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Dynamic model extension for the design of full-scale artificial free superficial flow wetland systems

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ABSTRACT

Addressing the low total nitrogen removal percentages observed during the sewage treatment in free superficial flow wetland systems is crucial to the design of full-scale facilities. A well-controlled pilot-scale experiment with two parallel shallow basins, one planted with *Typha latifolia* and the other without, enabled the development of a mathematical model, following the activated sludge model framework. The pilot unit was operated so as to achieve both organic matter and nitrogen removal. The key processes accounted for were ammonification, heterotrophic growth, nitrification, algal growth and plant transpiration. The dynamic model developed predicts the plant mass and evapotranspiration rate throughout the year. The predictive ability of the model was tested with a free water surface constructed wetland serving a population of 400, with the sole modification being the need to account for oxygen limitation in the rate of nitrification. The required inputs include the inflow characteristics and rainfall and air temperature climatic data, directly influencing the plant evapotranspiration rate. The seasonal dependence of the water temperature was determined through an energy balance.

1. Introduction

When treating wastewater in constructed wetlands, the contaminants removal efficiencies are quite satisfactory for organic matter (BOD_5) and for total suspended solids (TSS), but usually not for total nitrogen (TN) [1]. In particular, the observed removal efficiencies are in the range 80–90% for BOD_5, 80–90% for TSS, but only 40–50% for TN. Tayade et al. [2] studying the efficiency of free water surface FWS constructed wetlands reported 85% BOD_5, 83% TSS and 60% TN removal rates for *Typha latifolia* vegetation. Tunciper et al. [3] reported an annual average removal efficiency of 53% for TN. These total nitrogen removal efficiencies are considered inadequate and insufficient for the accomplishment of the usually required effluent quality.

In order to better understand and model total nitrogen removal in FWS, a small pilot unit was constructed [4]. It consisted of two parallel identical basins, one with plants (*Typha latifolia*) and the other without plants. The vegetation coverage was sparse in the basin with plants, and aerobic conditions dominated within. The key processes which described adequately the key contaminants' removal were: (i) Aerobic heterotrophic growth, consuming organics and ammonia; (ii) autotrophic growth (nitrification); (iii) ammonification of organic nitrogen and (iv) algal growth, consuming nitrate nitrogen (suspended algae "phytoplankton" in the basin without plants and "periphyta" at the bottom of the basin with plants) [5]. A mathematical model assuming the above processes followed the approach of activated sludge models [6]. Given the model structure, the model parameters were determined in order to describe the behavior of both basins during a whole year-round operation of the pilot unit. Model validation was done using the data from the operation in a second year, taking into account the rainfall, the evaporation and the plant transpiration rates. The model predicted, in agreement with the observed data, annual removal efficiencies of 82% and 65% for BOD_5 and TN respectively for the vegetated basin [4]. The pilot unit basins were modeled as homogeneous (continuous stirred tank reactor CSTR) [7].

The developed model assumed known (measured) time-series for the water temperature and the net volume changes due to rainfall–evapotranspiration, and also a given plant mass in the basin with plants. In order to be able to design a new full-scale facility, the model needs to be extended so as to predict plant growth and evapotranspiration rates, as well as typical year-round temperature and rainfall profiles. The objective of

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Nomenclature

ASM	activated sludge model
S-NH	influent concentrations of the ammonium nitrogen (mg/L)
S-NH_{out}	effluent concentrations of the ammonium nitrogen (mg/L)
S-NH	model predicted concentrations of the ammonium nitrogen (mg/L)
S-NO_{in}	influent concentrations of nitrate nitrogen (mg/L)
S-$NO_{modelout}$	model predicted effluent concentrations of nitrate nitrogen (mg/L)
S-NOS_{in}	influent model predicted concentrations of organic nitrate nitrogen (mg/L)
S-NS_{outin}	inffluent concentrations of organic nitrogen (mg/L)
S-NS_{out}	effluent concentrations of organic nitrogen (mg/L)
S-NS_{model}	model predicted concentrations of organic nitrogen (mg/L)
S-S_{in}	influent BOD_5 concentrations (mg/L)
S-S_{out}	effluent BOD_5 concentrations (mg/L)
S-S_{model}	model predicted BOD_5 concentrations (mg/L)
S-TN_{model}	model predicted concentrations of total nitrogen (mg/L)

the current paper is to extend the developed model so that it may be usable directly for design and simulation purposes and to validate it using real data from an existing full-scale unit of 400 population equivalent.

2. Materials and methods

2.1. Extension of the model to predict plant growth and evapotranspiration

During the first year-round operation of the pilot unit from October to September, harvesting was performed three times in order to assess the nitrogen uptake by the plants. The plant mass was weighed and the moisture was measured, whereas the total nitrogen was estimated by Kjeldahl analysis as the percentage of total nitrogen per dry matter (%w/w). These measurement results for each harvesting period are given in Table 1. The average annual weight percentage of nitrogen on a dry plant mass basis was 1.33%, in good agreement with the literature value of 1.37% [8] for *Typha latifolia*.

The operational experience of the pilot unit provides observations that allow us to extend this dynamic model so as to predict plant growth throughout the year. The plant evapotranspiration rate Q_{plants} [L/d] is expressed as a function of the air temperature and the plant mass, according to the equation:

$$Q_{plants} = a \cdot \theta_P^{Ta-10} \cdot m_p \tag{1}$$

where θ_p is a dimensionless temperature coefficient, T_α [°C] is the air temperature of the region, m_p [g_plants] is the plant mass and α [L/(g_plants·d)] is a constant (reference evapotranspiration rate per plant mass at 10 °C). The rate of plant mass growth is assumed to be proportional to the rate of the nitrogen uptake rate:

$$\frac{dm_p}{dt} = b \cdot Q_{plants} \cdot C_N \tag{2}$$

where t [days] is the time, C_N [mg N/L] is the total nitrogen concentration in the water and b [g_plants/mg N] is the yield of plant mass per total nitrogen. The parameter values in Eqs. (1) and (2) were determined based on the experimental measurements for each harvesting period of the pilot unit Table 1. The average annual value of the total nitrogen percentage on a dry basis was 1.33% and the corresponding average annual plant moisture was 75.13%, so that the plant humidity data are consistent with the literature value of 77.10%, reported by [9] for *Typha latifolia*. The *b* parameter value was determined based on the experimental average annual percentage of the total nitrogen per dry matter, giving $b = 0.3$ g_plants/mg *N*.

The AQUASIM simulation framework [10] was used to solve the two Eqs. (1) and (2) and to estimate simultaneously the parameters $\theta_{p,}$ α and m_{po2} [g_plants], the initial plant mass of the second harvesting period (from February to the middle of July). The parameter estimation was carried out with the experimental average monthly values per day Q_{plants_meas} of the pilot unit. Parameter estimation in the framework of AQUASIM [10] was carried out through least-squares fitting of the experimental values. The following function $x^2(p)$ (the sum of the squares of the calculated deviations) was minimized:

$$x^2(p) = \sum_{i-1}^{n} \left(\frac{y_{meas,i} - y_i(p)}{\sigma_{meas,i}} \right)^2 \tag{3}$$

where: $y_{meas,i}$ is the i-th measured data, $\sigma_{meas,i}$ is the standard deviations of $y_{meas,i}$, y_i (p) is the calculated value of the model variable, corresponding to the i-th measurement, $p = (p_1, \ldots, p_m)$ are the model parameters and n is the number of data.

The best parameter values were found to be $\theta_p = 1.1612$, $\alpha = 0.000128$ L/ (g_plants·d) and $m_{po2} =$ 3948 g_plants. Validation of these parameter values was carried out with the experimentally measured Q_{plants} of the pilot unit basin with plants and the plant mass increase during the second year operation of the pilot unit. For the parameter estimation, polynomial forms were used that fitted with time *t* in days (Table 2) the air temperature Data T_α [°C] and for the experimentally determined data of the total nitrogen C_N [mgN/L] during the operation of the pilot unit basin with plants.

As at the end of the first harvesting period, 462 g_plants were cut, the total plant mass was 4410 (= 3948 + 462) g_plants at that time. Simulating with reversing time for the first harvesting period, the initial plant mass at the beginning of the first period was found to be $m_{po1} = 4026$ g_plants.

The plant mass prediction at the end of the second harvesting period reached 4611 g_plants. The plants were cut from their upper section and the plant mass weighed was 1532 g_plants (Table 1).

Table 1
Measurements of key parameters upon harvesting during the first year of operation of the pilot unit.

Harvesting period	Weight of plants	Moisture	Dry weight of plants	Harvest total time	Dry total mass of each period	% Nitrogen per dry matter
	g plants	%	mg plants	days	mg plants/d	%w/w
1st (1st–119th)	462	48.5	224,070	119	1882	0.13
2nd (120th–289th)	1532	83.6	251,248	170	1477	1.78
3rd (290th–364th)	1216	93.3	81,472	75	1086	2.19