DYNAMIC MODELLING AND DESIGN OF FREE WATER SURFACE CONSTRUCTED WETLAND SYSTEMS

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ABSTRACT

A dynamic mathematical model, based on the biochemical kinetic processes dominated in shallow free water systems was developed following the Activated Sludge Model (ASM) methodology. The model predicts plant mass and water uptake rate, BOD_5 and total nitrogen (TN) removal on a year round basis, given climatic data (temperature and rain variation). The model was developed based on the operation of two parallel pilot-plant basins, one with plants and one without. The dynamic model was used for the design of full scale constructed wetland facilities for given effluent quality requirements (average annual values of 25 mg l^{-1} BOD_5 and 15 mg l^{-1} TN). It is demonstrated that given inflow information, climatic data and effluent requirements, the required surface area to achieve adequate treatment while securing treated water effluent throughout the year can be determined. In addition, the required initial planting and the amount of plant mass that needs to be cropped on an annual basis is determined. It is also demonstrated that given a total wetland surface, the system performance is optimized if the wetland is divided into two sequential basins, the first with and the second without plants.

Keywords: full-scale design; organics and nitrogen removal; free water surface; constructed wetland

1. Introduction

Constructed wetlands have been utilized to treat municipal, agricultural and industrial wastewaters (Knight *et al.*, 1999; Haberl *et al.*, 2003; Babatunde *et al.*, 2009). As described in the study of Vymazal, (2007) frequently low percentages of total nitrogen removal are observed in free water surface wetland systems. A recent review by Wu *et al.*, (2014) mentions the necessity for the development of new optimal designs aiming at securing nitrogen removal.

A model-based method of designing full-scale free water surface constructed wetland systems can secure a satisfactory removal of both organics and nitrogen from a wastewater. The USEPA, (2000) has emphasized the need for the development of appropriate methods are based on the framework of the Activated Sludge Model (ASM) by Henze *et al.*, (1987) adapted for free water surface (FWS) constructed wetlands. Given key input data (climatic data, wastewater quantitative and qualitative characteristics and effluent requirements) the required dimensions of the wetland and the required annual plant harvesting can be determined. This model structure had been used by Nasr and Ismail (2015) to improve the water quality in "Bahr El-Baqar" full-scale drain system on the north-eastern edge of the Nile Delta, receiving a mixture of urban and agricultural discharges. Their simulated results are very satisfactory when using a free water surface system for the organic removal and nitrogen transformation.

2.   Methods

2.1 Dynamic modelling for FWS constructed wetland

The model was based on pilot-scale experiments as shown in Figure 1. It considered Typha Latifolia as the special vegetation type as described in Kotti *et al.*, (2010) and was fitted by Galanopoulos *et al.*, (2013) using the model software AQUASIM (Reichert, 1998). The pilot systems inflow and outflow characteristics for an annual period (from October 2010 to September 2011) are presented in Table 1.
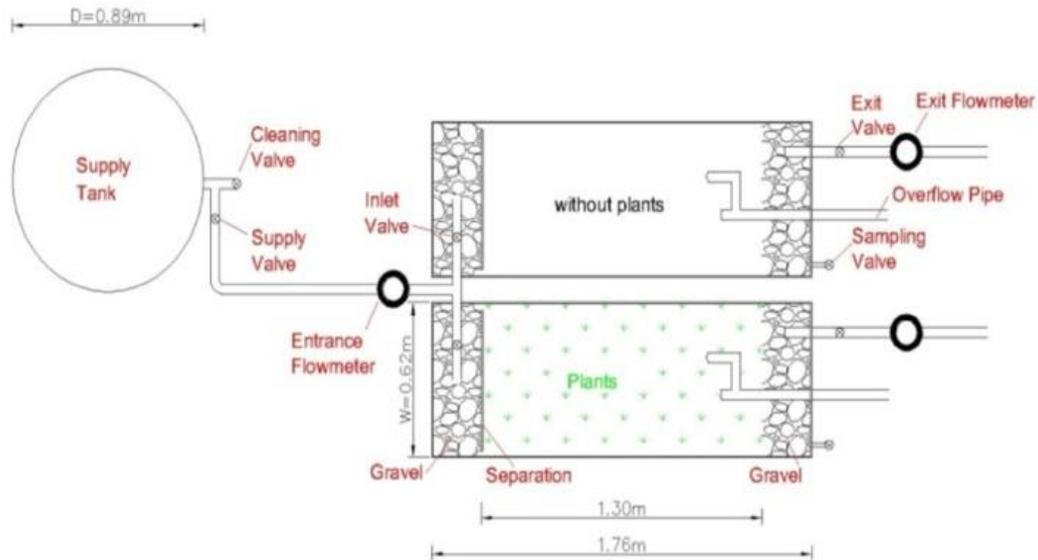
Figure 1. Top view of the identical pilot systems, one planted with Typha Latifolia, the other without

Table 1. Pilot systems inflow and outflow values with their standard deviations.

Parameter	Average inflow sewage values	Average outflow values without plants	Average outflow values with Plants
pH	7.69±0.26	8.44±0.42	7.69±0.15
Dissolved Oxygen [mg O_2 l^{-1}]	-	9.8±4.3	4.0±1.9
Ammonium Nitrogen [mg N l^{-1}]	16.7±3.0	2.3±3.0	2.5±2.6
Nitrate Nitrogen [mg N l^{-1}]	1.0±0.6	2.6±1.3	2.3±1.2
Total Kjeldahl Nitrogen [mg N l^{-1}]	23.0±5.2	7.8±2.7	5.7±2.7
Organic Nitrogen [mg N l^{-1}]	7.0±4.6	5.4±1.8	3.2±1.6
BOD [mg BOD_5 l^{-1}]	108±28	22±5	13±10
COD [mg COD l^{-1}]	176±41	105±47	36±22

The literature values of the model parameters by Galanopoulos *et al.* (2013) are given in Table 2. The key model variables are the heterotrophic biomass X_H, the autotrophic biomass X_A, the algal biomass X_{Alg}, the organic concentration S_S, the nitrate nitrogen concentration S_{NO}, the ammonium nitrogen concentration S_{NH}, the organic nitrogen concentration S_{NS} and the plant mass m_p [g_plants] as shown in Table 3. The maximum specific growth rates of the various species (m_H, m_A and m_{Alg}) are expressed as functions of the water temperature T_w as also shown in Table 3. The dimensionless temperature coefficients θ are considered different above and below 15 °C following Mara, (1975). The key processes of the dynamic

model are presented in Table 3 and the stoichiometric coefficients for each process are given in Table 4. The model was then extended (Galanopoulos *et al.*, 2014) to account explicitly for plant growth and water uptake. The plant uptake rate Q_{plants} [l d^{-1}] depends on air temperature and on the plant mass m_p and the plant growth is assumed to be proportional to the nitrogen uptake rate, as shown in Table 3. Time is denoted as t [d], θ_p is a dimensionless temperature coefficient, T_a [°C] air temperature, α [l/(g_plants·d)] is a constant (a reference evapotranspiration rate per plant mass at 10 °C), C_N [mg N l^{-1}] is the total nitrogen concentration and b [g_plants/mgN] is the yield of plant mass per total nitrogen taken up. The value of the parameter *b* was determined to be 0.3 g_plants/mgN. The parameters θ_p and α were 1.1612 and 0.000128 l/(g_plants·d)] respectively.

Table 2. Literature values of model parameters

Description	Symbol	Units	Literature values
constant saturation substrate heterotrophic biomass	K_S	mg BOD$_5$ l^{-1}	25-100
constant saturation ammonium heterotrophic biomass	K_{NHN}	mg N l^{-1}	0.01
constant saturation ammonium nitrification	K_{NH}	mgN l^{-1}	0.2-2
constant saturation ammonification	K_a	l/(mgCOD·d)	0.00016-0.7
yield factor in heterotrophic biomass	Y_H	mgVSS/ mgBOD	0.45
yield factor in autotrophic biomass	Y_A	mgCOD/ mgN	0.24
yield factor of nitrogen in algae	Y_{Alg}	mgN/ mgCOD	0.093
yield factor of nitrogen content in biomass	Y_N	mgN/ mgCOD	0.07-0.086
constant maximum specific rate heterotrophic biomass	K_{20}	d^{-1}	0.0057-1
dimensionless temperature (T>15 °C) coefficient heter. biomass	θ_1	dimensionless	1-1.135
dimensionless temperature (T<15 °C) coefficient heter. biomass	θ_2	dimensionless	1-1.135
constant maximum specific rate autotrophic biomass	K_{15}	d^{-1}	0.01-0.47
dimensionless temperature (T>15 °C) coefficient autotr. biomass	θ_{N1}	dimensionless	1-1.12
dimensionless temperature (T<15 °C) coefficient autotr. biomass	θ_{N2}	dimensionless	1-1.12
dimensionless temperature (T>15 °C) coefficient algal growth	θ_{Alg1}	dimensionless	1-1.12
dimensionless temperature (T<15 °C) coefficient algal growth	θ_{Alg2}	dimensionless	1-1.12
constant maximum specific rate algal growth	K_{Alg}	l/(mgN·d)	0.01-0.47

Table 3. Processes and rates

No	Process	Process rate
j1	aerobic growth of heterotrophic bacteria	$m_H \cdot S_S / (K_S + S_S) \cdot S_{NH} / (K_{NHN} + S_{NH}) \cdot X_H$ where $m_H = K_{20} \cdot \theta^{(Tw-20)}$
j2	Ammonification of organic nitrogen	$K_a \cdot S_{NS} \cdot X_H$
j3	aerobic growth of autotrophic bacteria	$m_A \cdot S_{NH} / (K_{NH} + S_{NH}) \cdot S_O / (K_{OA} + S_O) \cdot X_A$ where $m_A = K_{15} \cdot \theta_N^{(Tw-15)}$
j4	algal growth	$m_{Alg} \cdot S_{NO} \cdot X_{Alg}$ where $m_{Alg} = K_{Alg} \cdot \theta_{Alg}^{(Tw-15)}$
j5	plant growth	$$\frac{dm_p}{dt} = b \cdot Q_{plants} \cdot C_N$$ where $Q_{plants} = a \cdot \theta_p^{(Ta-10)} \cdot m_p$

A full-scale FWS validation showed the need to account for oxygen limitation of the nitrification rate in virtue of the low concentrations of the dissolved oxygen, according to Wu *et al.* (2001). The annual water temperature profile, is determined following by the energy balance equation:

$$T_i - T_w = \frac{(T_a - T_w) \cdot f \cdot A}{Q_{in}}$$

(1)

where f is a transport coefficient with a typical value of 0.5 m d^{-1}, *A* [m^2] is the wetland basin surface, Q_{in} [m^3 d^{-1}] the influent flow rate and T_i the inlet water temperature (sewage temperature) with a representative literature value of 15.6 °C. The limitation was accounted for by multiplying the nitrification

rate by a factor ($S_o/K_{OA}+S_o$) as shown by equation j3 in Table 3, where S_o is the dissolved oxygen concentration (average annual value was 1mg l^{-1} as measured) and K_{OA} the saturation constant for oxygen taken 0.7 mg l^{-1} by Rittmann and McCarty (2001). The final model parameter values are given in Table 5.

2.2 Full-scale design for FWS constructed wetland

The plant rate Q_{plants} is the significant factor which depends on the plant mass. When the initial vegetation is too large, the plant mass is greatly increased in the summer months, leading to a very high evapotranspiration rate. The net outflow rate E [l d^{-1}] given by the water balance:

$$E = Q_{in}+ Rain - Q_{plants} \tag{2}$$

may then become zero or even negative in these months leading to depletion of the liquid volume of the wetland basin. This fact then imposes an upper limit on the vegetation that needs to be present initially, and determines the amount of annual harvesting that is required to secure stable operation.

Table 4. Stoichiometric coefficients (variable → **i** and **j**→process).

No		X_H i1	X_A i2	X_{Alg} i3	S_S i4	S_{NO} i5	S_{NH} i6	S_{NS} i7
j1	aerobic growth heterot. bacteria	1			$-1/Y_H$		$-Y_N$	
j2	ammonification organic nitrogen						1	-1
j3	aerobic growth autot. bacteria		1			$1/Y_A$	$-Y_N$ $-1/Y_A$	
j4	algal growth			1		$-Y_{Alg}$		

Assuming no vegetation, the required surface *A* that will ensure the effluent quality of organic charge (BOD$_5$) and/or total nitrogen (TN) with the annual average value as accepted, according to EU directive 1991/271/EEC may be determined. The year-round average effluent quality x_{av} of any parameter x is determined using the equation:

$$x_{av} = \frac{1}{n}\int_0^{365} x\cdot dt \tag{3}$$

Table 5. Model parameter values

Symbol	Units	Model parameter value	Symbol	Units	Model parameter value
K_S	mgBOD$_5$ l^{-1}	99	K_{15}	d^{-1}	0.0486
K_{NHN}	mg N l^{-1}	0.01	θ_{N1}	-	1.1130
K_{NH}	mg N l^{-1}	1	θ_{N2}	-	1.0129
K_a	l/(mgCOD·d)	0.00016	θ_{Alg1}	-	1.0059
Y_H	mgVSS/mgBOD	0.450	θ_{Alg2}	-	1.0960
Y_A	mgCOD/ mgN	0.240	K_{Alg}	l/(mgN·d)	0.0167
Y_{Alg}	mgN/ mgCOD	0.093	S_O	mg O_2 l^{-1}	1.0
Y_N	mgN/ mgCOD	0.071	K_{OA}	mg O_2 l^{-1}	0.7
K_{20}	d^{-1}	0.2130	a	l/(g_plants·d)	0.000128
θ_1	-	1.0101	b	g_plants/mgN	0.3
θ_2	-	1.0143	θ_p	-	1.1612

The design problem then is the following:

Given: (a) wastewater inflow characteristics (flow rate, organics and total nitrogen), (b) Climatic data, i.e. year-round mean daily air temperature and average monthly rainfall rate, (c) Effluent requirements for organics and total nitrogen and (d) An assumed water depth, determine the required surface area to achieve the effluent requirements, the initial plant mass and the required annual plant harvesting.

3.   Results and discussion

3.1 Basin surface determination for a FWS wetland system

Consider the design of a wetland for a small city of population 400. Assuming a wastewater production of 120 [l/(person·d)], the inlet charge Q_{in} for the plant design is 48,000 [l d^{-1}]. Also, an organic loading of 60 [g/(person·d)] and a total nitrogen loading of 12 [g/(person·d)] are assumed (Metcalf and Eddy (2003)). Then, the influent organics concentration is 0.5 [gBOD$_5$ l^{-1}], whereas the total nitrogen concentration is 0.1 [gN l^{-1}], of which 0.06 [g N l^{-1}] is ammonium nitrogen and 0.04 [g N l^{-1}] organic nitrogen.

The rainfall data (average monthly values) in [mm d^{-1}] (Rio, Patras for the years 2010, 2011 and 2012) have been fitted by a 3rd degree polynomial for Q_{rain} [l d^{-1}·m^{-2})] with t in d, which was used in the Eq. (2) as Rain=Q_{rain}×*A*:

$$Q_{rain}=1.512e-0.7t^3+4.611e-0.5t^2-.033362t+4.2115 \qquad (4)$$

Average monthly air temperature data T_a were determined to give the following 3rd degree polynomial T_{a_polyn} at [°C] for time t [days] was used in Eq. (1):

$$T_{a\_polyn}=-2.1618e-0.6\cdot t^3+0.00067924\cdot t^2+0.032439\cdot t+8.8246 \qquad (5)$$

The depth level of the water in the wetland basin is assumed to be regulated at 0.35m, which implies that the total basin volume is A m^2×0.35 m=0.35A m^3. The model application requires an estimate of the water temperature T_w [°C] of the wetland through the Eq. (1), and to this end, the polynomial T_{a_polyn} (Eq. (5)). The presence or absence of plants in a basin does not have an impact on the required surface area to achieve a desired effluent concentration. It only influences the water outflow rate from the basin. Assuming no plants in the basin, the model may then be used to determine the effluent concentrations of BOD (organic matter) along with the required effluent quality of BOD$_5$<25 mg l^{-1} as a function of basin surface. Satisfactory BOD removal is achieved with a basin surface of at least A=0.4 ha. This, however, does not satisfy the required effluent quality of total nitrogen TN<15 mg l^{-1} (Fig.2). When the basin surface is increased to A=1.2 ha, then the required total nitrogen TN effluent is accomplished.
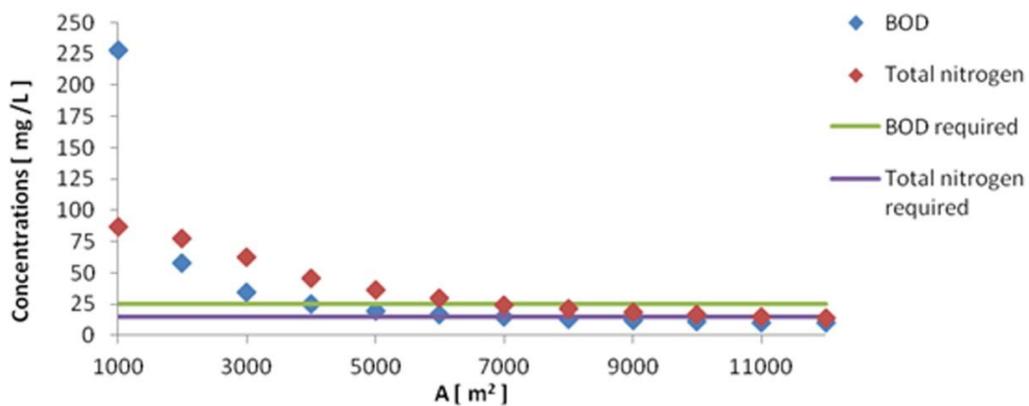

Figure 2. Annual average predicted values of effluent quality for BOD$_5$ and TN for the basin of one FWS constructed wetland as a function of the basin surface

The presence of vegetation, now, will remove water volume from the wetland basin via water uptake by plants, which grow during the year, leading to a decrease in the outflow rate E. The evolution of plant mass m_p depends on the initial plant mass m_{po} [g_plants], and the plant rate Q_{plants} and the availability of nitrogen nutrients C_N as predicted by equations j5 in Table 3. A maximum initial plant mass m_{po_max} of 3,380,340 g_plants is then determined in order to have nonnegative E.

For the case of A=0.4 ha for a free water surface wetland basin, in which the outflow rate value is marginally close to zero at a particular point during the summer, the various flow rates are shown in

Figure 3. It is worth noting that the total mass plant growth during the year reaches 64.06 tn_plants. If from the previous amount of vegetation the moisture percentage 77.10% for Typha Latifolia by Boyd (1968) is subtracted, the dry total plant mass per year is 36.67 tn_plants/ha. For the biggest aquatic plants it ranges from 4.3 tn_plants/ha to 22.5 tn_plants/ha and a typical dry plant mass of 15.3 tn_plants/ha according to Mitchell (1974).
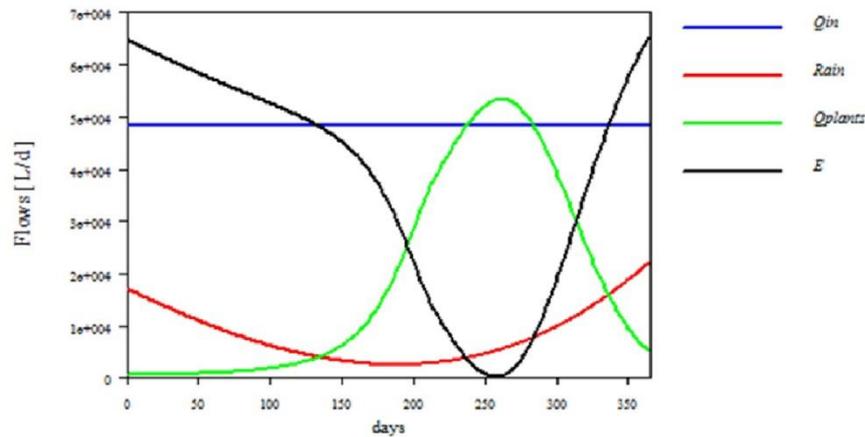
Figure 3. Year-round flow rate estimations of a FWS constructed wetland
(E stands for effluent flow rate)

3.2 Design of FWS wetland basin systems in sequence

The total required wetland surface to achieve both organics and nitrogen removal may be reduced by employing two basins in sequence. Let us assume that we already have a basin of 0.4 ha surface area which barely meets the BOD but not the nitrogen requirement, and initial plant mass m_{po_max1}=3,380,340 g_plants (as already determined to secure nonzero effluent thoroughly the year). The water temperature of each basin is assumed to be equal to that of the first basin water temperature T_{w1} [°C] (Eq. (1)).
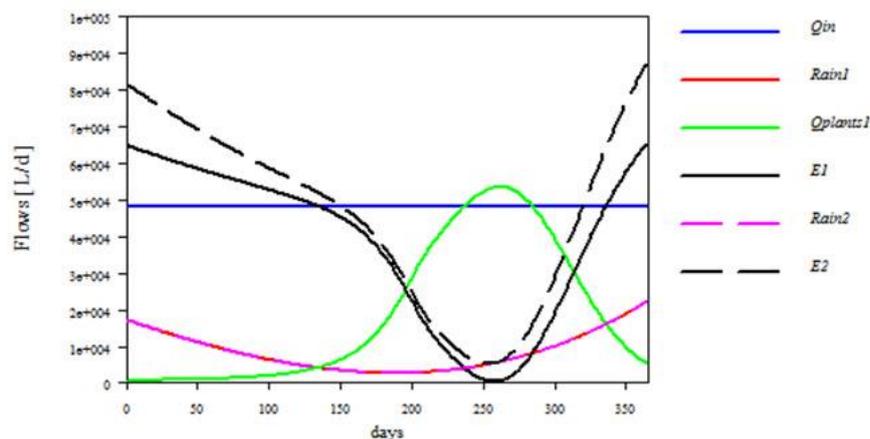
Figure 4. Year-round flow rate estimations of two FWS constructed wetland basins in sequence of a total surface 0.8 ha, the first basin with plants and the second without.

The effluent quality has yearly average values of BOD_{5_1}=25 mg l^{-1} and $TN_{\_1}$=46.0 mg l^{-1} (Eq. (3)), barely meeting the BOD but not the total nitrogen requirement. In order to avoid a level reduction in the second basin during the summer (negative E_2), the second basin should not be planted at all. For the second basin the oxygen limitation does not need to be taken into account. The estimated effluent quality in terms of total nitrogen of a two-basin in sequence system for various surface areas of the second (not planted)

basin A_2 are: TN=10.9 mg l^{-1} for A_2=0.6 ha, TN=12.3 mg l^{-1} for A_2=0.5 ha, TN=14.7 mg l^{-1} for A_2=0.4 ha and TN=16.7 mg l^{-1} for A_2=0.35 ha.

So an additional required surface A_2=0.4 ha is needed to achieve the required effluent quality of total nitrogen (TN<15 mg l^{-1}) of the wetland system. It is clear then, that two sequential basins require a smaller total wetland surface (0.8 ha) than a single basin (1.2 ha) for meeting the nitrogen requirement. The flow rates of each basin are depicted in Figure 4.

This then implies that if we had initially a 0.4 ha basin meeting the BOD but not the nitrogen requirement and we need to extend this (retrofit) to achieve also the required nitrogen removal, the best policy is simply to add downstream an unplanted basin of equal size (0.4 ha).

4.   Conclusions

The required information for designing a free water surface water basin removing both organic matter and total nitrogen is:

- the annual variation profile of the ambient temperature and rainfall
- the annual profile of the inlet flow rates
- influent wastewater characteristics (organic and nitrogen content)
- the imposed effluent quality in annual average values according to legislation

The design for a wetland basin then includes:

- the determination of the total minimal required surface for achieving the organic and total nitrogen effluent requirements
- the assessment of the initial maximum plant mass required
- the prediction of the plant mass which must be harvested annually

There is a possibility of reducing the total required surface when basins in sequence are used instead. A most suitable wetland system turns out to be two basins in sequence, the first with plants and the second without plants, leading to a reduced total surface requirement. The design of FWS constructed wetlands when both removal of organic and nitrogen charge is demanded is optimized via the dynamic model developed following the Activated Sludge Model framework.

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