# Simulation of the treatment performance of outdoor subsurface flow constructed wetlands in temperate climates

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## Abstract

Numerical models are a means to increase the understanding of the processes occurring in the "black box" constructed wetland. Once reliable models for constructed wetlands are available they can be also used for evaluating and improving existing design criteria. The paper shows simulation results for outdoor experimental subsurface vertical flow constructed wetlands using CW2D, a multi-component reactive transport module developed to simulate transport and reactions of the organic matter, nitrogen and phosphorus in subsurface flow constructed wetlands. The surface area of the experimental vertical flow bed was 20 m$^2$. The organic load applied was 27 g COD m$^{-2}$ d$^{-1}$ (corresponding to a specific surface area of 3 m$^2$ per person). The aim of the work is to calibrate the model for temperature dependency that has been implemented in CW2D. Water temperature during the investigation period varied between 4 °C and 18 °C. The measured effluent concentrations during summer could be simulated using the standard CW2D parameter set when the flow model was calibrated well. However, the increasing effluent concentrations at low temperatures could not be simulated with the standard CW2D parameter set where temperature dependencies are considered only for maximum growth, decay, and hydrolysis rates. By introducing temperature dependencies for half-saturation constants for the hydrolysis and nitrification processes it was possible to simulate the observed behaviour. The work presented is a step on the way to validate the CW2D module. Model validation is a necessary step before numerical simulation can be finally used in practice, e.g. for checking existing design guidelines.
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*Keywords:* CW2D; Numerical simulation; Subsurface vertical flow constructed wetlands; Temperature dependency; Wastewater treatment

## 1. Introduction

Although much experience exists in constructing and operating constructed wetlands (e.g. Kadlec et al., 2000) they are still often looked at as a "black box" in which water is purified. Therefore up to now the design of constructed wetlands is mainly based on rules of thumb using specific surface area requirements (e.g. ÖNORM B 2505, 2005) or simple first-order decay models (e.g. Kadlec and Knight, 1996). Numerical models can provide insight into the "black box" and therefore increase the system understanding. Once reliable numerical models exist they can be used for evaluating and improving existing design criteria.

The multi-component reactive transport module CW2D (Langergraber, 2001; Langergraber and Šimůnek, 2005) was developed to model transport and reactions of the main constituents of municipal wastewater in subsurface flow constructed wetlands. CW2D is able to describe the biochemical elimination and transformation

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processes for dissolved forms of organic matter, nitrogen and phosphorus.

Main research needs regarding modelling of constructed wetland processes include (Langergraber, 2003): detailed hydraulic investigations on full-scale constructed wetlands, simulations of outdoor constructed wetland systems, investigation of plant uptake models, improving the simulation tool by including a model that is able to describe substrate clogging processes, and development of experimental techniques for the measurement of CW2D model parameters.

The paper shows simulation results for outdoor experimental subsurface vertical flow constructed wetlands to calibrate the model for temperature dependency that has been implemented in CW2D. The special focus of the paper therefore is simulating the treatment performance for different water temperatures.

## 2. Materials and methods

### 2.1. The multi-component reactive transport module CW2D

The multi-component reactive transport module CW2D (Langergraber, 2001) was developed to describe the biochemical transformation and degradation processes in subsurface flow constructed wetlands. CW2D is incorporated into the HYDRUS-2D variably-saturated water flow and solute transport program (Šimùnek et al., 1999) and considers 12 components and 9 processes. The components include dissolved oxygen, organic matter (three fractions of different degradability), ammonium, nitrite, nitrate, and nitrogen gas, inorganic phosphorus, and heterotrophic and autotrophic micro-organisms. Organic nitrogen and organic phosphorus are modelled as nutrient contents of the organic matter. The processes considered are hydrolysis, mineralization of organic matter, nitrification (modelled as a two-step process), denitrification, and a lysis process for the micro-organisms. The mathematical structure of CW2D is based on the mathematical structure of the Activated Sludge Models (ASMs) introduced by Henze et al. (2000). For a detailed discussion of the CW2D module see Langergraber and Šimùnek (2005).

As CW2D is coupled with a mechanistic model able to describe variably saturated water flow the tool can be applied for both subsurface vertical and horizontal flow constructed wetlands. A recently developed model (Rousseau, 2005) uses a similar reaction model. However, tanks-in-series are applied for describing water flow and therefore it can only be used for modelling horizontal flow systems where saturated water conditions occur. The main drawback of CW2D is that up to now only dissolved substances are considered. A more realistic model should

Table 1
Layout of the experimental CW in Ernsthofen (Lower Austria)

| Parameter | Unit | Bed 1 | Bed 2 | Bed 3 |
|---|---|---|---|---|
| Surface area | $m^2$ | 17.8 | 18.5 | 18.2 |
| Specific surface area | $m^2/PE_{COD}$ | 4 | 3 | 2 |
| Organic loading (design) | $g\ COD/m^2$ | 20 | 27 | 40 |
| Organic loading (measured) | $g\ COD/m^2$ | $17.5 \pm 0.5$ | $23.4 \pm 0.7$ | $35.1 \pm 1.5$ |
| Daily hydraulic loading | L | 573 | 795 | 1177 |

also include particulate wastewater constituents (Langergraber and Šimùnek, 2005).

In CW2D the reaction rates are calculated using Monod-type kinetic expressions by

$$r = -\mu_{max} \cdot \frac{c}{K_s + c} \cdot X \tag{1}$$

where $r$ is the reaction rate [M L$^{-3}$ T$^{-1}$], $\mu_{max}$ is the maximum growth rate [T$^{-1}$], $c$ is the substrate concentration [M L$^{-3}$], $K$s is the half-saturation constant [M L$^{-3}$], the concentration when the reaction rate is half the maximum rate, and $X$ is the biomass concentration [M L$^{-3}$].

In the standard parameter set for CW2D (Langergraber, 2001) the following parameters are considered to be temperature dependent:

- the saturation concentration of oxygen,
- the diffusion coefficients,
- the maximum growth/decay rates of the micro-organisms, and
- the maximum hydrolysis rate.

In the calculated reaction rates temperature dependency therefore is only included in the maximum growth rates. The half-saturation constants are considered to be independent from temperature such as proposed by Henze et al. (2000).

In HYDRUS-2D (Šimùnek et al., 1999) the Arrhenius equation is used to describe the temperature dependencies. For a temperature dependent parameter "$a$" the Arrhenius equation can be written as follows (e.g. Stumm and Morgan, 1996):

$$a_T = a_{20°C} \cdot e^{\frac{Ea \cdot \left(T^A - T^A_{20}\right)}{R \cdot T^A \cdot T^A_{20}}} \tag{2}$$

where $T^A$ is the absolute temperature [K], $a_T$ is the parameter value at the absolute temperature $T^A$, $T^A_{20}$ is the absolute reference temperature (20 °C = 293.15 K), $a_{20\ °C}$

Table 2
Measured influent concentrations in (mg/l)

| Parameter | SS | COD | BOD$_5$ | TOC* | NH$_4$–N | NO$_3$–N | Norg* | TN* | PO$_4$–P | TP* |
|---|---|---|---|---|---|---|---|---|---|---|
| No. of samples | 49 | 49 | 45 | 6 | 55 | 49 | 6 | 6 | 49 | 6 |
| Median value | 130 | 545 | 380 | 179 | 68.0 | 0.4 | 14.7 | 83.9 | 12.5 | 12.0 |
| 95% Conf.-Int. | 10 | 17 | 11 | 18.8 | 1.5 | 0.0 | 3.5 | 3.2 | 0.3 | 0.6 |
| Mean value | 133 | 554 | 375 | 183 | 67.6 | 0.4 | 15.8 | 84.8 | 12.5 | 12.1 |
| Standard dev. | 34 | 61 | 37 | 23.4 | 5.8 | 0.1 | 4.3 | 4.0 | 1.0 | 0.8 |
| Minimum | 70 | 402 | 280 | 146 | 52.9 | 0.3 | 10.9 | 81.0 | 9.5 | 11.0 |
| Maximum | 270 | 728 | 460 | 216 | 81.7 | 0.6 | 23.1 | 89.6 | 15.2 | 13.2 |

*Analysed in the university lab; Conf.-Int.=Confidence interval; Standard dev.=Standard deviation.

is the parameter value at the reference temperature, $R$ is the universal gas constant [8.314 J/(mol.K)], and Ea is the activation energy [J/mol].

## 2.2. The experimental plant

The experimental constructed wetlands are located at the site of the wastewater treatment plant Ernsthofen (Lower Austria). A 3-chamber unit is used for mechanical pre-treatment. The experimental plant consists of three parallel operated subsurface vertical flow beds with a surface area of about 20 m$^2$ each (Table 1) operated with intermittent loading (4 loadings a day). The organic loads applied are 20, 27 and 40 g COD m$^{-2}$ d$^{-1}$, which corresponds to a specific surface area requirement of 4, 3 and 2 m$^2$ per PE$_{COD}$, respectively. The resulting hydraulic loading rates for bed 1 through 3 are 32.2, 43.0, and 64.7 mm/d. The organic load of 20 g COD m$^{-2}$ d$^{-1}$ has been found to be the limit up to which subsurface vertical flow beds with sandy substrate for the main layer can be operated in temperate climates without clogging problems (e.g. Winter and Goetz, 2003).

In this paper the results of bed 2 (3 m$^2$/PE$_{COD}$) are used for the investigations.

The main layer of the filter consists of 50 cm sandy substrate (gravel size 0.06–4 mm, $d_{10}$=0.2 mm). An

intermediate layer of 10 cm thickness with a gravel size of 4–8 mm prevents fine particles to be washed out into the drainage layer (15 cm thick; gravel 16–32 mm) where the effluent is collected by means of tile drains. The filter is planted with common reed (Phragmites australis).

The experimental plant was operated automatically using a LabView® program over a period of 20 months (including two winters). The pore water content in different depths of the main layer and effluent flow rates have been recorded on-line. Water samples have been collected by the local plant staff on a weekly basis and have been analysed in the plant laboratory for suspended solids (SS), organic matter (COD and BOD$_5$), nitrogen (NH$_4$–N, NO$_2$–N, and NO$_3$–N) and phosphorus (PO$_4$–P). The plant lab data have been checked every two months by analysing parallel samples in the university lab. In addition the following parameters have been analysed in the university lab: Total organic carbon (TOC), organic and total nitrogen (Norg and TN, respectively), and total phosphorus (TP).

For small plants (i.e. less than 500 persons) the standards in Austria (1.AEVkA, 1996) allow a maximum ammonia nitrogen effluent concentration of 10 mg/l. However, this limit only has to be met at water temperatures higher than 12 °C. Effluent concentrations for organic matter (90 mg/l for COD and

Table 3
Measured effluent concentrations of bed 2 (3 m$^2$/PE$_{COD}$)

| Parameter | | Unit | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Temperature | | °C | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 |
| No. of samples* | | | 7 (15) | 9 (14) | 3 (4) | 2 | 8 | 7 | 9 | 3 |
| COD | Mean value | mg/l | 57.6 | 43.4 | 33.6 | 30.4 | 26.8 | 27.4 | 27.6 | 30.0 |
| | Standard deviation | mg/l | 8.1 | 6.3 | 2.7 | 9.5 | 6.3 | 5.1 | 2.6 | 1.7 |
| BOD$_5$ | Mean value | mg/l | 28.4 | 14.3 | 5.0 | 6.0 | 4.7 | 4.0 | 4.0 | 4.3 |
| | Standard deviation | mg/l | 7.2 | 6.6 | 1.4 | 4.2 | 1.5 | 1.3 | 0.7 | 0.6 |
| NH$_4$–N | Mean value | mg/l | 27.23 | 13.48 | 3.53 | 0.64 | 0.06 | 0.06 | 0.05 | 0.03 |
| | Standard deviation | mg/l | 5.89 | 6.26 | 3.16 | 0.23 | 0.05 | 0.07 | 0.04 | 0.01 |
| NO$_3$–N | Mean value | mg/l | 25.5 | 42.4 | 53.6 | 55.3 | 56.4 | 47.9 | 58.2 | 63.7 |
| | Standard deviation | mg/l | 7.6 | 9.9 | 5.0 | 5.8 | 6.8 | 8.6 | 6.3 | 5.0 |

*Values in brackets for NH$_4$–N that was analysed biweekly during the winter month.
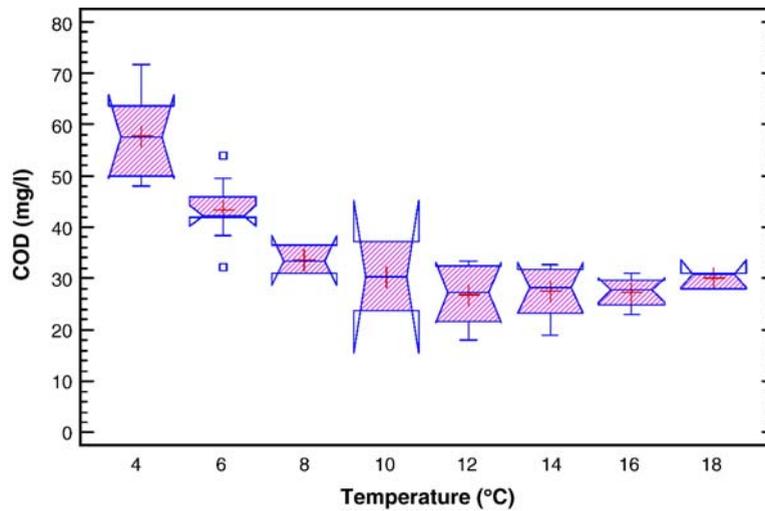
Fig. 1. Measured COD effluent concentration vs. temperature.

25 mg/l for BOD$_5$, respectively) have to be met the whole year around. For small plants there is no standard for total nitrogen and phosphorus.

### 2.3. Statistical methods

"STATGRAPHICS Plus for Windows 4.0" was used for statistical evaluation of the data. Figures show "Box-and-Whisker Plots": The box encloses the middle 50% and the median value is drawn as a vertical line inside the box, the mean value is given as a cross. Horizontal lines (whiskers) extend from each end of the box. The lower/upper whisker is drawn from the lower/upper quartile to the smallest/largest value within 1.5 inter-quartile ranges. The dots represent outliers. The length of the notch around the median value represents a 95%

confidence interval for the median. If the notches of 2 median values do not overlap there is a statistically significant difference amongst the median values at the 95% confidence level.

### 3. Results and discussion

#### 3.1. Measured data

Table 2 shows the analyses of the measured concentrations of the mechanically pre-treated influent from May 2004 until April 2005. The influent concentrations have been rather constant throughout the investigation period.

Table 3 shows the effluent concentrations of COD, BOD$_5$, NH$_4$–N and NO$_3$–N for bed 2 (3 m$^2$/PE$_{COD}$) as a function of the effluent water temperature. During the
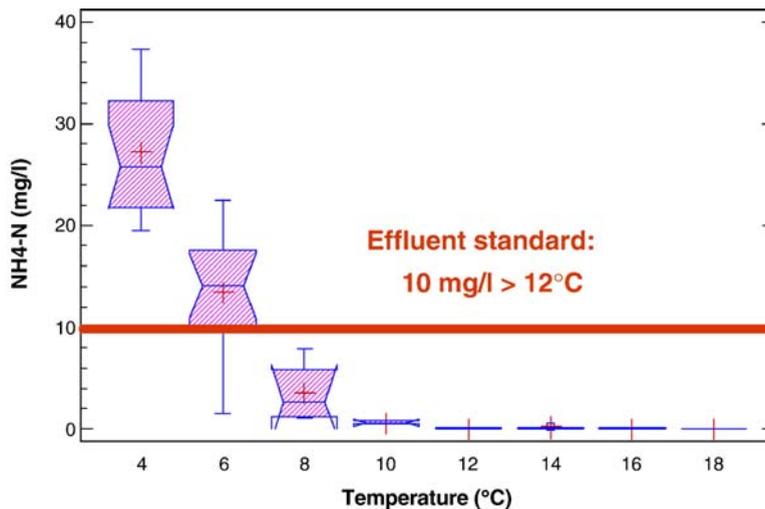


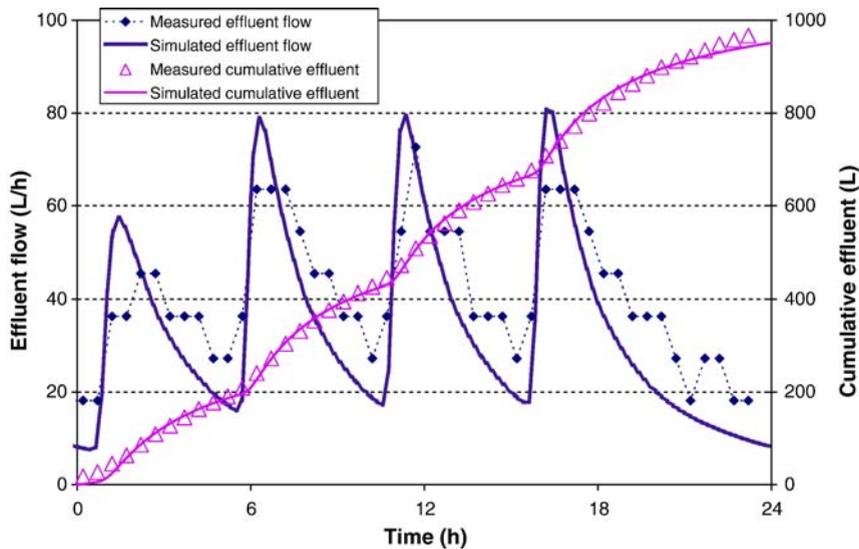Fig. 2. Measured NH$_4$–N effluent concentration vs. temperature.

Fig. 3. Measured and simulated effluent flow and cumulative effluent.

investigation period wastewater temperatures varied between 4 and 18 °C. Figs. 1 and 2 show the Box-and-Whisker-Plots for effluent concentrations vs. wastewater temperature for COD and $NH_4$–N, respectively. The effluent concentration of COD does not exceed the Austrian effluent standards (Fig. 1) whereas they have been exceeded for $BOD_5$ (Table 3). For $NH_4$–N the effluent standards have been met also for wastewater temperatures of 8 °C (Fig. 2). Effluent concentrations higher than 10 mg $NH_4$–N/l only occurred at wastewater temperatures lower than 8 °C.

### 3.2. Model set-up

The width of the transport domain in the numerical simulations was 4 m, and its depth 0.8 m, while the transport domain itself was discretized into 31 columns

and 33 rows. This results in a two-dimensional finite element mesh consisting of 1023 nodes and 1920 triangular finite elements. An atmospheric boundary condition was assigned to the top of the system representing the influent distribution system, and a constant pressure head boundary condition (constant head of −4 cm) to one side of the drainage layer.

### 3.3. Simulation of water flow

It has been shown that a good match of simulation results with CW2D can only be achieved once the hydraulic behaviour of the system has been modelled successfully (Langergraber, 2003). Therefore as a first step the flow model has to be calibrated. The main layers of the experimental plant consist of the same sandy substrate as pilot-scale constructed wetlands (PSCWs)

Table 4
CW2D influent concentrations and simulated effluent concentrations

| Parameter | Temperature | 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 | – | 350 | 180 | 15 | 540 | 64 | 0.015 | 0.5 |
| Effluent | 18 | 0.3 | 2.8 | 24.1 | 27.1 | 0.066 | 0.024 | 60.4 |
| | 15 | 0.3 | 2.8 | 22.8 | 25.9 | 0.073 | 0.024 | 64.4 |
| | 12 | 0.3 | 2.9 | 21.7 | 24.8 | 0.085 | 0.026 | 65.5 |
| | 10 | 0.2 | 2.9 | 21.0 | 24.2 | 0.095 | 0.028 | 66.1 |
| | 8 | 0.2 | 2.9 | 20.5 | 23.6 | 0.114 | 0.031 | 67.5 |
| | 6 | 0.2 | 2.9 | 19.9 | 23.1 | 0.138 | 0.036 | 70.3 |
| | 4 | 0.2 | 3.0 | 19.5 | 22.7 | 0.171 | 0.041 | 74.1 |

CR, CS, CI: readily, and slowly biodegradable, and inert organic matter, respectively (Langergraber, 2001) Influent fractionation of COD: $COD_{influent} = CR + CS + CI$; $CI = 0.5 * COD_{effluent}$; $CR = ca. 2 * CS$.
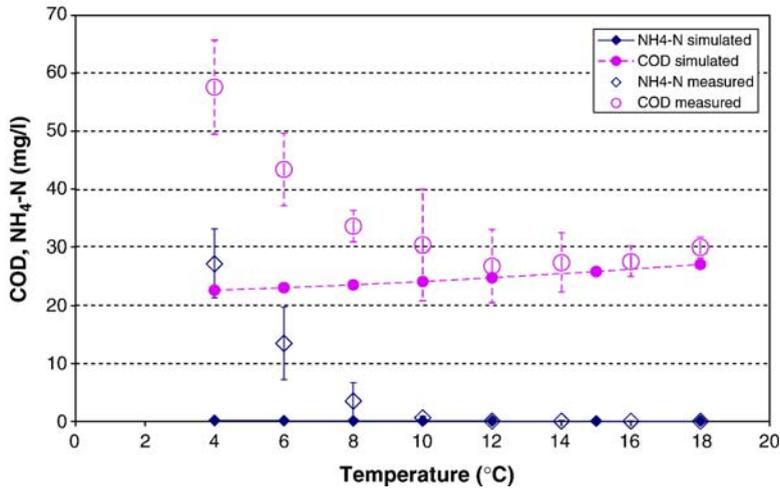
Fig. 4. Measured and simulated COD and NH$_4$–N effluent concentrations using the CW2D standard parameter set.

in Vienna (Langergraber et al., 2004). Effluent flow measurements of the PSCWs were used as input data for the inverse simulation to determine the parameters of the model describing the unsaturated hydraulic properties (Mollner, 2005). The parameters obtained from the PSCWs then have been used for the simulations of the experimental plant Ernsthofen. Fig. 3 compares measured and simulated effluent flow rate and cumulative effluent of the experimental plant. The simulation results match the measured data well.

### 3.4. Simulations with the standard parameter set

Table 4 shows the CW2D influent concentrations used for the simulations. For the simulations the model influent concentrations were kept constant as the measured

concentrations have been rather constant during the investigation period (Table 2). Only the temperature was changed for the different simulation runs.

The simulated effluent concentrations using the standard parameter set of CW2D (Langergraber, 2001) also are shown in Table 4 for different water temperatures. The simulated effluent concentrations for 18 °C matched the measured data (Table 3).

Fig. 4 compares the mean values of the simulated COD and NH$_4$–N effluent concentrations and the measured data. The increased effluent concentrations measured at lower temperatures could not be simulated. Applying only the temperature dependencies of the maximum growth, decay, and hydrolysis rates it was not possible to simulate the observed behaviour. In contrast to the measured data the COD effluent concentrations
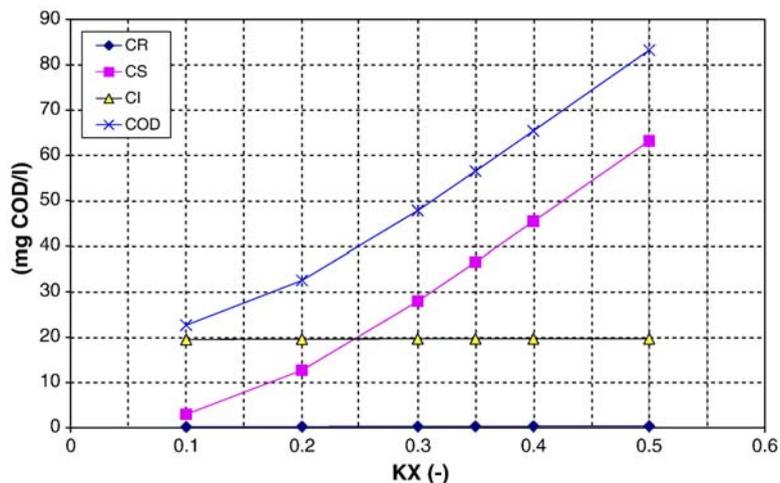


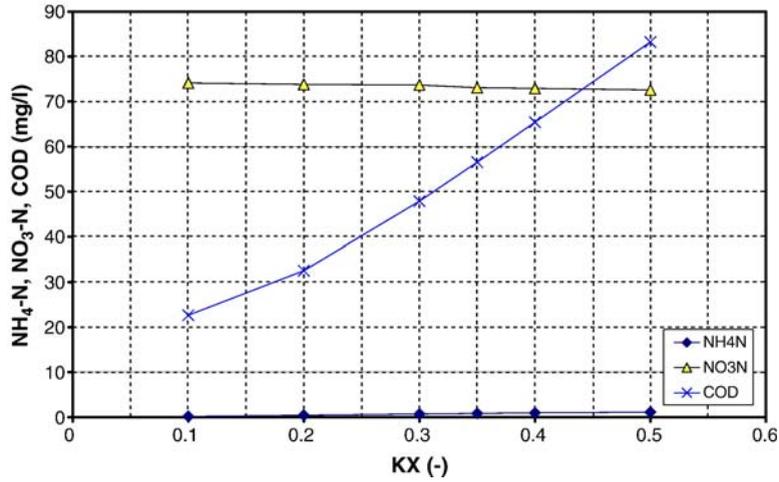Fig. 5. Organic matter fractions and COD effluent concentrations at 4 °C for varying $K_X$.

Fig. 6. COD, $NH_4$–N and $NO_3$–N effluent concentrations at 4 °C for varying $K_X$.

decreased with decreasing temperature. This can be explained because at low temperatures less lysis causes less production organic matter and in addition hydrolysis was over predicted. For $NH_4$–N only a slight increase of the simulated effluent concentration occurred indicating that simulated nitrification rates at low temperatures have been too high.

### 3.5. Modification of the parameter set

Bornemann et al. (1998) defined a parameter set for the ASM1 in which they introduced a temperature dependency for the half-saturation constants for hydrolysis and nitrification. The same concept has been applied for this work. The simulations to obtain the temperature dependencies of the half-saturation constants have been carried out at a water temperature of 4 °C.

According to Langergraber and Šimùnek (2005) the reaction rate for hydrolysis, i.e. the conversion of slowly biodegradable organic matter CS into readily biodegradable organic matter CR, is written as

$$rc_1 = K_h \frac{c_{CS}/c_{XH}}{K_X + c_{cs}/c_{XH}} c_{XH} \qquad (3)$$

where $rc_1$ is the reaction rate for hydrolysis, $K_h$ is the maximum hydrolysis rate, $c_{CS}$ is the concentration of slowly biodegradable organic matter, $c_{XH}$ is the concentration of heterotrophic bacteria, and $K_X$ is the half-saturation constant for hydrolysis.
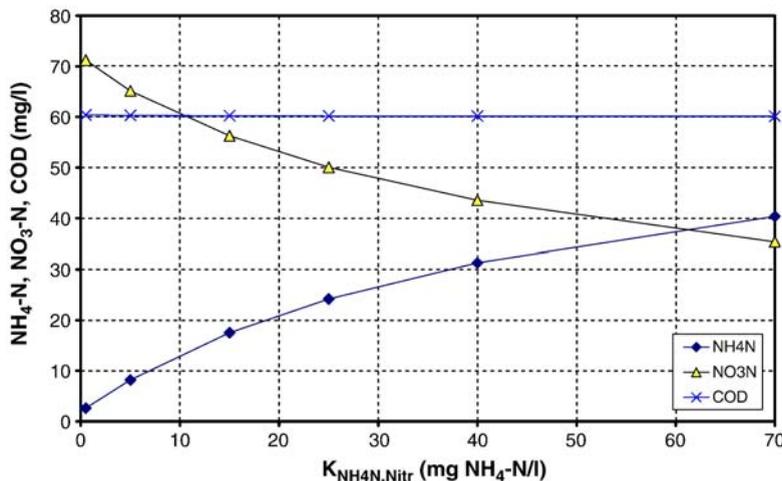


Fig. 7. COD, $NH_4$–N and $NO_3$–N effluent concentrations at 4 °C for varying $K_{ANs,NH4}$ ($K_X$=0.35).

Table 5
Calculated activation energies for $K_X$ and $K_{ANs,NH4}$

| Parameter | Value at 4 °C | Value at 20 °C | Ea (J/mol) |
|---|---|---|---|
| $K_X$ | 0.35 | 0.1 | −53,000 |
| $K_{ANs,NH4}$ | 25 | 0.5 | −160,000 |

An increasing $K_X$ value influences only the organic matter fractions by allowing less slowly biodegradable organic matter to be converted into readily biodegradable organic matter. Therefore the COD effluent concentration increases (Fig. 5). Fig. 6 shows the COD, $NH_4$–N and $NO_3$–N effluent concentrations at 4 °C for different half-saturation constants for hydrolysis $K_X$. $NH_4$–N and $NO_3$–N concentrations are not effected by changing $K_X$ values. For 4 °C half-saturation constant for hydrolysis was determined to be $K_X(4\,°C)=0.35$.

The reaction rate for the first step of nitrification, i.e. the conversion of ammonia into nitrite, is according to Langergraber and Šimùnek (2005):

$$rc_6 = \mu_{ANs} \frac{c_{O2}}{K_{ANs,O2} + c_{O2}} \frac{c_{NH4}}{K_{ANs,NH4} + c_{NH4}}$$
$$\times \frac{c_{IP}}{K_{ANs,IP} + c_{IP}} c_{XANs} \qquad (4)$$

where $rc_6$ is the reaction rate for the first step of nitrification, $\mu_{ANs}$ is the maximum aerobic growth rate on ammonia, $c_{O2}$ and $K_{ANs,O2}$ are the concentration and the half-saturation constant of dissolved oxygen, $c_{NH4}$ and $K_{ANs,NH4}$ of ammonia, $c_{IP}$ and $K_{ANs,IP}$ of inorganic phosphorus, respectively, and $c_{XANs}$ is the concentration of ammonia oxidizing bacteria (*Nitrosomonas* spp.).

Fig. 7 shows the COD, $NH_4$–N and $NO_3$–N effluent concentrations at 4 °C for different half-saturation constant of ammonia $K_{ANs,NH4}$. As expected the inhibition of the first step of nitrification due to increasing $K_{ANs,NH4}$ values has no influence on the

COD effluent concentrations. The half-saturation constant of ammonia at 4 °C was determined to be $K_{ANs,NH4}(4\,°C)=25$ mg/l.

Table 5 gives the calculated activation energies for $K_X$ and $K_{ANs,NH4}$ for the Arrhenius Eq. (2) using the parameters obtained from Figs. 6 and 7. Bornemann et al. (1998) report a value of 0.03 for $K_X$ at 20 °C and a temperature coefficient of 0.11 (resulting in a three-fold value for $K_X$ at 10 °C). For ASM2 Henze et al. (2000) report $K_X$ values of 0.1 for 20 °C and 0.3 for 10 °C, respectively. Calculating the activation energy one e gets −74,000 J/mol for both literature values. The values obtained in this study, $K_X(4\,°C)=0.35$ and Ea= −53,000 J/mol, result in a $K_X$ values 0.22 for 10 °C. Compared to the literature values the values obtained in this study are in a similar range. Hydrolyses processes are predicted to occur at a lower rate. For $K_{ANs,NH4}$ Bornemann et al. (1998) report a value of 0.5 at 20 °C and a temperature coefficient of 0.09 (resulting in a two-fold value for $K_X$ at 10 °C). The activation energy calculated from these parameters is −46,000 J/mol. In this study $K_{ANs,NH4}(4\,°C)=25$ mg/l and Ea=−160,000 J/mol result in $K_{ANs,NH4}(10\,°C)=5.5$ mg/l, i.e. the five-fold value as the literature value. One has to take into account that the values by Bornemann et al. (1998) are reported for activated sludge systems and for nitrification modelled a single step process.

Table 6 shows the values of $K_X$ and $K_{ANs,NH4}$ calculated for different temperatures and the simulated effluent concentrations using these values. Fig. 8 finally compares the measured and simulated COD and $NH_4$–N effluent concentrations using the modified parameter set. The simulation results match the measured data well for COD and $NH_4$–N effluent concentrations. However, the simulated effluent concentrations of $NO_3$–N are over predicted. Due to the reduced hydrolyses processes less readily biodegradable organic matter that is required for denitrification is produced. In the model

Table 6
Values for $K_X$ and $K_{ANs,NH4}$ used and simulated effluent concentrations for the modified parameter set

| Parameter | Temperature | $K_{ANs,NH4}$ | $K_X$ | 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) | (mg/l) |
| Effluent | 18 | 0.8 | 0.12 | 0.2 | 3.9 | 24.1 | 28.2 | 0.1 | 0.020 | 60.8 |
| | 15 | 1.6 | 0.15 | 0.2 | 6.2 | 22.8 | 29.2 | 0.4 | 0.020 | 66.6 |
| | 12 | 3.3 | 0.18 | 0.2 | 9.2 | 21.7 | 31.2 | 1.2 | 0.020 | 69.3 |
| | 11 | 5.5 | 0.22 | 0.3 | 14.2 | 21.1 | 35.6 | 2.5 | 0.021 | 69.9 |
| | 8 | 9.0 | 0.25 | 0.2 | 18.8 | 20.5 | 39.6 | 4.8 | 0.021 | 67.6 |
| | 6 | 15.0 | 0.30 | 0.3 | 27.1 | 20.1 | 47.5 | 11.5 | 0.026 | 61.8 |
| | 4 | 25.0 | 0.35 | 0.3 | 36.1 | 19.6 | 56.0 | 25.9 | 0.030 | 50.2 |

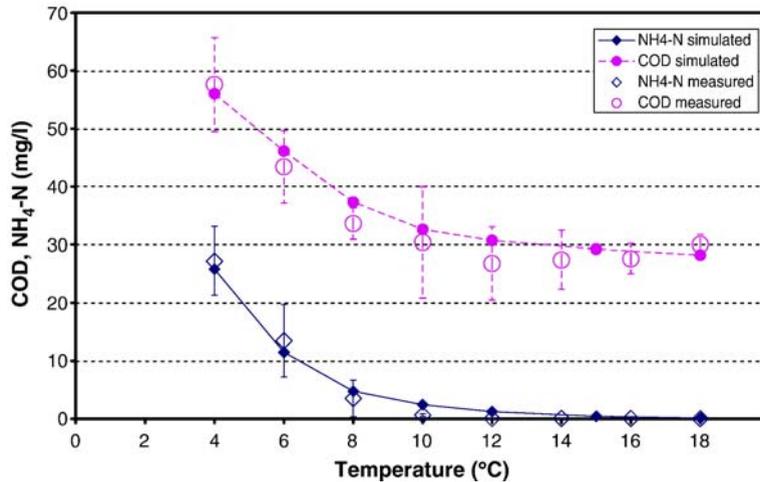CR, CS, CI: readily, and slowly biodegradable, and inert organic matter, respectively (Langergraber, 2001).

Fig. 8. Measured and simulated COD and NH$_4$–N effluent concentrations using the modified parameter set.

this could be compensated by reducing the denitrification half-saturation constant for organic matter resulting in enhanced denitrification at low organic matter concentrations.

## 4. Summary and conclusions

The paper shows simulation results for an outdoor experimental subsurface vertical flow constructed wetland. The effluent concentrations during summer could be simulated using the standard CW2D parameter set when the flow model was calibrated well. However, the effluent concentrations at low temperatures could not be simulated with the standard CW2D parameter set where temperature dependencies are considered only for maximum growth, decay, and hydrolysis rates. Measured COD and NH$_4$–N effluent concentrations could not be simulated because hydrolysis and nitrification at low temperatures were over predicted.

It was shown that by introducing temperature dependencies for the half-saturation constants of hydrolysis and nitrification it is possible to simulate the COD and NH$_4$–N effluent concentrations at low temperatures. Temperature dependency for $K_X$ and $K_{ANs,NH4}$ has been considered also by e.g. Bornemann et al. (1998). However, the new parameter set introduced still has to be validated for other constructed wetland systems.

The work is a step on the way to validate the multi-component reactive transport module CW2D. Model validation is necessary before numerical simulation can be finally used in practice, e.g. for checking existing design guidelines.

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