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Numerical Simulation of vertical flow wetlands with special emphasis on treatment performance during winter

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Abstract

In Austria, single stage vertical flow (VF) wetlands with intermittent loading are a state-of-the-art technology for treating domestic wastewater. They are designed according to the Austrian design standard with a specific surface area of 4 m^2 per person (i.e. 20 g COD/m^2/d) and thus demand a bigger amount of land to treat the same amount of wastewater compared to intensified technical treatment systems. In order to reduce the amount of land needed, a modified design for VF wetlands have been proposed. The modified design has a specific surface area of 2.5 m^2 per person (i.e. 32 g COD/m^2/d) and it has been shown to be able to meet the Austrian effluent requirements. To allow higher organic loading, more loadings per day but lower volume of a single loading, a constant loading interval, and increased number of openings per m^2 are applied. A simulation study using the HYDRUS Wetland Module was carried out to compare the treatment efficiencies of single-stage VF wetlands with classical and modified design. Data from a classical Austrian single-stage VF wetland was used for calibration of the model using the standard parameter set for the CW2D biokinetic model. The influent COD fractionation was calibrated to adapt to the wastewater. The simulations showed a good performance of the modified design compared to a classical VF wetland for COD removal with COD effluent concentrations in winter (effluent water temperature of 4.5 °C) of 35 and 29 mg/L, respectively. The simulation study showed that during high-loading events the VF wetland with modified design has lower maximum NH_4-N effluent concentrations. Single-stage VF wetlands with modified design seem to be very effective and allow applying higher organic loads compared to single-stage VF wetlands with classical design.

Keywords

HYDRUS Wetland Module, numerical simulation, specific surface area, Treatment wetlands, vertical flow.

INTRODUCTION

Treatment wetlands (TWs) are engineered systems designed to optimize the chemical, physical and biogeochemical processes that occur in wetland ecosystems to treat wastewater. TWs have a broad range of applications, ranging from secondary and/or tertiary treatment of urban wastewater (Dotro et al. 2017), treatment of raw wastewater in French VF wetlands (Molle et al., 2005), to specific treatments, such as industrial effluents treatment, water recycling or sludge dewatering (Wu et al., 2015; Martín et al., 2013; Brix, 2017).

In Austria ammonia nitrogen has to be removed for all wastewater treatment plants (WWTPs), the maximum allowed effluent concentration for small WWTPs (≤ 500 persons connected) is 10 mg NH4-N/L at effluent water temperatures higher than 12 °C (1.AEVkA, 1996). Thus, only vertical flow (VF) wetlands can be implemented. Therefore, single stage VF wetlands with intermittent loading are a state-of-art technology used for secondary treatment of domestic wastewater. In fact, 20% of all small WWTPs in Austria are VF wetlands (Langergraber et al., 2018) and most of them are designed according to the Austrian design standard (ÖNORM B 2505, 2009) with a specific surface area of 4 m^2 per person. Those VF wetlands are situated mostly in rural areas, where VF wetlands are a very suitable technology for wastewater treatment due to its robustness, the low operation, and maintenance requirements and the high availability of land required. Decreasing the specific area required would allow TWs to be used in other areas with less availability of land.

A modified design approach has been proposed and implemented in Austria by a company. This modified design aims to reduce the specific surface area requirement to 2.5 m^2 per person by still meeting the Austrian effluent standards. Additional differences of the modified design are the higher number of loadings, a controlled loading interval and the density of openings in the distribution pipes (Table 1).

Table 1: Differences of VF wetland design parameters

Design	***Classical Austrian single-stage VF wetland (ÖNORM B 2505, 2009)***	***Modified design***
Specific surface area	4 m^2 per person	2.5 m^2 per person
Organic load	20 g COD/m^2/d	32 g COD/m^2/d
Loadings	3-4 times per day	8 times per day
Loading interval	Not controlled, depending on wastewater generation	Controlled, every 3 hours (storage tank required)
Openings distribution pipes	1 per 2 m^2	1 per m^2

The aim of this work is to compare the effluent quality of classical Austrian single-stage VF wetlands during winter conditions with different design parameters. For comparing the different VF wetland designs, a numerical simulation study using the HYDRUS Wetland Module (Langergraber and Šimůnek, 2012) was carried out. The simulations have been run for different temperatures and focus on the operation in winter, as these correspond to the most extreme conditions to which the treatment system is subjected.

MATERIALS AND METHODS

Experimental Data

Table 2 shows measured effluent flow and quality data used for this work that were obtained in 2008 from the experimental site situated in the WWTP Ernsthofen (Lower Austria). The VF wetland was designed according to the Austrian design standards for secondary treatment with a specific surface area of 4 m^2 per person, i.e. it was loaded with an organic load of 20 g COD/m^2/d. The total surface area of the VF bed was 20 m² (4 m width, 5 m length) and 4 pipes evenly distributed along the width of the bed were used to distribute the wastewater on the surface of the bed. The grain size of the sand used for the 50 cm main layer was 0.06-4 mm (d_{10} = 0.2 mm; d_{60} = 0.8 mm). Additionally, the filter consisted of a 10 cm intermediate layer with grain size 4-8 mm and a 15 cm drainage layer with grain size 16-32 mm. The VF wetland was planted with common reed (*Phragmites australis*). It was constructed in spring 2003 and has been in operation for 5 years at the time the data were collected.

Table 2: Measured influent and effluent concentrations at different temperatures for the classical Austrian single-stage VF wetland (data derived from Langergraber et al., 2010).

Parameter	**Temperature**	**COD**	**NH_4-N**	**NO_2-N**	**NO_3-N**	**PO_4-P**
Unit	°C	mg/L	mg/L	mg/L	mg/L	mg/L
Influent	-	495	65	0.015	0.4	11.9
Effluent	4.5	27	6.47	0.692	49.2	8.3
	7.5	18	0.02	0.015	57.4	8.3
	10.5	19	0.02	0.015	72.1	10.6
	13.5	19	0.02	0.015	60.6	10.5
	16.5	21	0.03	0.022	70.0	11.1
	19.5	18	0.02	0.015	60.6	10.5

A constant volume for each loading was applied. The classical VF wetland was loaded intermittently 4 times per day. The times of loading were 07:40, 11:40, 19:00 and 21:40 hours. The loading times have been calculated from the diurnal variation for the influent flow given in the standard ON EN 12556-3 (2005) for testing small wastewater treatment plants. During the experiments, the different loading scenarios described for the 48 week testing procedure of the standard were applied to the VF wetland. For more details of the experimental site and the experiments carried out in this period the reader is referred to Langergraber et al. (2010). In this paper, this system is referred to as "classical VF wetland".

For wetlands with the modified design, only effluent concentrations collected during the self-monitoring of the plant were available. As no influent data for these wetlands were available, the data could not be used for the simulation study and are thus not presented here. To make a comparison of the two designs possible, influent data from the Ernsthofen site were used for both designs.

Simulation Study

The HYDRUS Wetland Module (Langergraber and Šimůnek, 2012) was used for this simulation study. The HYDRUS software can be used to simulate partially saturated porous media, such as used in TWs, since HYDRUS numerically solves the Richards Equation for water flow and uses the convection-dispersion equation to simulate heat and solutes transport. Accordingly, given that the TWs used for the study were VF wetlands, the CW2D biokinetic model (Langergraber and Šimůnek, 2005) was chosen. Its mathematical formulation is based on Activated Sludge Models (Henze et al., 2000) and it describes aerobic and anoxic processes to simulate the transformation and degradation processes of compounds (organic matter, nitrogen, and phosphorus).

A modified parameter set was introduced by Langergraber (2007) to simulate temperature dependencies in the degradation of COD and NH_4-N. It was achieved by adjusting the half-saturation constants included in the Monod terms in the reaction rates equations for hydrolysis and nitrification processes. Thus, the standard biokinetic parameters, defined in Langergraber and Šimůnek (2012), have been used for all the temperatures and the different designs to compare its performance. As phosphorus has not been the focus of the study, no adsorption processes have been considered.

The water flow model was calibrated using measured data from the 2008 experiments (see before) using a constant volume of 175 L for each loading. The reactive transport was calibrated for the classical Austrian VF wetland design using the data shown in Table 2. Firstly, the effluent COD at the highest effluent water temperature of 19.5 °C was fitted by adjusting the inert fraction of the influent COD, secondly, the ratio between slowly and readily biodegradable COD was calibrated at the lowest effluent water temperature of 4.5 °C. For reactive transport simulations, the volume of each loading was 202 L per loading to guarantee the desired organic loading rate of 20 g COD/m^2/d.

For the modified design the organic load was 32 g COD/m^2/d (i.e. 2.5 m^2 per person) resulting in a daily hydraulic loading of 1300 L/d. The eight loadings per day had a volume of 162 L each and were applied with a constant interval of 3 hours between loadings. Additionally, simulations were run for a high-load classical VF wetland, designed with a reduced specific surface area of 2.5 m^2

per person. The loadings were applied at 07:40, 11:40, 19:00 and 21:40 hours with the volume of a single load of 323 L.

Additionally, the two designs were compared for the high load phases according to ON EN 12556-3 (2005), i.e. a 14-days simulation was carried out. The load on the first two of the 14 days was 150 % of the design load (Rizzo and Langergraber, 2016). Again, these simulations have been carried out again for different temperatures. The results from the previous simulations with design load have been taken as initial conditions for these simulations.

Model set-up

The transport domain was delimited by a two-dimensional finite element mesh and a simple geometry representing a surface area of 20 m^2. Considering the length of the VF bed of 500 cm, the 2D cross section had a width of 400 cm (horizontal plane) and a depth of 75 cm (vertical plane). The finite element mesh consisted of 1'421 nodes and 2'688 elements for the classical VF wetland design. Each opening was simulated by three nodes in the horizontal top plane that was set as atmospheric boundary condition. For the classical VF wetland design, 4 openings were distributed uniformly on the horizontal top plane. . A node at the bottom right was set as the constant head with a pressure head of -2 cm to simulate the water outlet of the system. For the modified design, the mesh consisted of 2'813 nodes and 5'376 elements and 4 openings were distributed uniformly on the horizontal top plane.

As proposed by Mollner (2005), only two filter materials have been considered. The intermediate layer and the drainage layer are considered as a single 25 cm thick layer. This approach is carried out to simplify the model, as the calibration of the soil hydraulic parameters with two layers (main and drainage) is well adjusted to the measured data and requires less calculation time. Moreover, it was assumed that the drainage layer properties did not change since 2005. The retention time of the water flow in the drainage layer is very short, so the main biological processes take place in the main layer and this is well simulated by the HYDRUS Wetland Module.

RESULTS AND DISCUSSION

Soil hydraulic model parameters calibration

Material parameters have been shown to have the strongest influence on effluent concentrations (Langergraber, 2001). Therefore, a successful calibration of the hydraulic behavior determines the quality of the simulation of water quality parameters. According to Langergraber et al. (2010), a volume of 175 L was applied for each loading (700 L/d) during the period of 2008/09. This is the volume used for soil hydraulic parameters calibration.

The objective function for the inverse simulation to fit soil hydraulic parameters from Mollner (2005) was defined using measured effluent flow data obtained in 2008. Table 3 shows soil hydraulic parameters for main and drainage layers. The parameters for the soil hydraulic model as obtained by Mollner (2005) were used as a starting point. Two inverse simulations were carried out to fit hydraulic parameters. Firstly, the residual water content *Qr*, the shape parameters *α* and *n*, and the tortuosity parameter *l* were fitted. A second simulation was carried out to fit hydraulic conductivity, *Ks*. Figure 1 shows a good match of simulation results compared to measured data for the daily loading pattern.

Table 3: Soil hydraulic parameters of the van Genuchten - Mualem model used for simulations and results of the simulations using Inverse Solution of HYDRUS.

Layers	**Parameter**	***Qr***	***Qs***	*α*	***n***	***Ks***	***l***
	Unit	-	-	1/cm	-	cm/h	-
Main	**Mollner (2005)**	0.130	0.42	0.063	3.90	128	0.73
	Simulation 1	0.045[a]	0.42	0.065[a]	3.164[a]	128	0.974[a]
	Simulation 2	0.045	0.42	0.065	3.164	124.5[a]	0.974
Drainage		0.045[b]	0.43[b]	0.145[b]	2.68[b]	150,000 [c]	0.50[b]

[a] Fitted value

[b] Standard parameters for "sand" as provided by the HYDRUS software

[c] Mollner (2005)

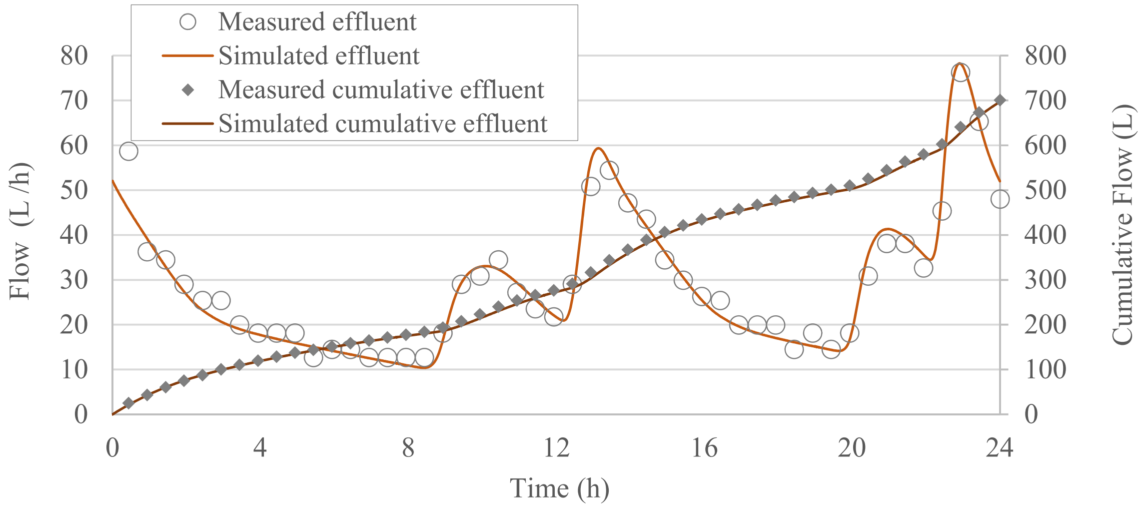

Figure 1: Measured and simulated data for effluent flow and cumulative effluent flow.

Calibration of the reactive transport model

Default biokinetic model parameters of CW2D (Langergraber and Šimůnek, 2012) have been used for the simulations. Influent COD fractionation have been calibrated in order to adapt the model to the wastewater simulated in this study case. An inert COD (CI) of 7 mg/L has been used to match measured COD data at 19.5 °C by trial and error method. A CR: CS ratio (readily and slowly biodegradable soluble COD, respectively) of 2:1 was applied as described by Langergraber (2007) for the wastewater of the experimental plant.

Figure 2 shows measured COD effluent concentrations (median values) with error bars (95% confidence interval) compared to simulated COD effluent concentrations. Simulated effluent concentrations follow the COD pattern measured for different temperature ranges well.

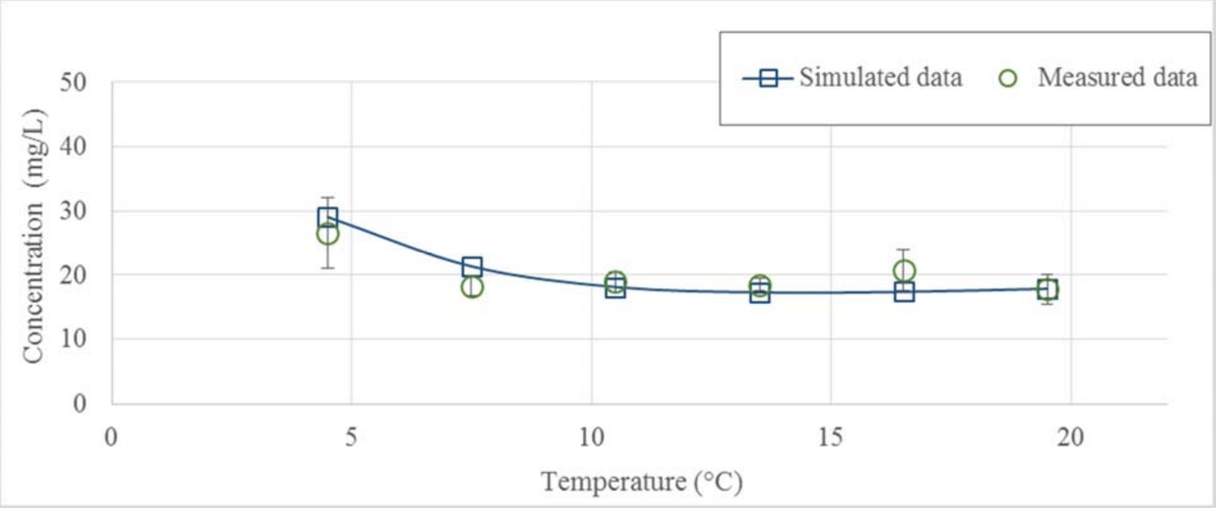

Figure 2: Measured and calibrated COD effluent concentration for classical Austrian single-stage VF wetland. Error bars indicate the 95% confidence interval for measured data.

Comparison of classical VF wetland with the modified design

Table 4 and Table 5 show influent and simulated effluent concentrations for COD, NH_4-N, NO_2-N and NO_3-N as well as soluble organic matter fractions as a function of temperature for classical single-stage VF wetland and modified design, respectively.

Table 4: Measured influent concentrations and simulated effluent concentrations for classical single-stage VF wetland.

Parameter	**Temp.**	**CR**	**CS**	**CI**	**COD**	**NH_4-N**	**NO_2-N**	**NO_3-N**
Unit	°C	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Influent	-	325	163	7	495	65	0.015	0.4
Effluent	4.5	0.1	13.5	15.4	29.1	4.09	0.017	56.3
	7.5	0.1	5.4	15.8	21.4	2.13	0.019	56.2
	10.5	0.1	1.7	16.3	18.2	1.01	0.019	55.2
	13.5	0.1	0.4	16.7	17.3	0.46	0.020	54.8
	16.5	0.2	0.1	17.2	17.4	0.25	0.022	53.8
	19.5	0.2	0.0	17.7	17.9	0.13	0.027	52.6

Table 5: Measured influent concentrations and simulated effluent concentrations for modified design.

Parameter	**Temp.**	**CR**	**CS**	**CI**	**COD**	**NH_4-N**	**NO_2-N**	**NO_3-N**
Unit	°C	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Influent	-	325	163	7	495	65	0.015	0.4
Effluent	4.5	0.1	20.2	14.3	34.6	4.22	0.018	54.9
	7.5	0.1	8.8	14.7	23.7	2.14	0.019	54.8
	10.5	0.2	3.1	14.9	18.1	1.02	0.019	53.3
	13.5	0.2	0.8	15.2	16.1	0.50	0.020	51.4
	16.5	0.2	0.1	15.4	15.7	0.25	0.022	49.2
	19.5	0.2	0.0	15.6	15.8	0.13	0.027	47.7

Figure 3 compares the simulated COD effluent concentrations of a classical VF wetland with nominal load (20 g COD/m^2/d), a high loaded single-stage VF wetland (32 g COD/m^2/d) and a VF wetland with modified design (32 g COD/m^2/d). It shows - as expected - that by increasing the input organic load per day, removal efficiency of organic matter at low temperatures is reduced. Efficiency does not vary significantly at high temperatures. For the modified design, the constant loading interval and an increase in the number of loadings in the modified design (3-4 to 8 loadings per day) ensure lower hydraulic load at each single loading, lower flow velocities in the filter, increased contact time between pollutant and bacteria and thus better COD removal. The higher number of openings in the distribution pipes further contribute to these effects by a more even distribution of the wastewater onto the surface of the VF wetland. At the lowest simulated temperature (4.5 °C), effluent concentrations of COD are 29.1, 34.6 and 47.5 mg/L for classical VF wetland design, modified design, and high-load VF wetland design, respectively. The results are still far below the legal requirements required for COD effluent concentration (90 mg/L).

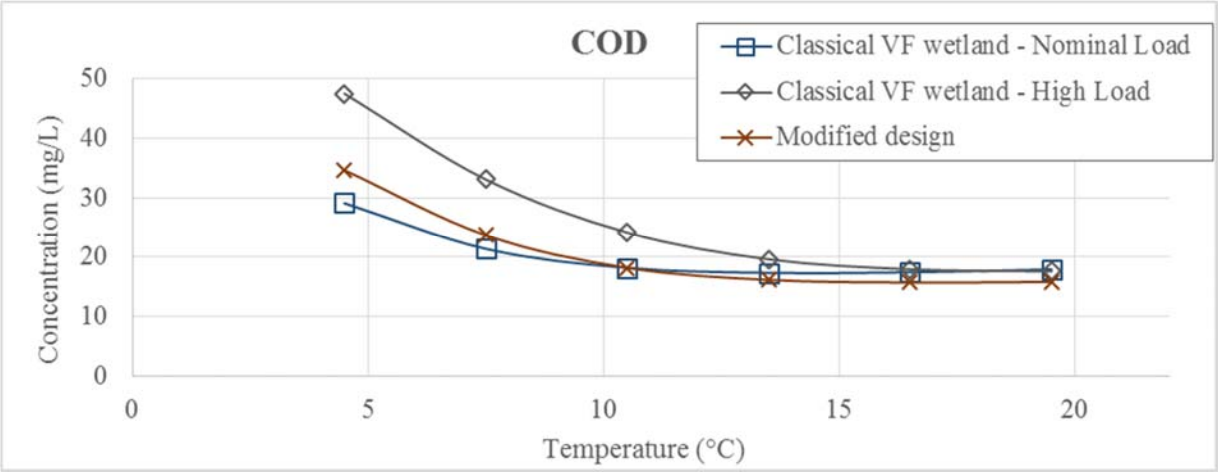

Figure 3: Comparison of COD effluent concentration for a single-stage VF wetland loaded with nominal loading (ÖNORM B 2505, 2009), high loading and the modified design, for different temperatures.

Regarding the NH_4-N effluent concentrations, the differences between the different designs are not significant. Figure 4 shows that simulated NH_4-N effluent concentrations remain close to zero and increase substantially as the temperature decreases in all compared designs. Simulated effluent concentrations meet legal requirements (10 mg NH_4-N/L) even at all simulated temperatures below 12 °C.

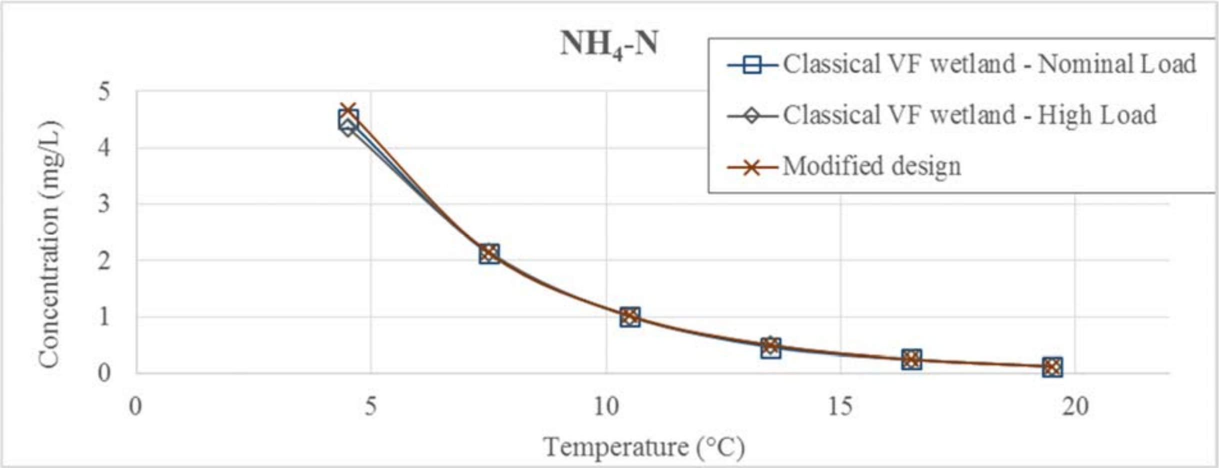

Figure 4: Comparison of NH_4-N effluent concentration for a single-stage VF wetland loaded with nominal loading (ÖNORM B 2505, 2009), high loading and the modified design, for different temperatures.

Álvarez et al. (2017) presented results from two parallel operated VF beds in India. They found lower COD and NH_4-N effluent concentrations in the VF bed that had less but higher single loads compared the VF bed that received more frequent but lower doses. However, no details on the loading regime (intervals between single doses and volume of a single dose) were presented. It seems that a loading interval much less than 3 hours (as used for the modified design) was applied and led to limited oxygen exchange and reduced nitrification capacity, respectively. More frequent loadings and smaller single doses as applied at the modified design did not result in limited oxygen exchange and reduced treatment efficiency.

Figure 5 and Figure 6 compare the behaviour of the single-stage VF wetlands during the high-load phase according to ON EN 12556-3 (2005). The COD effluent concentrations (Figure 5) are similar for higher temperatures. For lower temperatures, the more frequent loading of the VF wetland with modified design results in less fluctuations of the COD effluent concentrations compared to the classical design.

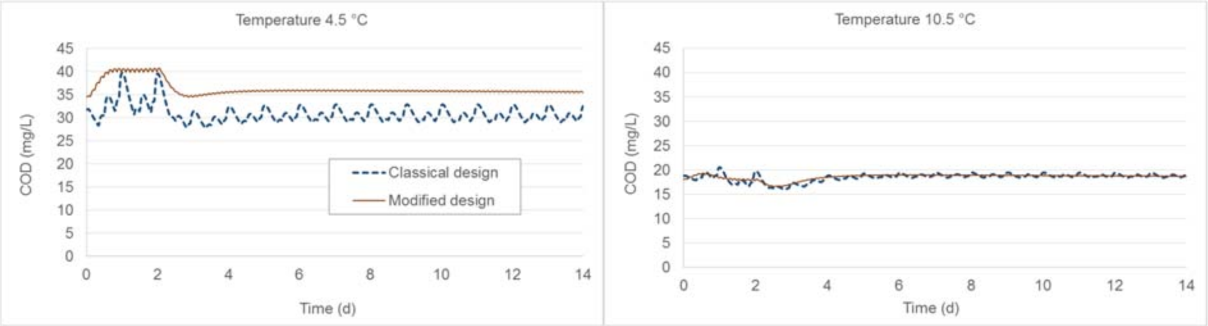

Figure 5: COD effluent concentration for a single-stage VF wetland with classical design (ÖNORM B 2505, 2009) and modified design during the high-load phase according to ON EN 12556-3 (2005) for 4.5 °C (left) and 10.5 °C (right).

For the NH_4-N effluent concentrations the difference is more important at higher temperatures. During the 2-days high-loading the NH_4-N effluent concentration for the VF wetland at 10.5 °C increases from about 1 mg/L up to 4 mg/L whereby for the modified design the maximum effluent concentration is only about 2.5 mg/L (Figure 6, right). This can be explained by the uniform loading intervals and thus more uniform of the wastewater distribution for the modified design. At cold temperatures, the behaviour of the VF wetlands with classical and modified design are similar (Figure 6, left).

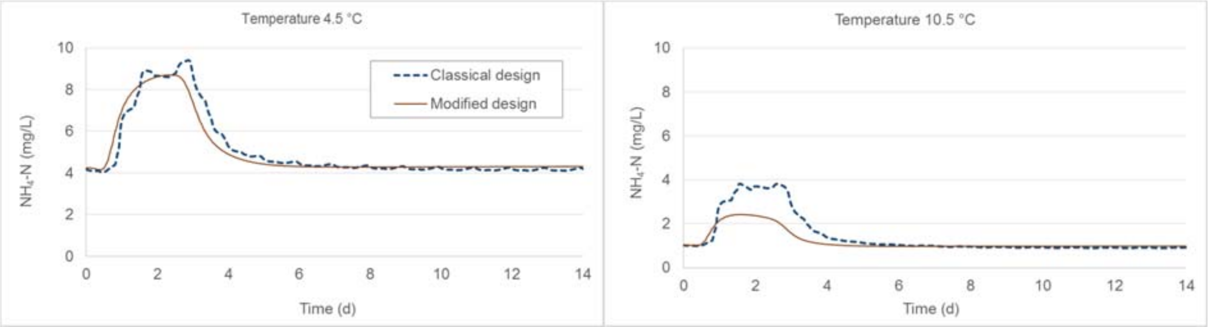

Figure 6: NH_4-N effluent concentration for a single-stage VF wetland with classical design (ÖNORM B 2505, 2009) and modified design during the high-load phase according to ON EN 12556-3 (2005) for 4.5 °C (left) and 10.5 °C (right).

CONCLUSIONS

From the simulation study, it can be concluded that:

1. The model of the classical single-stage Austrian VF wetland could be calibrated well to measured effluent water flow and effluent concentrations, respectively.
2. By increasing the organic loading for the classical Austrian VF wetland, the COD effluent concentrations are significantly higher for lower temperatures.
3. By applying the modified design, lower COD effluent concentrations can be reached again.
4. During high-loading events at higher temperatures, VF wetlands with modified design have lower maximum NH_4-N effluent concentrations.
5. The main modifications in the design, i.e. more loadings per day but lower volume of a single loading, constant loading interval, and increased number of openings per m², seem to be very effective to allow applying higher organic loads.

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