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SYSTEM DYNAMIC MODELING OF UPTAKE RATE OF NITROGEN BY PLANT IN SUBSURFACE CONSTRUCTED WETLANDS

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ABSTRACT

Constructed wetlands have great ability for nitrogen removal from wastewater. The common removal process for nutrients in constructed wetlands through a biological means is plant uptake; yet, research works on plant contribution to pollutants removal are limited. This research paper is centered on development of simulation model for the absorption rate of nitrogen by plants in a horizontal sub surface flow constructed wetland receiving septic tank effluent. Wetland characteristics, plant characteristics and nitrogen transformation processes were addressed in the model using STELLA 9.1.3 as a means for graphical formulation. Field measurement and laboratory analyses were conducted. The results of the study indicate that uptake rate of NH_4*-N is within the range of 0.0075 and 0.0150 mg/kg.day while that of* NO_3*-N range from 9.326e-6 to1.712e-3 mg/kg.day. The simulated results were in accordance with the trends in literature. The data from model runs show that increase in nitrogen demand made a significant change in plant uptake rate while the variation in other parameters caused little or no change on plant uptake rate. This is an indication that uptake rate of nitrogen in wetland strongly depends on the vegetation type considered for a constructed wetland. Understanding the quantitative representation of the separation mechanisms is required for proper management of wetland.*

Keywords: *Waste water, Dynamic, Nitrogen, Wetland*

INTRODUCTION

Wetland is used around the world as treatment option for water pollution control because of its cost effectiveness. (Vymazal *et al*., 2006). A constructed wetland is an engineered system specifically designed and constructed for the purpose of pollution control and waste management by using wetland plants, soil and microbial populations at a location other than existing natural wetlands. It takes the shape of an open cuboids filled with gravel or sand on which plants grow.

The constructed wetland can be divided into three main types according to different hydrologic modes: Free Water Surface (FWS) wetland in which wastewater flows above the substrate, horizontal subsurface flow wetlands (SF) in which wastewater flows below the substrate and vertical subsurface wetlands involve vertical flow of wastewater through the filter bed to the bottom of the basin. The potential nitrogen removal mechanisms in constructed wetland are plant and other living biomass uptake, sedimentation in soil, ammonia volatilization, nitrate leaching and denitrification.

Modeling nitrogen dynamics in wetland has been carried out in the past for different types of constructed wetlands using different models. Tuncsiper *et al.* (2006) evaluated constructed wetland systems for removal efficiencies of nitrogenous pollutants in tertiary stage of wastewater treatment by considering two types of model: first-order plug flow and multiple regressions. Singo *et al.* (2012) worked on modeling nitrogen transformation and removal in a natural wetland. Xuan *et al*. (2010) modeled subsurface up flow wetland system for wastewater effluent treatment using system dynamic modeling. Their purpose was to determine the effectiveness of the constructed wetland and the impact of each compartment in the removal of nitrogenous pollutants. Michael (1996) developed a model for plant uptake of metals in constructed wetland by using system dynamic modeling. He concluded that metals could accumulate in plant tissues.

This present research is aimed to develop dynamic simulation model for understanding the nitrogen uptake in constructed wetland plants which can serve as a tool of simulation under different conditions using system dynamic modeling (STELLA). Although all components are important and necessary for the proper functioning of wetland, this research was focused mainly on the substrate, plant, water components and nitrogen transformation by microorganism. Uptake of nitrogen by microbial populations and vertebrates and invertebrate was not considered because of their negligible contribution as indicated in Khatiwada (1999).

MATERIALS AND METHODS

Description of the System

The research was conducted at one of the sections of constructed wetland in University of Lagos, Nigeria. In this study, a subsurface horizontal constructed wetland system receiving septic effluent was considered. The wetland receives wastewater at the rate of 1200l /day. The test bed with the dimension 3.5 m wide x 7.5 m long x 0.85 m deep consists of impermeable barrier which prevent flowing of ground water into the system. The bed contains media which will support the growth of emergent vegetation. The system is built with a slight inclination (2%) between inlet and outlet.

Plant Sampling

The mass of the shoot and root were taken adequately using weighing balance. The change in plant height within a month divided by plant height was used to determine growth fraction. At the early stage of plant growth, the death rate of plant is very low, hence, small number was assumed as death fraction (0.001).

Wastewater Sampling and Analysis

Water samples were taken for laboratory analysis from the influent flow to the test bed. The volumetric flow rate with bucket and stopwatch was taken between 7.30 am and 10.00 am and 03.30 pm and 05.30 pm. This was to account for varying values during the day. Temperature and P^H was measured using P^H meter and mercury filled glass thermometer respectively. Dissolved oxygen concentrations were also measured in situ using digital DO meter. Water samples were analyzed for ON, NO_3-N, NH_4-N concentrations at environmental laboratory using standard methods.

DEVELOPMENT OF SYSTEM DYNAMICS MODELING

System dynamics modeling is considered to describe the extremely complex behavior exhibited by the wetlands. As one of the most advanced graphical system programming dynamics software package, STELLA was used to develop the mathematical model. The model consists of three sections: Wetland section, Plant section and Nitrogen transformation and plant uptake section.

Wetland Hydrological Section

The model diagram for hydrological section developed by STELLA software package is shown Figure 1 with all the flows expressed in l/day. Water enters the constructed wetland via stream inflow and precipitation while water leaves through the outlet and evaporation. The wastewater balance in the system considered for the research is expressed in Equation (1).

$$Q_i - Q_o + (P - ET)A = dV/dt \qquad (1)$$

Q_i, influent wastewater flow (l/day); Q_o, effluent wastewater flow (l/day);t, time (day); P, precipitation (m/day); ET, Evapotranspiration (m/day); V, volume of water (l); A, surface area of the wetland (m^2).

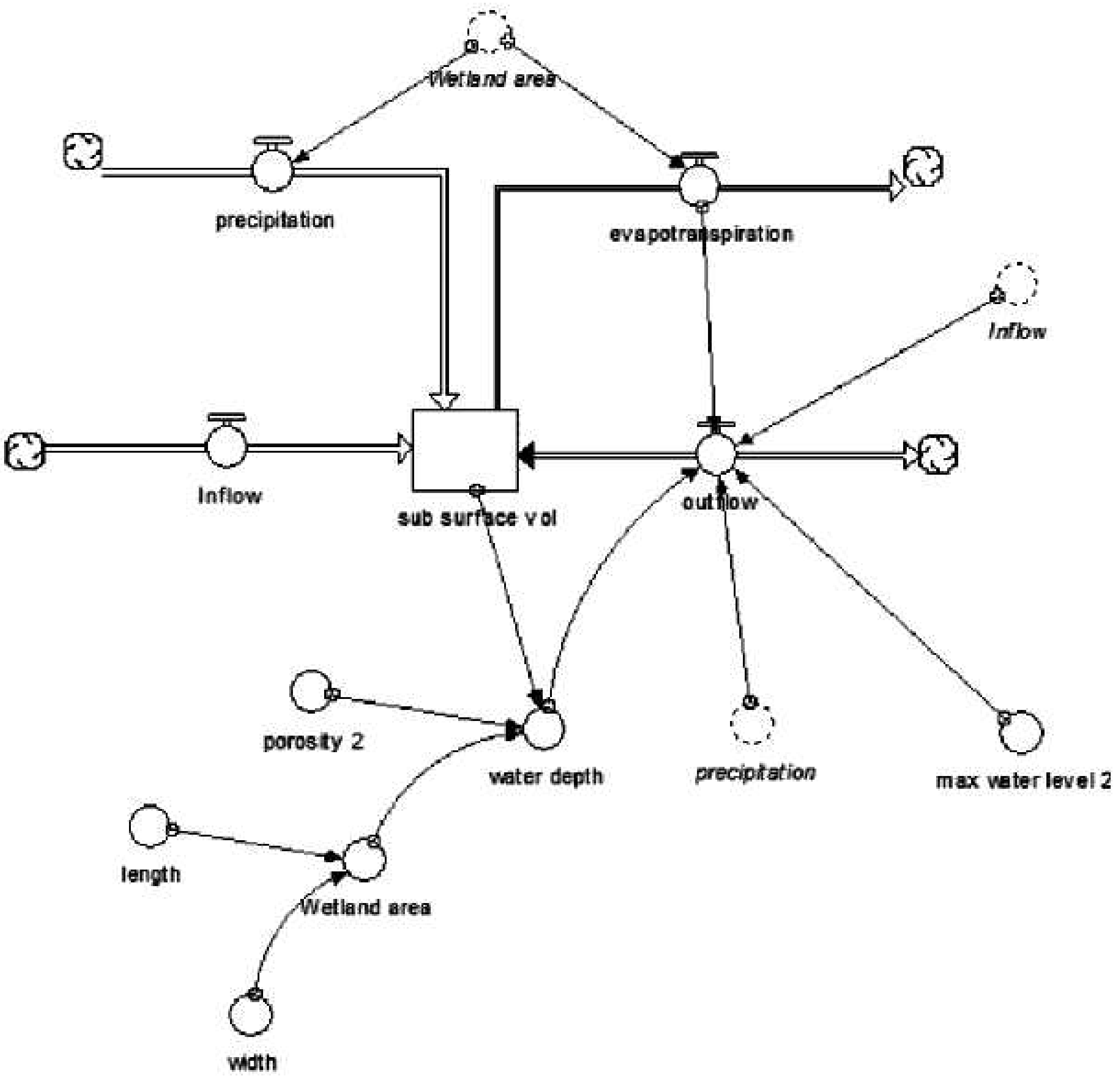

Figure 1: Flow diagram for water balance in constructed wetland

Plant Parameters

The determinants of plant biomass on the test bed are growth and death rate. The growth and death rate were calculated by the product of constant fraction and the existing biomass stock. The stock flow diagram of plant biomass is shown in Figure 2. Plant biomass balance can be expressed as follows:

$$d(PLBI)/dt = G - D \tag{2}$$

$PLBI$, Plant Biomass in kg;G, growth rate in kg/day; D, death rate in kg/day; $d(PLBI)/dt$, rate of change of plant biomass in the wetland.

Over an extended period of time, the existing biomass remains unchanged. The maximum plant biomass value per square metre in a constructed wetland is 10 kg (Smekrud, 1994).

$d(PLBI)/dt$ is zero wher PLBI= 10 kg/m^2 and Equation (2) becomes :

$$G = D \tag{3}$$

Nitrogen Uptake Parameters

Transformation and removal processes considered in this model are mineralization, nitrification, denitrification, plant uptake, plant decay and accretion. The negligible contribution of volatilization due low P^H value was discarded in the model. It was assumed that one litre of wastewater equals one kilogram of plant biomass. The stock flow diagram of nitrogen plant uptake model and representation of the symbols used in the diagram are shown in Figure 3 and Table 1 respectively.

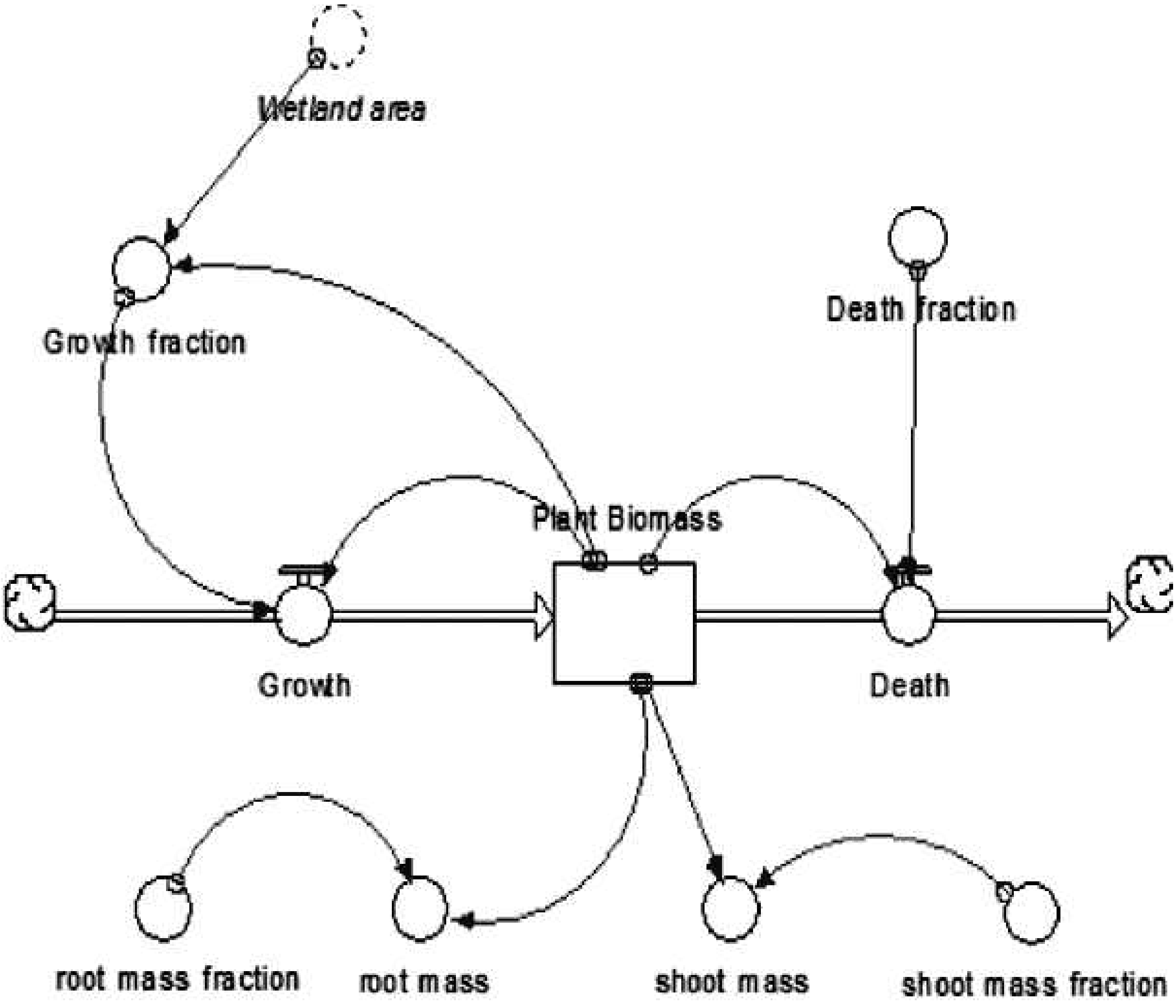

Figure 2: Flow diagram for plant biomass balance

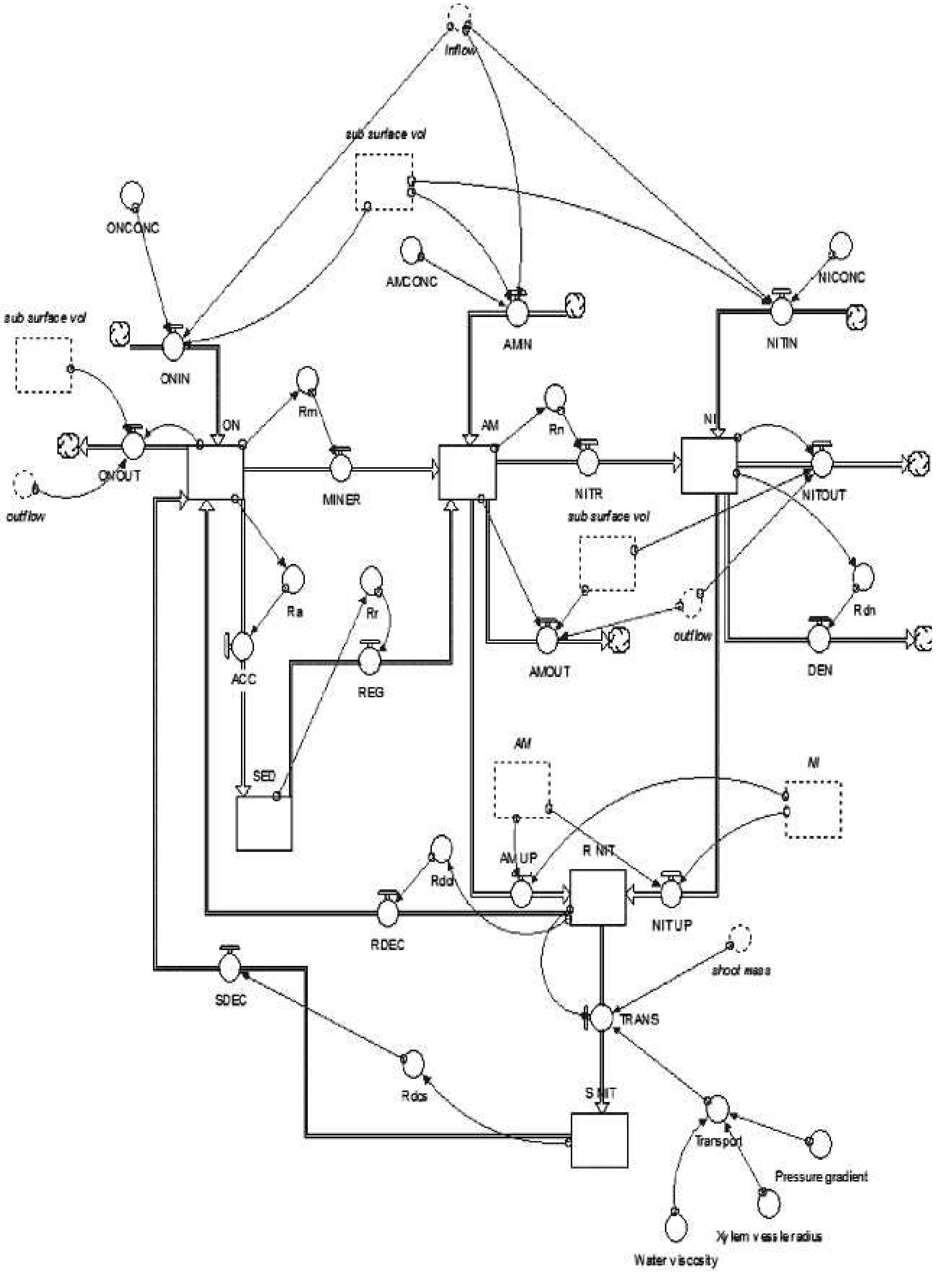

Figure 3: The stock flow diagram of nitrogen uptake model

Table 1: Description of Stocks and Flows in nitrogen uptake parameters model

Symbols	Descriptions
ON	Organic nitrogen concentration in the wetland(mg/l)
AM	Ammonia nitrogen concentration in the wetland (mg/l)
NI	Nitrate nitrogen concentration in the wetland (mg/l)
SED	Nitrogen concentration in wetland sediment (mg/l)
RNIT	Root nitrogen concentration (mg/l)
SNIT	Shoot nitrogen concentration (mg/l)
Rm	Mineralization rate (mg/l.day)
Rn	Nitrification rate (mg/l.day)
Rdn	Denitrification rate (mg/l.day)
Ra	Accretion rate (mg/l.day)
Rr	Regeneration rate (mg/l.day)
AMUP	Ammonia uptake rate (mg/l.day)
NITUP	Nitrate uptake rate (mg/l.day)
NITOUT	Nitrate nitrogen in the effluent (mg/l.day)
NITIN	Nitrate nitrogen in the influent (mg/l.day)
AMOUT	Ammonia nitrogen in the effluent (mg/l.day)
AMIN	Ammonia nitrogen in the influent (mg/l.day)
ONOUT	Organic nitrogen in the effluent (mg/l.day)
ONIN	Organic nitrogen in the influent (mg/l.day)
ONCONC	Organic nitrogen concentration in the effluent (mg/l)
AMCONC	Ammonia nitrogen concentration in the effluent (mg/l)
NICONC	Nitrate nitrogen concentration in the effluent (mg/l)

As shown in Figure 3, the mathematical Equations 5 through 8 are used to predict ON, AM, NI, SED, RNIT and SNIT in the wetland.

$$d(ON)/dt = \frac{Q_i(ONCONC)}{V} - \frac{Q_o(ON)}{V} - MINER - ACC + SDEC + RDEC \quad (4)$$

$$d(AM)/dt = Q_i(AMCONC)/V - Q_o(AM)/V - NITR - AMUP + MINER + REG \quad (5)$$

$$d(NI)/dt = Q_i(NICONC)/V - Q_O(NI)/V + NITR - NITUP - DEN \quad (6)$$

$$d(RNIT)/dt = AMUP + NITUP - RDEC - TRANS \quad (7)$$

$$d(SNIT)/dt = TRANS - SDEC \quad (8)$$

$MINER$, Mineralization (mg/l.day); DEN, denitrification (mg/l.day); SDEC, Shoot decomposition (mg/l.day); ACC, accretion (mg/l.day); RDEC, root decomposition (mg/l.day) NITR, nitrification (mg/l.day); REG, regeneration of ammonia (mg/l.day); TRANS, transportation of root nitrogen to the shoot of plant (mg/l.day).

The transformation processes in Figure 3 are modeled by Equations 9 to 15.

$Rn = Y_n(K_n + NH_4)/Y_n(K_n + NH_4) \times (DO)/(K_nO_2 + DO) \times e^{\alpha(T-T_o)} \times 1 - 0.833(7.2 - P^H)$ as considered by Kadlec and Knight (1996) (9)

T_o, reference temperature; α, empirical constant ; K_N, half saturation constant for nitrosomonas; μ_n, maximum nitrosomonas growth rate; Y_n, yield coefficient of nitrosomonas; K_nO_2=Oxygen nitrosomon as half saturation. A half rate saturation constant value of 6.8g/m^3 was considered. The values of 25°C for T_o and 0.098/°C for μ_n were adopted (Senzia, 1999). The maximum *nitrosomonas* growth *rate* of 0.05/d was adopted (Senzia, 2003), yield coefficient, Y_n of *Nitrosomonas* was recommended by Singo *et al.* (2012) to be 0.13. The oxygen *Nitrosomonas* half saturation K_nO_2 was also recommended to be 1.3mg/l (Charley *et al.*, 1980).

$Rdn = K_{20d} Q_d^{(T-20)} NO_3 - N$ According to Mayo and Mutamba (2005). (10)

Q_d, Arhenius constant; K_{20d} ,denitrification constant; Q_d= 1.09 and K_{20d} = 0.3 recommended by Singo *et al*. (2012).

$Rm = Am \times (ON)$ asused in Beran and Kergi (2005) (11)

The mineralization rate constant (Am) was taken as 0.08/d adopted from Martin and Reddy (1997).

$$Ra = Kac\ (ON) \quad (12)$$

Kac of 0.85/d was adopted according to (Senzia, 2003).

The regeneration of NH_3-N from ON accumulated in sediment was also modeled with the Equation 13.

$$R_r = K_{rr} \times N_{sediment} \quad (13)$$

Regeneration rate constant (K_{rr}) of 0.015/d was recommended by Singo *et al.* (2012). .

$$R_{dcr} = K_{dc}(RNIT) \quad (14)$$

$$R_{dcs} = K_{dc}(RNIT) \quad (15)$$

K_{dc}, plant nitrogen decaying rate of 0.006/d was adopted (Senzia, 2003).

The nitrogen uptake by the roots can be represented with Michaelis-Menten kinetics, the rate of nitrogen uptake by the roots of plant is given by Equation 16 and 17.

$$AMUP = N_{demand} \times NH_4 - N/(K_m + NH_4 - N) \times NH_4 - N/(NH_4 - N + NO_3 - N) \quad (16)$$

$$AMUP = N_{demand} \times NO_3 - N/(K_m + NO_3 - N) \times NO_3 - N/(NH_4 - N + NO_3 - N) \quad (17)$$

K_m, Nitrogen half saturation constant of 0.1 mg/l.d and N-demand of 0.015 mg/l.d were adopted (Senzia, 2003).

The transport of nitrogen from the roots was modeled using Poiseuille's volumetric flow equation given in equation 18.The pressure gradient in transpiring plant is -0.03 x 10^6 kg/m^{2}s^2 and the xylem vessel radii range from 8 to 500 micros Nobel (1991) . 178 x 10^{-6}m was used in the model.

$$Flow = \left(\pi r^4/8\eta\right) \times (dp/dx) \quad (18)$$

dp/dx), the negative gradient of the hydrostatic pressure; r, the cylinder radius; η, fluid viscosity.

RESULTS AND DISCUSSION

The authenticity of the three sections of the model was confirmed by checking the conformity of the model output with the anticipated behaviours. Figure 4 presents the hydrological component of the model. Water flows out of the wetland when the water depth equals designed maximum water level and this is attained on the graph within the first month of operation. At this point, the total input must be equal to the total output of the system. The equivalence was confirmed from the graph by adding wastewater rate entering the wetland and precipitation rate (13336.5l/day) and the sum of effluent and evapotranspiration rate (1336.5 l/day). The behaviours of the entities shown on the graph agree with the anticipated result dictated by conjectural design.

Figure 5 illustrates the vegetation biomass calculated by the model. For the purposes of these analyses, the vegetation biomass is held at constant value when the wetland is fully covered (10 kg/m^2).The expected biomass value was calculated by multiplying the wetland area (26.25 m^2) by 10 kg/m^2 to get 262.5 kg which is equal to the model output value obtained from Figure 5. Therefore, the vegetative component behaves as expected.

The potential nitrogen uptake capacity of plant is controlled by vegetative and hydrological component. It is obvious in the Figure 6 that there is rapid nitrogen uptake before attaining an approximate steady state in the wetland. This might be attributed to high concentration of NH_4-N in the septic effluent (80-90%). The diminishing nature of NO_3-N uptake curve might possibly due to reduction of concentration of NO_3-N in the wetland. The saturable process shown on the graph is an indication that uptake mechanism is working as expected. According to Mayo and Bigambo (2005), uptake of nitrogen by plants is normally entirely from ammonia because of preference of plant for ammonia rather than nitrate.. Wetzel (2000) also reported that NH_4-N preference is common in macrophytes living in environment with limited nitrification when NH_4-N is abundant. This study also revealed in Figure 6 that preference is given to NH_4-N by wetland plant over NO_3-N.This might probably due to increment in concentration of NH_4-N nitrogen in the wetland..

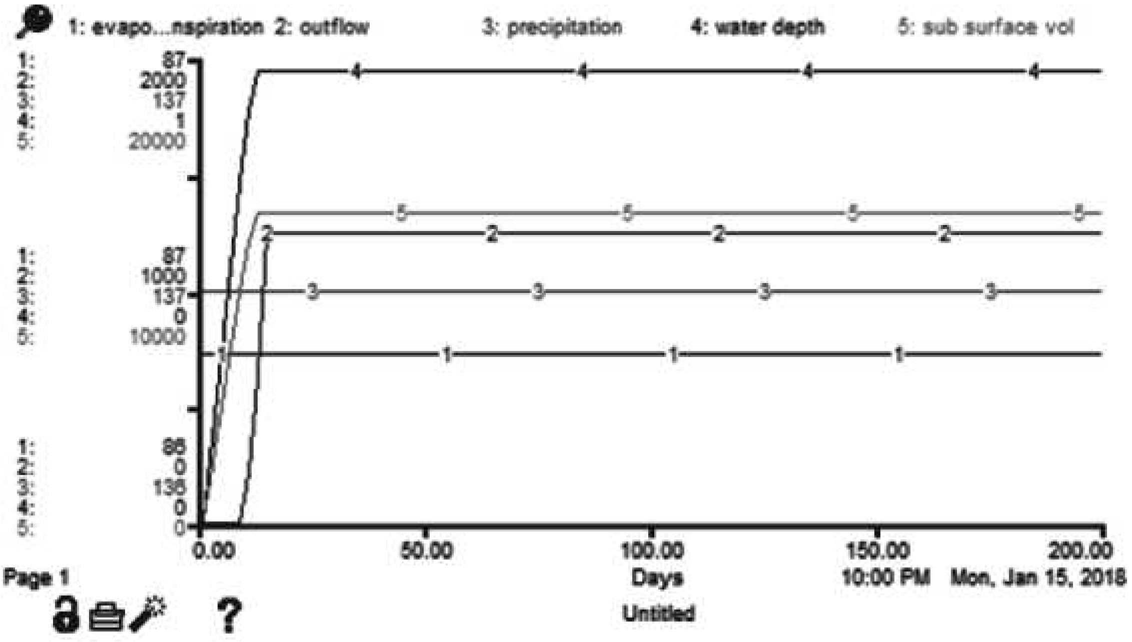

Figure 4: Hydrological component of wetland model

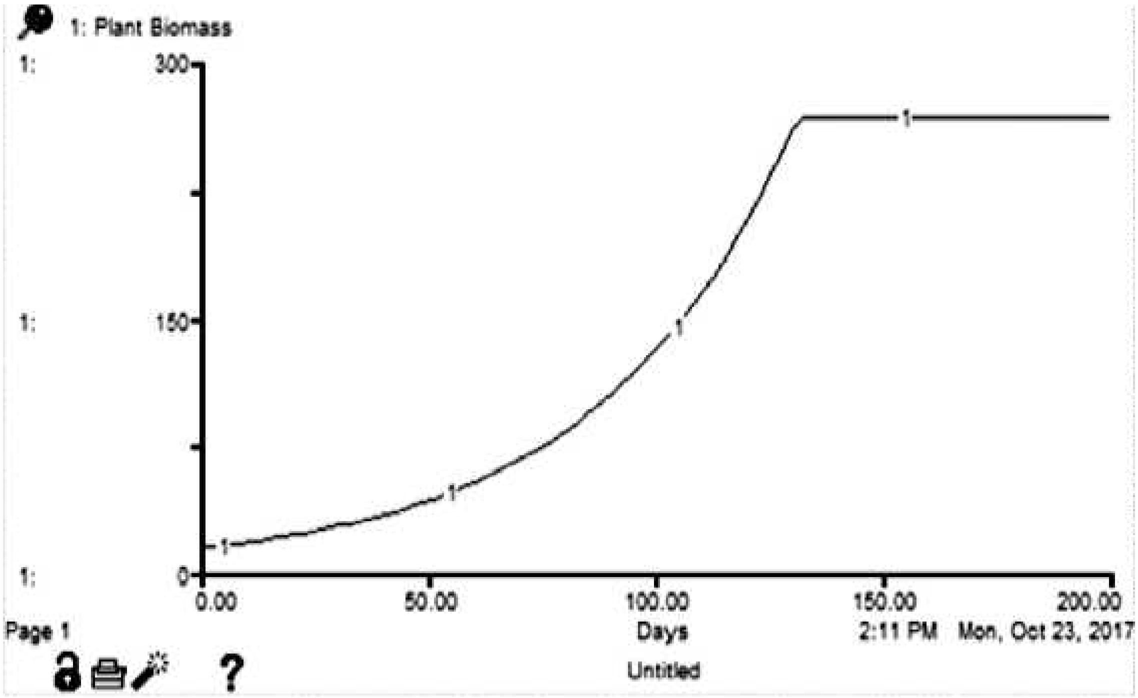

Figure 5: Vegetative component of wetland model

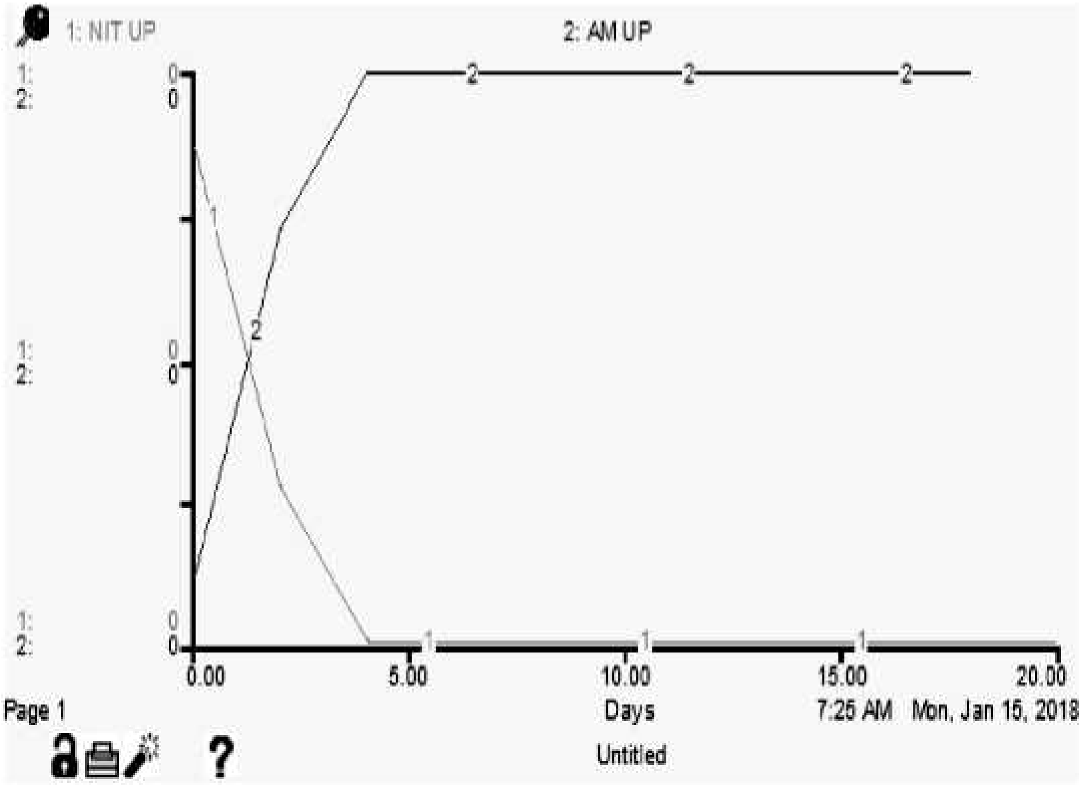

Figure 6: Uptake rate of nitrogen species in wetland plants

Model results given in Figure 6 give an indication that the model perform correctly and satisfactorily. The simulated values of NH_4-N uptake (AMUP) ranges from 7.497×10^{-3} mg/kg.day to 1.498×10^{-2} mg/kg.day while that of NO_3-N (NITUP) ranges from 9.326×10^{-6} mg/kg.day to 1.712×10^{-3} mg/kg.day.

The effect of doubling nitrogen species concentration, inflow rate and plant nitrogen demand within the first ten day was studied. The data from model runs shown in Table 2 indicate that increase in nitrogen demand makes a significant change in plant uptake rate while the variation in other parameters caused little or no change on plant uptake rate. This is an indication that uptake rate of nitrogen in wetland strongly depends on the vegetation type considered for a constructed

Table 2: Effect of change in some parameters on plant uptake of nitrogen

	Days	2	4	6	8
Base case	AMUP	0.03497	0.03499	0.03499	0.03499
	NITUP	1.383e-6	2.197e-7	1.862e-7	8.718e-6
Doubled	AMUP	0.03496	0.03498	0.03499	0.03499
Inflow rate	NITUP	8.474e-6	3.757e-6	6.315e-7	4.928e-7
Doubled	AMUP	0.03841	0.03496	0.03499	0.03499
Concentration	NITUP	8.427e-4	8.474e-6	6.315e-7	4.928e-7
Doubled nitrogen	AMUP	0.06990	0.06997	0.06996	0.06998
Demand	NITUP	2.658e-4	9.435e-6	2.278e-6	3.866e-6

CONCLUSION

Modeling the plant uptake of nitrogen using data obtained from experiment, measurement, theoretical calculation or published literature reveals certain hidden behaviours in the constructed wetland when exposed to septic effluent. To confirm the basic concepts defined in the model, some important components in the wetland were checked. It was discovered from the result of the analysis that the hydrological, vegetative and nitrogen uptake sections values calculated by the model conform to expected behaviors. The results also indicate that at any point in time, the concentration of ammonia nitrogen is higher than that of nitrate nitrogen making it possible for the assimilation of ammonia nitrogen to be preferred over nitrate nitrogen by the plant. Changes in wetland parameters affect the rate at which nitrogen is being taken up by plant. It could be inferred from the results that plant uptake of nitrogen is highly sensitive to change in plant nitrogen demand in the wetland.

Studying and understanding plant and wetland characteristics is required to properly manage constructed wetlands.

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