




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

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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 2505 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.

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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 therefore of the treatment performance for coarser media when using the standard parameter set for the biokinetic model (Langergraber & Šimůnek 2012). A detailed description of this topic is available elsewhere (Morvannou *et al.* 2013; Pucher & Langergraber 2018).

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 $\text{NH}_4\text{-N}$ 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 the VF 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:

- organic loading rates (OLRs) of 20, 40 and 80 g COD $\text{m}^{-2}\cdot\text{d}^{-1}$;
- 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.

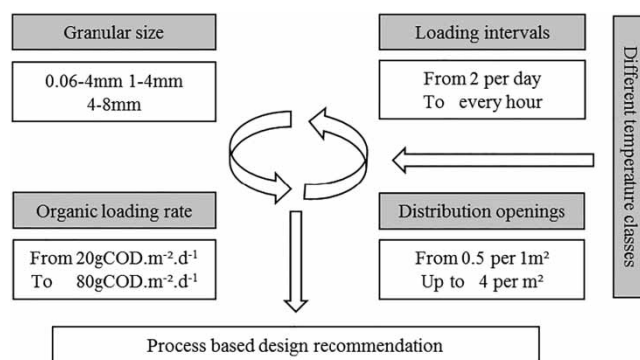


Figure 1 | Illustration of the simulation approach.

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

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

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 effluent 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

Table 2 | Influent concentrations (in mg.L⁻¹) used for the simulation study (from Langergraber *et al.* 2010)

Parameter	COD	CR	CS	CI	NH ₄ -N	NO ₂ -N	NO ₃ -N	PO ₄ -P
Influent	495	325	163	7	65	0.015	0.4	11.9

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

Table 3 | Soil hydraulic parameters of the van Genuchten - Mualem model for the different filter materials as results of the simulations using Inverse Solution in HYDRUS

Filter material	Parameter Unit	Qr cm ³ .cm ⁻³	Qs cm ³ .cm ⁻³	α cm ⁻¹	n	Ks. cm.h ⁻¹	l
Sand 0.06–4 mm ^a		0.045	0.42	0.065	3.164 ^a	128	0.974
Coarse sand 1–4 mm ^b		0.063	0.37	0.124	3.2	3,300	0.49
Gravel 4–8 mm ^c		0.105	0.38	0.133	4	9,000	0.013

^aCanet Martí *et al.* (2018).

^bPucher *et al.* (2017).

^cThis study.

of a VF wetlands. The models were set up as identical despite the filter material used for the 50 cm main layer.

The soil hydraulic parameters of the three filter materials used for the main layers were obtained by running the inverse simulations provided by the HYDRUS software. The objective functions for the inverse simulation were obtained from the measured effluent flow data (Table 1). Table 3 shows the soil hydraulic parameters for the three main layers.

For simulations of the VF wetlands with filter material 0.06–4 mm sand, the standard parameter set of the CW2D biokinetic model (Langergraber & Šimůnek 2012) was used (Canet Martí *et al.* (2018)). The value of the maximum aerobic growth rate of XANs in the standard parameter set is $\mu_{ANs} = 0.9 \text{ d}^{-1}$. For coarse sand 1–4 mm, μ_{ANs} was amended to 0.2538 d⁻¹ to take into account the over prediction of the HRT for materials without a fraction smaller than 1 mm (for the calibration procedure, see Pucher & Langergraber 2018). The same value for μ_{ANs} was used for the simulations of the VF filters with 4–8 mm gravel.

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

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 m² (maximum concentrations in brackets)

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

^aOLR > 20 g COD m⁻².d⁻¹ is not experimentally verified in temperate climates.

Table 5 | Median and maximum NH₄-N effluent concentrations in mg/L of VF wetlands loaded every 6 hours with 0.5 holes in distribution pipes per m² (maximum concentrations in brackets)

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

^aOLR > 20 g COD m⁻².d⁻¹ is not experimentally verified in temperate climates.

^bResults for NH₄-N of the 4–8 mm main layer could not be fitted well (see Pucher & Langergraber 2018).

efficiencies. The increase is even more significant for maximum COD and NH₄-N effluent concentrations. A higher increase of the maximum compared to the median COD and NH₄-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 m². 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.

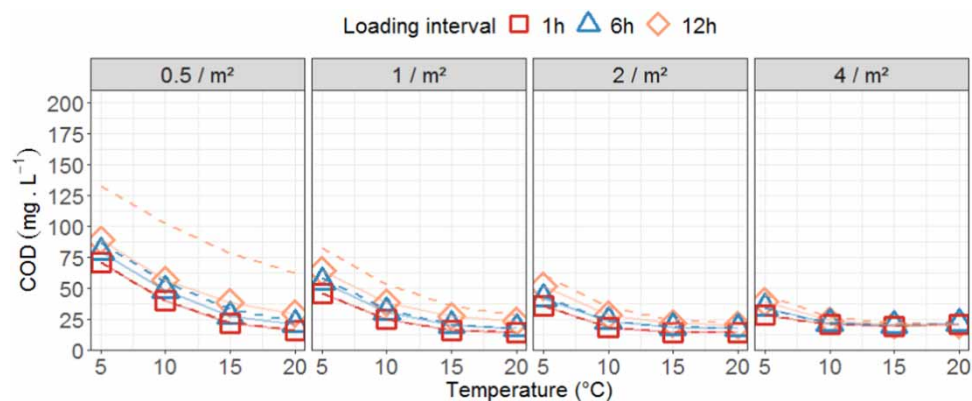
Figures 2 and 3 show the effect of different loading intervals and different numbers of holes in the distribution pipes on simulated COD and NH₄-N effluent concentrations, respectively, for a VF wetland with a 50 cm main layer of sand (0.06–4 mm) operated with an OLR of 20 g COD m⁻².d⁻¹. As expected, the simulated COD effluent

Table 6 | Median and maximum COD effluent concentrations in mg.L^{-1} of VF wetlands loaded every 6 hours operated with an OLR of $20 \text{ g COD m}^{-2}.\text{d}^{-1}$ (maximum concentrations in brackets)

Filter material	Holes in distr. pipes per m^2	5 °C		10 °C		15 °C		20 °C	
		Median	(Max)	Median	(Max)	Median	(Max)	Median	(Max)
0.06–4 mm	0.5	42	(45)	24	(25)	18	(18)	17	(17)
	1	27	(28)	18	(19)	17	(17)	18	(18)
	2	23	(23)	18	(18)	18	(18)	19	(19)
	4	23	(23)	21	(22)	22	(23)	24	(24)
1–4 mm	0.5	56	(65)	32	(38)	21	(24)	19	(20)
	1	38	(42)	23	(25)	19	(19)	19	(19)
	2	31	(33)	20	(20)	19	(19)	20	(20)
	4	28	(30)	20	(20)	20	(20)	20	(20)
4–8 mm	0.5	58	(67)	33	(40)	23	(26)	20	(22)
	1	38	(43)	23	(26)	20	(21)	21	(21)
	2	27	(30)	20	(21)	21	(21)	22	(22)
	4	24	(26)	20	(20)	20	(20)	22	(22)

Table 7 | Median and maximum COD effluent concentrations in mg.L^{-1} of VF wetlands loaded every 6 hours operated with an OLR of $80 \text{ g COD m}^{-2}.\text{d}^{-1}$

Filter material	Holes in distr. pipes per m^2	5 °C		10 °C		15 °C		20 °C	
		Median	(Max)	Median	(Max)	Median	(Max)	Median	(Max)
1–4 mm	0.5	131	(149)	100	(130)	67	(107)	43	(86)
	1	123	(139)	84	(118)	56	(92)	38	(73)
	2	101	(118)	63	(84)	38	(55)	25	(37)
	4	92	(115)	58	(81)	37	(57)	25	(38)
4–8 mm	0.5	139	(148)	104	(127)	73	(106)	47	(86)
	1	126	(143)	90	(117)	63	(91)	38	(74)
	2	110	(132)	70	(97)	42	(68)	31	(50)
	4	95	(114)	61	(82)	36	(52)	25	(37)

**Figure 2** | Simulated COD effluent concentrations of a VF filter with main layer of sand (0.06–4 mm) for an OLR of $20 \text{ g COD m}^{-2}.\text{d}^{-1}$ for different loading intervals and different number of holes in the distribution pipes (median concentrations: symbols; maximum concentrations: dashed lines).

concentrations (Figure 2) increase if water temperatures decrease. If the distribution network gets denser (i.e. more openings per m^2), the removal efficiencies increase. The

reduction is even more significant for maximum effluent concentrations (dashed lines in Figure 2). For the OLR of $20 \text{ g COD m}^{-2}.\text{d}^{-1}$ no significant differences at $\text{NH}_4\text{-N}$

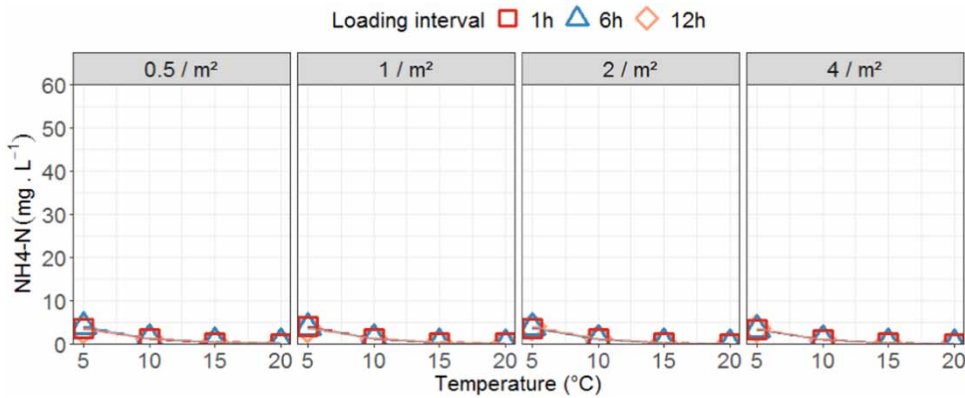


Figure 3 | Simulated $\text{NH}_4\text{-N}$ effluent concentrations of a VF filter with main layer of sand (0.06–4 mm) for an OLR of $20 \text{ g COD m}^{-2}.\text{d}^{-1}$ for different loading intervals and different number of holes in the distribution pipes (median concentrations: symbols; maximum concentrations: dashed lines).

effluent concentrations can be observed for different loading intervals and more openings per m^2 , respectively (Figure 3).

Figures 4 and 5 show the same graphs for simulated COD and $\text{NH}_4\text{-N}$ effluent concentrations, respectively, for

a VF filter with main layer of coarse sand (1–4 mm) operated with an OLR of $80 \text{ g COD m}^{-2}.\text{d}^{-1}$. The removal efficiencies for COD and $\text{NH}_4\text{-N}$ can be increased if (a) the loading interval is decreased (i.e. more doses with less volume per

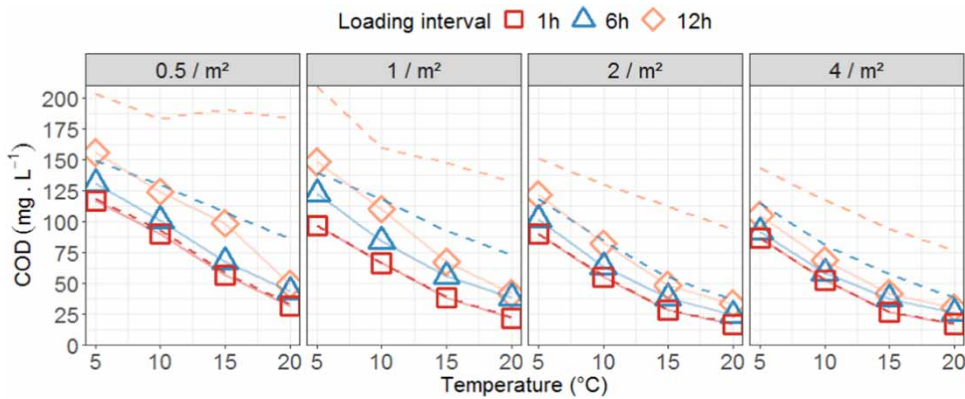


Figure 4 | Simulated COD effluent concentrations of a VF filter with main layer of coarse sand (1–4 mm) for an OLR of $80 \text{ g COD m}^{-2}.\text{d}^{-1}$ for different loading intervals and different number of holes in the distribution pipes (median concentrations: symbols; maximum concentrations: dashed lines).

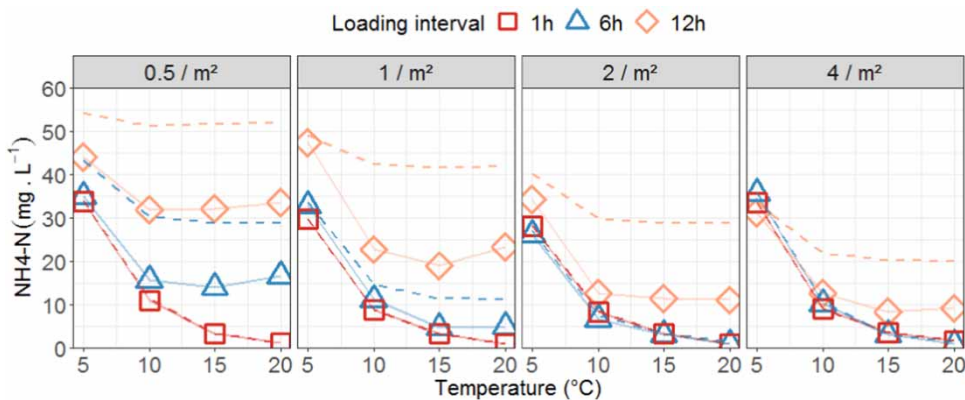


Figure 5 | Simulated $\text{NH}_4\text{-N}$ effluent concentrations of a VF filter with main layer of coarse sand (1–4 mm) for an OLR of $80 \text{ g COD m}^{-2}.\text{d}^{-1}$ for different loading intervals and different number of holes in the distribution pipes (median concentrations: symbols; maximum concentrations: dashed lines).

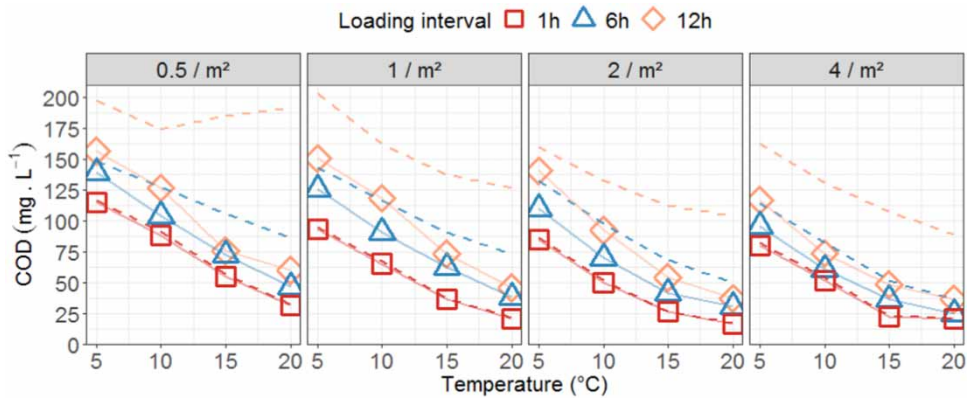


Figure 6 | Simulated COD effluent concentrations of a VF filter with main layer of gravel (4–8 mm) for an OLR of $80 \text{ g COD m}^{-2} \cdot \text{d}^{-1}$ for different loading intervals and different number of holes in the distribution pipes (median concentrations: symbols; maximum concentrations: dashed lines).

single dose) or (b) the distribution network gets denser (i.e. more openings per m^2). 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 $80 \text{ g COD m}^{-2} \cdot \text{d}^{-1}$ for simulated COD and $\text{NH}_4\text{-N}$ 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 $\text{NH}_4\text{-N}$ 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 m^2) 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 $40 \text{ g COD m}^{-2} \cdot \text{d}^{-1}$ (Figures S-1 and S-2).
- Filter material coarse sand (1–4 mm) and OLRs of $20 \text{ g COD m}^{-2} \cdot \text{d}^{-1}$ (Figures S-3 and S-4) and $40 \text{ g COD m}^{-2} \cdot \text{d}^{-1}$ (Figures S-5 and S-6).
- Filter material gravel (4–8 mm) and OLRs of $20 \text{ g COD m}^{-2} \cdot \text{d}^{-1}$ (Figures S-7 and S-8) and $40 \text{ g COD m}^{-2} \cdot \text{d}^{-1}$ (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

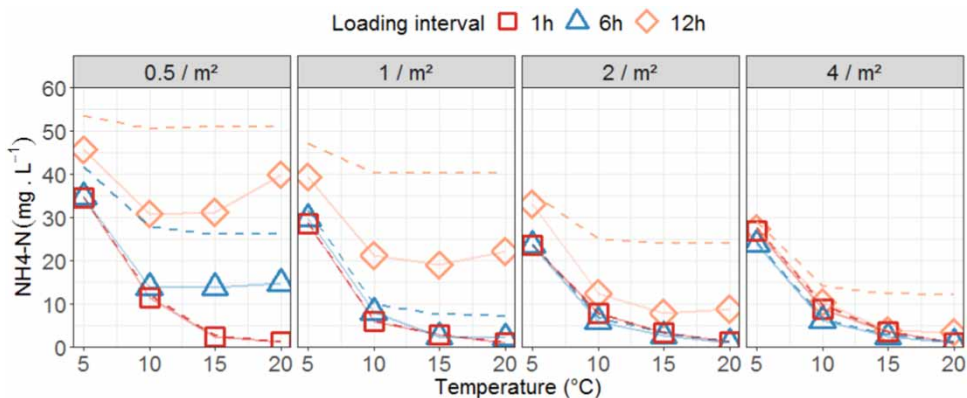


Figure 7 | Simulated $\text{NH}_4\text{-N}$ effluent concentrations of a VF filter with main layer of gravel (4–8 mm) for an OLR of $80 \text{ g COD m}^{-2} \cdot \text{d}^{-1}$ for different loading intervals and different number of holes in the distribution pipes (median concentrations: symbols; maximum concentrations: dashed lines).

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.

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