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Modeling nitrogen removal in a vertical flow constructed wetland treating directly domestic wastewater

Ania Morvannou [a], Jean-Marc Choubert [a,*], Marnik Vanclooster [b], Pascal Molle [a]

[a] Irstea, UR MALY, 5 rue de la Doua CS70077, 69626 Villeurbanne Cedex, France
[b] Earth and Life Institute – Environmental Sciences, Université Catholique de Louvain, Croix du Sud 2 Box 7.05.02, B-1348 Louvain-la-Neuve, Belgium

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ABSTRACT

The present work deals with modeling of the fate of nitrogen through a vertical flow constructed wetland (VFCW) using gravel, treating directly domestic raw wastewater. The experimental design of the work involved lab-scale and full-scale experiments to calibrate the multi-component reactive transport model for constructed wetlands (CW2D). Besides measured values for the hydraulic parameters and the maximum autotrophic growth rate, we calibrated two other parameters (oxygen re-aeration rate and adsorption coefficients of ammonium) to reduce the difference between predictions and measurements. The obtained model determined the time-variation of nitrogen concentrations in the effluent with reasonable performances. With the use of the model we demonstrate that, during feeding period, the ammonium was significantly adsorbed onto organic matter besides conversion into nitrates; the adsorbed mass of ammonium was nitrified during the rest period provoking high nitrates concentrations during the first two subsequent batches. We also demonstrated that heterotrophic biomass was mainly present in the sludge layer (first 20 cm), whereas autotrophic biomass was located in the first 50 cm of the VFCW (sludge and 30 cm biomat).

1. Introduction

Constructed wetlands (CWs) offer an attractive wastewater treatment technology for small communities (<5000 p.e.). The simplicity of operation, the low operation costs and the reliable treatment efficiency are adapted to the limited resources that small communities are able to dedicate to wastewater treatment (Kadlec, 2000; Gullicks et al., 2011). Vertical flow constructed wetlands (VFCWs) are popular when the nitrogen forms contained in wastewater have to be nitrified. Current practice usually involves vertical sand filters, with successive periods of feeding by primary treated wastewater, and rest periods (with no feeding by wastewater) to maintain permeability and oxygen. Irstea (French National Research Institute of Science and Technology for Environment and Agriculture) has developed a VFCW made of gravel, accepting raw wastewater without primary settler, and designed at 1.2 m^2 p.e.$^{-1}$ (Molle et al., 2008). As this configuration partially removes nitrogen (reaching about 60% removal of TKN), a better understanding of the processes and limitations taking place is necessary (Molle, 2014) and is simulated in this work.

The design guidelines of VFCWs are mostly based on empirical rules-of-thumb: use of the specific surface area (Brix and Johansen, 2004), use of the maximum nitrogen loading rate (Molle

Abbreviations: b_A, rate constant for autotrophic biomass lysis; BCOD, biodegradable COD among total COD; BOD_5, biological oxygen demand for 5 days; C_{CI}, concentration in inert soluble organic matter; $C_i^{measured}$, measured concentrations for pollutant *i*; C_{IP}, concentration in inorganic phosphorus; $C_i^{simulated}$, simulated concentration for pollutant *i*; C_{NH4}, concentration in ammonium; C_{O2}, concentration of oxygen; COD, chemical oxygen demand; C_{CR}, concentration in rapidly biodegradable organic matter; C_{CS}, concentration in slowly biodegradable organic matter; CW, constructed wetland; C_{XAN}, concentration of the total autotrophic biomass (nitrifying bacteria); C_{XH}, concentration of the heterotrophic biomass; DM, dry matter content; FP, feeding period; HFCW, horizontal flow constructed wetland; $K_{AN,IP}$, saturation/inhibition coefficient for inorganic phosphorus; $K_{AN,NH4}$, saturation/inhibition coefficient for nitrogen; $K_{AN,O2}$, saturation/inhibition coefficient for oxygen; Kd, adsorption coefficient for ammonium onto organic matter; K_La, oxygen re-aeration rate; MAE, mean absolute error defined as $(1/n)\sum_{i=1}^{n}|C_i^{simulated} - C_i^{measured}|$; MARE, mean absolute relative error defined as $(1/n)\sum_{i=1}^{n}\frac{|C_i^{simulated} - C_i^{measured}|}{C_i^{measured}}$; *n*, number of experimental data; p.e., population equivalent; PLS, partial least-squares; RP, rest period; TKN, kjeldahl nitrogen (organic + ammonium); TSS, total suspended solids; VFCW, vertical flow constructed wetland; VM, volatile matter content; XAN, total autotrophic biomass; XH, heterotrophic biomass; Xi, inert particular organic matter; $\mu_{AN\text{-}max}$, maximum aerobic growth rate coefficient for autotrophic biomass; Y_{AN}, cellular yield coefficient.

* Corresponding author. Tel.: +33 (0)4 72 20 87 87.
E-mail address: jean-marc.choubert@irstea.fr (J.-M. Choubert).

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et al., 2008) or use of a kinetic approach (Kadlec and Knight, 1996; Rousseau et al., 2004). Several mathematical models were proposed in the literature as it is briefly stated hereafter and detailed in Supplementary material SPM1; Kadlec (2000) used variably saturated conditions. Langergraber and Šimůnek (2005) used unsaturated water flow convective-dispersive mass and heat transports. McGechan et al. (2005) and Freire et al. (2006) connected hydraulic and reactive processes with a combination of completely stirred reactors and dead zones. Wanko et al. (2006) and Giraldi et al. (2010) used Richards equation, whereas Ojeda et al. (2006), Forquet et al. (2009) and Petitjean et al. (2012) used a diphasic air–water flow approach prompted by the fact that air movement is a key issue for predicting the aeration of the system. The fate of ammonium was usually simulated with a biokinetic model (i.e. production by hydrolysis from organic nitrogen, uptake by the growth of biomass during conversion into nitrate) inspired from aerobic/anoxic activated sludge (Langergraber and Šimůnek, 2005; Ojeda et al., 2006; Giraldi et al., 2010; Petitjean et al., 2012) or anaerobic digestion (Langergraber et al., 2009). Some authors considered an additional process to predict the fate of ammonium in CWs, with sorption process onto organic matter and immediate equilibrium (Sikora et al., 1995; McBride and Tanner, 2000; Giraldo and Zarate, 2001; Langergraber and Šimůnek, 2005). Unfortunately, all these models were mostly tested for sand VFCWs. Their validation status may be low for the case of VFCW with gravel treating directly raw wastewater due to the sludge accumulation on the top (Molle, 2014).

The aim of this work was to obtain a model adapted to predict the concentrations in nitrogen forms in the effluent of a VFCW with gravel fed directly with wastewater. The originality is that the model takes into account the role of sludge accumulated on the top of the VFCW and short hydraulic retention time due to high permeability of gravel.

2. Materials and methods

The present section is divided in three parts. First, the data collection is described; second, the model and the procedures to determine the sensitive parameters are given; then, the method to determine the fate of nitrogen through the VFCW is explained.

2.1. Data collection

2.1.1. The experimental plant

The first stage of the Evieu wastewater treatment plant (Ain, France) is a VFCW with gravel planted with *Phragmites australis*. It has been in operation since 2004 and receives screened (4 cm) wastewater released by 100 p.e. (nominal load). It comprises three parallel VFCWs operating successively, fed with batches for 3.5 days each (feeding period noted FP) and then not fed for 7 days (rest period noted RP). We have worked on one of the VFCWs of 28 m^2 (2.9 m wide and 9.7 m long). The gravel had a d_{10} of 2.46 mm, an UC (d_{60}/d_{10}) of 1.39 and an average porosity of 40.4%. A sludge layer of about 20 cm was developed on the top. A comprehensive description of the studied VFCW is given in Fig. 1.

Eight batches per day of raw wastewater were applied on the VFCW, applying 5 cm of water at a flow rate of 1.2 $m^3/h/m^2$ (0.46 ± 0.12 m/d). Offline and online analyses were carried out in influent and effluent from April 26 to May 6, 2010, as described in the following sections.

2.1.2. Offline analysis

An automatic refrigerated (4 °C) ISCO sampler containing 24 1-L bottles (containers) was used to determine the chemical composition of raw wastewater of each individual batch, as well as the composition of 24 h-flow proportional composite sample. Chemical analyses were determined according to APHA (2012), and included total suspended solids (TSS), total chemical oxygen demand (COD), filtered COD (0.7 μm), kjeldhal nitrogen (TKN), ammonium (NH_4-N), nitrates (NOx-N) and phosphates (PO_4-P).

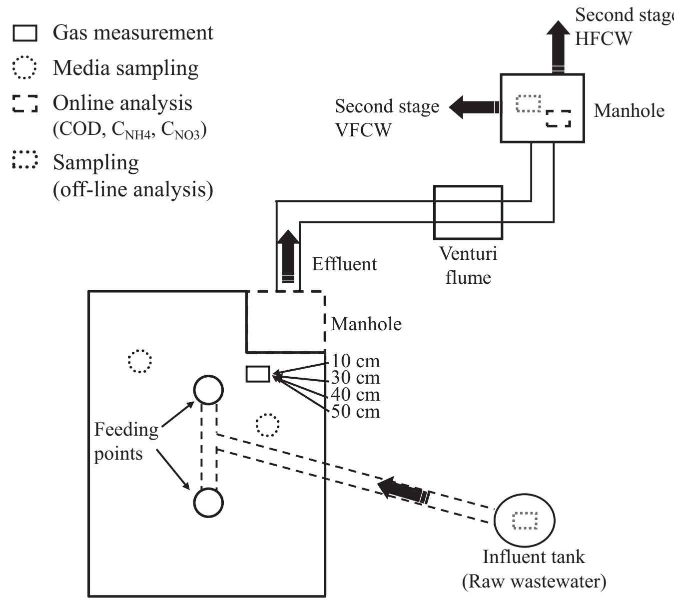

Fig. 1. Scheme of the studied first stage VFCW; locations of measurement and sampling points (not on scale).

The gas in the VFCW was also regularly sampled at four different depths (−10, −30, −40 and −50 cm) in one vertical sample port located at 2 m from a feeding point. Oxygen and carbon dioxide contents were measured with a DrägerSensor XS analyzer at the end of the rest period, and also 1 h after batches during the feeding period. The accuracy of the analysis was ±0.2% (oxygen saturation in air being 20.9%).

2.1.3. Online analysis

Inflow rate was measured by recording (pre-calibrated) pump functioning time, and outflow rate was continuously recorded with a flow meter (ISCO bubble type) on a Venturi flume. Online analyses were carried out in the effluent of the VFCW: ammonium concentrations were determined every 5 min with an online analyzer (Datalink instruments AM200 France), COD (total and filtered) and NOx-N concentrations were determined every 1 min with an online UV–vis probe (S::Scan Messtechnik, GmbH, Vienna Austria). Calibration of sensors was based on partial least-squares (PLS) regression carried out using 20 grab samples submitted to offline analysis.

2.2. Modeling

The following paragraph briefly set-up the content and the calibration strategy of the model adapted to the VFCW studied.

2.2.1. Model content

The multi-component reactive transport model for constructed wetlands (CW2D) was used via the HYDRUS software package version 2.0 (Šimůnek et al., 1999; Langergraber and Šimůnek, 2005) to simulate the concentrations of COD and nitrogen in the effluent of the first stage of the Evieu plant (as proposed in Supplementary material SPM2). It predicts the transport and reactions with a reasonable compromise between complexity and