows: CI (inert organic matter) was set to the measured influent COD concentration while the ratio of readily to slowly biodegradable organic matter; that is, CR:CS, was 2:1. The calibration was carried out by Canet Martí et al. (2018). The same fractionation was used for all three models.

It has to be noted that not all combinations of operational setting are applicable; that is, for VF wetlands using 0.06–4 mm sand as filter material in temperate climates an OLR of 40 g COD m⁻².d⁻¹ can only be applied when the systems are operated during the summer months, whereas an OLR of 80 g COD m⁻².d⁻¹ leads to clogging of the system. For the other filter material, all OLRs are applicable.

### RESULTS AND DISCUSSION

#### Model set-up and calibration

The transport domain of the model is set up as a two-dimensional finite element mesh representing 1 m² surface area. The higher hydraulic loads; that is, larger volumes of single doses.

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Influent concentrations (in mg.L⁻¹) used for the simulation study (from Langergraber et al. 2010)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
<td>COD</td>
</tr>
<tr>
<td>Influent</td>
<td>495</td>
</tr>
</tbody>
</table>

CR – readily and slowly biodegradable COD; CS – slowly biodegradable COD; CI – inert COD.

#### Simulation results for VF wetlands

Table 4 shows the simulated COD effluent concentrations for the different filter materials and different OLRs. VF wetlands in Table 4 were loaded every 6 hours with distribution pipes having 0.5 holes per m² (these are standard design values for VF wetlands using sand with grain size of 0.06–4 mm as filter material). Table 5 shows simulated NH₄-N effluent concentrations for the same settings.

Tables 4 and 5 clearly show the importance of the filter material used for the main layer on the achievable COD and NH₄-N effluent concentrations. The coarser the filter material of the main layer, the higher the effluent concentrations. If operated with the same loading interval, at higher OLR higher single doses are applied. When coarser filter material is used for the main layer, this results in higher flow velocities in the filter and thus reduced removal...
efficiencies. The increase is even more significant for maximum COD and NH$_4$-N effluent concentrations. A higher increase of the maximum compared to the median COD and NH$_4$-N effluent concentrations can also be observed at lower temperatures.

**Effect of design parameters on the treatment performance**

Table 6 shows simulated COD effluent concentrations of VF wetlands loaded every 6 hours and operated with an OLR of 20 g COD m$^{-2}$d$^{-1}$ that have different numbers of holes in the distribution pipes per m$^2$. At lower temperatures, a larger number of openings decreases simulated COD effluent concentrations (both median and maximum values). A larger number of openings decreases the water flow in the filter and thus increases the retention time, allowing better COD removal at lower temperatures. For higher temperatures the effect is different: median and maximum COD effluent concentrations even increase because the decreased water flow hinders sufficient re-oxygenation of the filter. Table 7 shows that a decrease of median and maximum COD effluent concentrations can be also achieved at a high OLR of 80 g COD m$^{-2}$d$^{-1}$ for coarser filter materials and all temperatures.

Figures 2 and 3 show the effect of different loading intervals and different numbers of holes in the distribution pipes on simulated COD and NH$_4$-N effluent concentrations, respectively, for a VF wetland with a 50 cm main layer of sand (0.06–4 mm) operated with an OLR of 20 g COD m$^{-2}$d$^{-1}$. As expected, the simulated COD effluent concentrations were lower at higher temperatures for both COD and NH$_4$-N.

**Table 4** | Median and maximum COD effluent concentrations in mg/L of VF wetlands loaded every 6 hours with 0.5 holes in distribution pipes per m$^2$ (maximum concentrations in brackets)

<table>
<thead>
<tr>
<th>Filter material</th>
<th>OLR g COD m$^{-2}$d$^{-1}$</th>
<th>5°C</th>
<th>10°C</th>
<th>15°C</th>
<th>20°C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Median (Max)</td>
<td>Median (Max)</td>
<td>Median (Max)</td>
<td>Median (Max)</td>
<td>Median (Max)</td>
</tr>
<tr>
<td>0.06–4 mm</td>
<td>20</td>
<td>42 (45)</td>
<td>24 (25)</td>
<td>18 (18)</td>
<td>17 (17)</td>
</tr>
<tr>
<td></td>
<td>40$^a$</td>
<td>79 (86)</td>
<td>48 (55)</td>
<td>28 (33)</td>
<td>21 (23)</td>
</tr>
<tr>
<td></td>
<td>80$^a$</td>
<td>115 (136)</td>
<td>82 (108)</td>
<td>55 (81)</td>
<td>39 (58)</td>
</tr>
<tr>
<td>1–4 mm</td>
<td>20</td>
<td>56 (65)</td>
<td>32 (38)</td>
<td>21 (24)</td>
<td>19 (20)</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>97 (117)</td>
<td>63 (85)</td>
<td>40 (57)</td>
<td>27 (59)</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>131 (149)</td>
<td>100 (130)</td>
<td>67 (107)</td>
<td>43 (86)</td>
</tr>
<tr>
<td>4–8 mm</td>
<td>20</td>
<td>58 (67)</td>
<td>33 (40)</td>
<td>23 (26)</td>
<td>20 (22)</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>99 (119)</td>
<td>65 (87)</td>
<td>43 (58)</td>
<td>27 (43)</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>139 (148)</td>
<td>104 (127)</td>
<td>73 (106)</td>
<td>47 (86)</td>
</tr>
</tbody>
</table>

$^a$OLR > 20 g COD m$^{-2}$d$^{-1}$ is not experimentally verified in temperate climates.

**Table 5** | Median and maximum NH$_4$-N effluent concentrations in mg/L of VF wetlands loaded every 6 hours with 0.5 holes in distribution pipes per m$^2$ (maximum concentrations in brackets)

<table>
<thead>
<tr>
<th>Filter material</th>
<th>OLR g COD m$^{-2}$d$^{-1}$</th>
<th>5°C</th>
<th>10°C</th>
<th>15°C</th>
<th>20°C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Median (Max)</td>
<td>Median (Max)</td>
<td>Median (Max)</td>
<td>Median (Max)</td>
<td>Median (Max)</td>
</tr>
<tr>
<td>0.06–4 mm</td>
<td>20</td>
<td>4.0 (4.0)</td>
<td>1.1 (1.1)</td>
<td>0.4 (0.4)</td>
<td>0.1 (0.1)</td>
</tr>
<tr>
<td></td>
<td>40$^a$</td>
<td>3.1 (3.6)</td>
<td>1.3 (1.4)</td>
<td>0.4 (0.4)</td>
<td>0.1 (0.1)</td>
</tr>
<tr>
<td></td>
<td>80$^a$</td>
<td>1.4 (9.3)</td>
<td>0.2 (5.6)</td>
<td>0.1 (4.5)</td>
<td>0.1 (4.7)</td>
</tr>
<tr>
<td>1–4 mm</td>
<td>20</td>
<td>29.8 (29.9)</td>
<td>8.0 (8.1)</td>
<td>2.9 (3.0)</td>
<td>0.9 (1.0)</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>28.1 (30.3)</td>
<td>7.1 (8.9)</td>
<td>2.9 (3.2)</td>
<td>1.1 (2.1)</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>34.9 (43.3)</td>
<td>15.6 (30.3)</td>
<td>14.1 (28.7)</td>
<td>16.7 (28.8)</td>
</tr>
<tr>
<td>4–8 mm$^b$</td>
<td>20</td>
<td>30.5 (30.6)</td>
<td>7.5 (7.5)</td>
<td>2.8 (2.9)</td>
<td>1.0 (1.0)</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>27.0 (29.0)</td>
<td>6.1 (8.3)</td>
<td>2.7 (3.0)</td>
<td>1.0 (1.6)</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>34.8 (41.7)</td>
<td>13.9 (27.8)</td>
<td>13.9 (26.3)</td>
<td>14.8 (26.2)</td>
</tr>
</tbody>
</table>

$^a$OLR > 20 g COD m$^{-2}$d$^{-1}$ is not experimentally verified in temperate climates.

$^b$Results for NH$_4$-N of the 4–8 mm main layer could not be fitted well (see Pucher & Langergraber 2018).
concentrations (Figure 2) increase if water temperatures decrease. If the distribution network gets denser (i.e. more openings per m²), the removal efficiencies increase. The reduction is even more significant for maximum effluent concentrations (dashed lines in Figure 2). For the OLR of 20 g COD m⁻².d⁻¹ no significant differences at NH₄-N...
effluent concentrations can be observed for different loading intervals and more openings per m², respectively (Figure 3).

Figures 4 and 5 show the same graphs for simulated COD and NH₄⁻N effluent concentrations, respectively, for a VF filter with main layer of coarse sand (1–4 mm) operated with an OLR of 80 g COD m⁻².d⁻¹. The removal efficiencies for COD and NH₄⁻N can be increased if (a) the loading interval is decreased (i.e. more doses with less volume per
single dose) or (b) the distribution network gets denser (i.e. more openings per m²). Both measures lead to lower water flow velocities in the filter and thus to higher performance and lower effluent concentrations. Again, the reduction is more significant for maximum effluent concentrations (dashed lines in Figures 4 and 5, respectively). If the same loading interval is applied, the difference between maximum and median effluent concentrations gets less by increasing the density of holes in the distribution pipes (i.e. less volume of water per opening and thus lower flow velocities).

Figures 6 and 7 show the results for a VF filter with main layer of gravel (4–8 mm) operated with an OLR of 80 g COD m⁻².d⁻¹ for simulated COD and NH₄-N effluent concentrations, respectively. The results are similar to those in Figures 4 and 5 and also show that if gravel is used low COD and NH₄-N effluent concentrations can be obtained when more loadings (i.e. shorter loading intervals) and/or a higher density of the distribution network (i.e. more openings per m²) are applied.

Additional results for the following combinations of design parameters are shown in the supplementary material (available with the online version of this paper):

- Filter material sand (0.06–4 mm) and OLR of 40 g COD m⁻².d⁻¹ (Figures S-1 and S-2).
- Filter material coarse sand (1–4 mm) and OLRs of 20 g COD m⁻².d⁻¹ (Figures S-3 and S-4) and 40 g COD m⁻².d⁻¹ (Figures S-5 and S-6).
- Filter material gravel (4–8 mm) and OLRs of 20 g COD m⁻².d⁻¹ (Figures S-7 and S-8) and 40 g COD m⁻².d⁻¹ (Figures S-9 and S-10).

The results show that the impact of design parameters on VF wetland treatment performance is similar to the impact of the design parameter of recirculating sand filter performance. Also for these systems, main design parameters impacting performance are filter media granular size, filter media depth, hydraulic and organic loading rates, and dosing frequency. Similar effects on the
treatment performance have been reported (Crites & Tchobanoglous 1998).

CONCLUSIONS

From the simulation study, the following can be concluded:

- Design parameters such as filter material, organic loading rate, loading intervals and number of openings per m² have a significant influence on the simulated treatment performance of VF wetlands.
- For VF wetlands that are operated under the same conditions, a coarser filter material results in reduced removal of pollutants and higher effluent concentrations.
- For fine filter material (e.g. 0.06–4 mm sand) the differences in removal efficiencies are not significant when using a longer loading interval and a higher density of distribution network. Longer loading intervals are preferable to maintain better aeration of the filter between loadings.
- For coarse filter material (e.g. 4–8 mm gravel) better treatment efficiency can be obtained by applying more loadings (i.e. shorter loading intervals) and/or a higher density of distribution network (i.e. more openings per m²).
- The changes in effluent concentrations are more significant for maximum effluent concentrations compared to median values.

ACKNOWLEDGEMENTS

The authors would like to thank their colleagues Sebastian Handl and David Kerschbaumer for their support in setting up an R-Code for the data analysis. Jamie Nivala (UFZ Leipzig) supported this work by sharing data of an experimental site using 4–8 mm gravel.

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First received 4 June 2019; accepted in revised form 29 July 2019. Available online 2 August 2019