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Dynamics of Nitrogen Transformation and Removal in a Pilot High Rate Pond

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Abstract

The transformation and removal of nitrogen was studied in a pilot high rate pond with a surface area of 10.2 m² and water depth of 60 cm. The pilot unit received wastewater from an existing field scale primary facultative pond at the University of Dar es Salaam. Wastewater samples were collected from the influent and effluent of high rate pond and were analyzed for physical-chemical parameters in the laboratory and *in situ.* An appropriate model complexity was selected, from which a conceptual model was then developed to model various processes in the system using STELLA 6.0.1 software. The study demonstrated that dominant nitrogen transformation processes in HRP were nitrification and denitrification, which transformed 0.95 and 0.87 gN/m²·d, respectively. These were followed by mineralization (0.37 gN/m²·d), ammonia uptake by microorganisms (0.34 gN/m²·d), volatilization (0.30 gN/m²·d), sedimentation (0.24 gN/m²·d), and regeneration (0.15 gN/m²·d). Uptake of nitrate was not observed because of microorganisms preference for ammonia, which was abundant in the pond. The major nitrogen transformation mechanisms in high rate pond were denitrification, net sedimentation and volatilization, which accounted for 69.1%, 7.1% and 23.8% of the total permanent removal mechanisms of nitrogen in High Rate Pond.

Keywords

High Rate Ponds, Nitrification, Denitrification, Nitrogen Transformation, Nitrogen Removal

1. Introduction

Waste stabilization ponds have found wide application in tropical climates [1] [2] although their application in temperate climate is not uncommon [3]. However, in cold climates, wastewater is applied at very low hydraulic loading rates [4] and low organic loading rates of less than 60 kgBOD_5/ha/d [5]. Waste stabilization ponds are

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commonly used for treatment of wastewater from domestic, industrial and agricultural sources [6]-[9] with an objective of reduction of organic matter [2] [10] [12], pathogenic organisms [13]-[15] and nutrients particularly nitrogen [3] [6] [16].

Waste stabilization ponds have numerous advantages over other biological wastewater treatment systems. These advantages include reduction of pathogenic microorganisms without addition of chemicals; low construction, operation and maintenance costs, low sensitivity to hydraulic and organic shock loads, minimum or no mechanical equipment are required for their operation and low requirement of external source of energy [13] [17] [18]. Unfortunately, ponds require large area of land for their construction and release large amount of biomass in the effluent [18]-[20]. In an effort to reduce land requirement more efficient systems such as high rate ponds, which can improve reaction rates substantially, are desired.

The release of nitrogen-rich wastewater effluents into receiving rivers and its long-term adverse effects on the environment and human health are of great concern [21]. Increased levels of nitrogen in receiving water bodies have lead to eutrophication that disturbs aquatic ecosystems [22], difficulties in water treatment and serious health problems especially to infants [9] [23]. Nitrite is known to oxidize the iron (II) and cause *methamoglobinaemia,* which binds oxygen less effectively than normal *haemoglobin*. *Methamoglobinaemia*, also known as blue baby disease, can lead to diarrhea, vomiting, and in extreme cases even death in young children [24]. On the other side, ammonia can deplete the dissolved oxygen in water and is extremely toxic to fish and many other aquatic organisms [25] and can cause shifts in microbial community structure and altering aquatic nitrogen cycle [26]. Consequently, fragile plants and animal species can be replaced by nitrogen-responsive species, which may lead to disruption or even extinction of the ecosystem [23].

Nitrogen transformation is adequately detailed in literature, but removal mechanisms in high rate ponds are not well understood. Previous studies on nitrogen removal have demonstrated fluctuations, variability and inconsistencies, because of different media, plants and environmental conditions [27]. This erratic removal pattern has made it difficult to optimize nitrogen removal in high rate ponds, which undermines the prospects of providing small communities with cheap and appropriate wastewater treatment technologies among other technologies that can remove nitrogen. For this reason the use of ponds is beneficial, especially for small communities that cannot afford such expensive conventional treatment systems. Different researchers have reported on the transformation and removal of nitrogen in waste stabilization ponds. This research therefore was focused on the study of biological nitrogen removal in a high rate pond with a view of establishing their effectiveness on transformation and removal of nitrogen and developing a mathematical model that simulates the transformation of nitrogen in such systems.

2. Methods and Materials

2.1. Pilot Plant

The pilot plant for this study is located downstream of a primary facultative pond treating wastewater from the University of Dar es Salaam (UDSM) community. The scheme is located at latitude 6˚48'S and longitude 39˚13'E, where the mean monthly air temperature of the site varies between 23˚C and 28˚C with a mean value of 26˚C [28]. The waste stabilization pond system receives wastewater of largely domestic characteristics; with some proportion of chemical wastes from the university dispensary, laboratories and workshops through a 20 mm diameter pipe. This unit, whose length and width were 9.2 m and 1.0 m, respectively was designed to receive 1.2 m^3/d of pre-treated wastewater, which provides a retention period of about 5 days. Effluent from the water hyacinth wetland was discharged into a receiving channel for final disposal (**Figure 1**).

2.2. Sampling and Examination of Samples

Wastewater samples for laboratory analyses were collected in clean 250 ml sampling bottles from the influent and effluent HRP between 10.00 a.m. and 10.30 a.m. at interval of one day. The collected samples were examined within 2 hours in the UDSM water quality laboratory. Samples were analyzed for Ammonium nitrogen $\left(NH_4^+ - N\right)$, total Kjeldahl nitrogen (TKN) and nitrate nitrogen $\left(NO_3^- - N\right)$ in the laboratory. Dissolved oxygen (DO), pH and water temperature were measured *in situ* during sampling. Temperature and pH were measured using a pH meter with a temperature electrode (Metrohm pH meter, model 704). Dissolved oxygen concentration was measured using a digital DO meter (YSI DO meter, model 50B). Nitrate was analyzed by cadmium re-

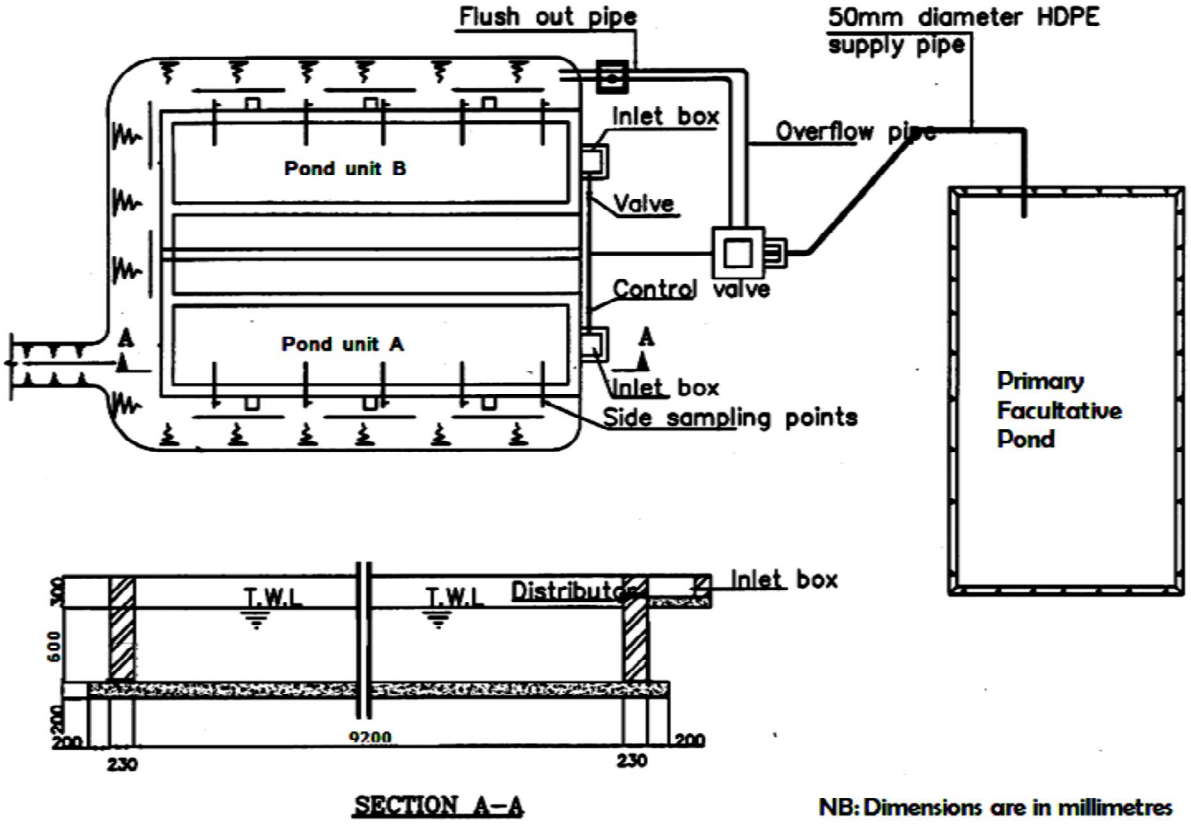


Figure 1. Layout of experimental ponds.

duction method; ammonia was extracted by distillation followed by titration with 0.02N sulphuric acid. TKN was determined using the semi micro-Kjeldahl method in accordance with *Standard Methods* [29].

2.3. Analysis of Data

A conceptual model was developed in which equations of various processes were entered into STELLA 6.0.1 software that was used to run the model. Nitrogen forms considered were organic nitrogen, ammonia nitrogen and nitrate-nitrogen, which were taken as state variables within the system. The transformation mechanisms considered in the models were mineralization, nitrification, denitrification, sedimentation, ammonia regeneration, uptake of inorganic nitrogen (ammonia and nitrates) by algae and bacteria, and ammonia volatilization. Appropriate model complexity was selected to avoid the complicated complexity and mathematical equations were used to link the relationship between the state variables and forcing functions. Equations defining transformation processes were entered into the model, which was then calibrated using the observed data versus model simulations. The model was then run while obeying the principle of conservation of mass, which was used to ensure mass balance in the system until the most efficient model results were obtained.

Figure 2 shows the conceptual model that encompasses important state variables included in this study. The model shows the flow of material from one state variable to another or in and out of the system through nitrogen transformation and removal mechanisms. A complete materials balance including all substances produced, consumed in biochemical reactions, inflows, outflows, accumulations and depletion was used. The system was assumed to be continuous completely mixed flow type and water loss through evaporation and seepage was insignificant. Equation (1) illustrates the general symbolic mass balance equation used as the basis for developing the various equations in the model.

$$V\frac{\mathrm{d}C}{\mathrm{d}t} = V\sum_{j=i}^{m}\left(r_c\right)_j + Q_i C_i - Q_o C_o \tag{1}$$

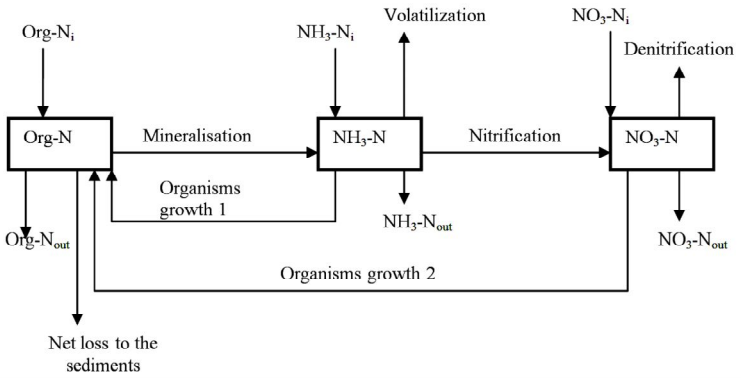


Figure 2. Nitrogen transformation and removal in HRP.

where C_o = effluent concentration (g/m^3), V = reactor volume (m^3), r_c = volumetric reaction rate (g/m^3·day), C_i = influent concentration (g/m^3), m = number of reactions that involve the substance, V (dC/dt) = volumetric rate of change of substance in the reactor (g/day), Q_i = influent flow rate (m^3/day), Q_o = effluent flow rate (m^3/day).

Mass balance equations for organic nitrogen, ammonia-nitrogen, and nitrate-nitrogen in high rate pond (HRP) are expressed in accordance with Equations (2)-(4), respectively.

$$\frac{\mathrm{d}(\mathrm{Org_N})}{\mathrm{d}t} = \frac{Q_i}{A}(\mathrm{Org_N})_i - \frac{Q_e}{A}(\mathrm{Org_N}) + r_{g1} + r_{g2} - r_m - r_s \quad (2)$$

where r_{g1} = rate of ammonia uptake by micro-organisms for growth (g/m^2·d), r_{g2} = rate of nitrate uptake by micro organisms for growth (g/m^2·d), r_m = mineralization rate of organic nitrogen (g/m^2·d), r_s = settling rate of organic nitrogen in water (g/m^2·d). Mineralization process was modeled using first order kinetics with respect to organic nitrogen concentration in accordance with Martin and Reddy [30].

Nitrification process was limited by the activity of *nitrosomonas* bacteria [31], because nitrite concentrations were always low. Therefore nitrite production and removal were not taken into consideration. In general nitrification process is influenced by temperature, DO and pH. Therefore the rates shown in Equation (3) were accordingly modified to take into account the influence of these forcing functions in accordance with Mayo and Bigambo [32].

$$\frac{\mathrm{d}(\mathrm{NH_3_N})}{\mathrm{d}t} = \frac{Q_i}{A}(\mathrm{NH_3_N})_i - \frac{Q_e}{A}(\mathrm{NH_3_N}) - r_n - r_v - r_{g1} + r_{reg} + r_m \quad (3)$$

where r_n = rate of nitrification of ammonia (g/m^2·d), r_{g1} = rate of ammonia uptake by micro organisms for growth (g/m^2·d), r_{reg} = rate of ammonia regeneration (g/m^2·d), r_v = rate of ammonia volatilization (g/m^2·d).

$$\frac{\mathrm{d}(\mathrm{NO_3_N})}{\mathrm{d}t} = \frac{Q_i}{A}(\mathrm{NO_3_N})_i - \frac{Q_e}{A}(\mathrm{NO_3_N}) + r_n - r_{dn} - r_{g2} \quad (4)$$

where r_{dn} = rate of denitrification of nitrate (g/m^2·d), r_{g2} = rate of nitrate uptake by micro organisms for growth (g/m^2·d).

Mass balance for nitrogen settled at the bottom (sink-N), was modelled using Equation (5) in which sedimentation and ammonia regeneration processes were considered.

$$\frac{\mathrm{d}(\mathrm{Sink\text{-}N})}{\mathrm{d}t} = r_s - r_{reg} \quad (5)$$

where r_s = settling rate of organic nitrogen in wetland (g/m^2·d), r_{reg} = rate of ammonia regeneration (g/m^2·d).

Denitrification rate was modelled by considering denitrifying bacteria suspended in the wastewater. Dawson and Murphy [33] described the denitrification process to follow the Arrhenius kinetics, which is described by Equation (6).

$$r_{dn} = \left[(DR_{20}) \times \theta_1^{(T-20)}\right] \times \mathrm{NO_3} \quad (6)$$

where: DR_{20} = Denitrification rate constant at 20˚C (d^{-1}) = 0 - 1.0 (Bacca and Arnett, 1976) and θ_1 = Arrhenius

constant, ranges from 1.02 - 1.09 [34].

2.3.1. Ammonia Uptake by Microorganisms

Biomass uptake by autotrophic bacteria involves NH_3-N or nitrates although ammonia is much preferred [35]. Both algae and bacteria prefer ammonia to nitrates. In this study it was assumed that ammonia must be depleted first before nitrate is consumed. This preferential uptake of ammonia to nitrates is accounted for by use of preference factors p_1 and p_2 into the modelling equations. The modelling of ammonia uptake followed the Monod kinetics as illustrated in Equation (7).

$$r_{g1} = \left[\left(\mu_{\max_20}\right)\times\theta^{T-20}\times\left(\frac{\mathrm{NH_3_N}}{K_{\mathrm{NH_3}}+\mathrm{NH_3_N}}\right)\right]\times\mathrm{Org_N}\times P_1 \tag{7}$$

where $\mu_{\max_20}$ = maximum growth rate of bacteria at 20˚C (d^{-1}), K_{NH_3} = Ammonia uptake half rate saturation constant, θ = Microorganisms growth temperature coefficient = 1.08 - 1.10 [36] and P_1 = Ammonia uptake preference factor.

2.3.2. Nitrate Uptake by Microorganisms

It was assumed that nitrate would be consumed only if all ammonia has been depleted in the system. The Monod kinetic equation for suspended bacteria discussed earlier was combined to give Equation (8) used to model the ammonia uptake by micro-organisms.

$$r_2 = \left[\left(\mu_{\max_20}\right)\times\theta^{T-20}\times\left(\frac{\mathrm{NO_3_N}}{K_{\mathrm{NO_3}}+\mathrm{NO_3_N}}\right)\right]\times\mathrm{Org_N}\times P_2 \tag{8}$$

where K_{NO_3} = Nitrate uptake half saturation constant and P_2 = Nitrate uptake preference factor.

2.3.3. Ammonia Regeneration Rate

The nitrogen settled in wetland due to sedimentation process taking place in the system eventually is regenerated back to ammonia. Bigambo [37] described the regeneration process to follow first order kinetics, which is described by Equation (9).

$$r_{reg} = Reg_\mathrm{rate}\times\left(\mathrm{Sink}_N\right) \tag{9}$$

where *Reg_rate* = Regeneration rate constant of ammonia (d^{-1}) and *Sink_N* = Organic nitrogen settled at the bottom (g/day).

2.3.4. Sedimentation Rate

Organic nitrogen, algae and bacteria settle down to form a sediment layer in aquatic systems. Algae and bacteria contain organic nitrogen in their body structures in which their deposition to the pond bottom contributes to permanent nitrogen removal. Net loss of settled organic nitrogen due to sedimentation depends on sedimentation rate and regeneration rate. Using Stokes law sedimentation rate in HRP was modelled based on Equation (10).

$$r_s = \frac{g\left(\rho_s-\rho\right)d^2}{18\times\mu\times h} \tag{10}$$

where g = acceleration due to gravity in ($m\cdot s^{-2}$), ρ_s = density of settling organic nitrogen particle in ($kg\cdot m^{-3}$), ρ = density of water ($kg\cdot m^{-3}$), d = diameter of the settling organic nitrogen particle (m), μ = coefficient of dynamic viscosity of the fluid ($N\cdot s\cdot m^{-2}$), h = depth of HRP (m).

The dynamic viscosity of water varies with temperature in accordance with Equation (11) for temperature above 20˚C. The density of wastewater was assumed to be equal to that of water which is 995.69 kg/m^3 at 30˚C [36]. Equation (11) was used to determine the viscosity of water in the system because in this study water temperature varied from 25.4˚C to 32.1˚C.

$$\log\left(\frac{\mu}{\mu_{20}}\right) = \frac{1.3220\left(T-20\right)-0.001053\left(T-20\right)^2}{T+105} \tag{11}$$

2.3.5. Ammonia Volatilization Rate

Factors influencing volatilization of ammonia are temperature and pH. Ammonia in fluids exist in two forms namely ammonium ion, NH_4^+ and dissolved ammonia gas, NH_3 (g). At 20˚C and a pH of 9.4 the concentrations of ammonia gas and ammonium ion are equal. At pH value above 9.4, NH_3 (g) is greater and below pH of 9.4, NH_4^+ dominates. The concentration of ammonia gas is expressed by Equation (12) [31].

$$\left(NH_3-N\right)_{Conc}=\frac{NH_3-N}{1+10^{(10.05-0.032T)-pH}} \tag{12}$$

The mass transfer of ammonia gas across a liquid interface depends on temperature and the depth of water. The influence of water depth and temperature on ammonia, NH_3 (g), mass transfer coefficient across a liquid is depicted by Equation (13) [31].

$$K_l=\frac{0.056}{d}\exp\left[0.13\left(T-20\right)\right] \tag{13}$$

where K_l = net convective mass transfer coefficient in liquid phases, d = water depth (m), T = Water temperature (˚C).

The combination of Equations (12) and (13) gives ammonia volatilisation rate in the system, which is represented by Equation (14) [31].

$$\frac{d\left(NH_3-N\right)}{dt}=\frac{0.056}{d}\exp\left[0.13\left(T-20\right)\right]\times\left[\frac{NH_3-N}{1+10^{(10.05-0.032T)-pH}}\right]\times NH_3-N_g \tag{14}$$

2.3.6. Model Calibration and Parameter Optimization

Stella II water quality modelling software was used in modelling process taking place in the system. Various equations were entered in the model as explained in previous section. The inputs were the daily mean concentration of NH_3-N, NO_3-N, Org-N as well as the daily mean temperatures, dissolved oxygen and pH values. These data were used as inputs to the model during calibration. After calibration, the biofilm activities were set to zero to study the effects of biofilm on nitrogen transformation and removal.

3. Results and Discussion

3.1. Physical-Chemical Parameters

The temperature of wastewater in the high rate pond varied from an average of 26.7˚C in the influent to only 26.6˚C in the effluent with an average standard deviation of 0.6. The temperature variation in HRP was small probably because temperature stratification within a pond is minimal. The temperatures observed in these systems were within optimum ranges for all biological nitrogen transformation reactions such as nitrification, denitrification, mineralization and volatilization processes, which proceed very well in aquatic systems at around 26.5˚C.

Daily variations of pH within the system ranged between 6.87 and 8.55 with an average value of 7.62, which was conducive for most of the biological nitrogen transformations processes, except for volatilization which is best at pH values above 9.4. Daily variations of DO in HRP increased from mean influent concentration of 1.8 mg/l to mean effluent concentration of 2.0 mg/l although in late afternoon hours concentrations in excess of 8 mg/l were not uncommon. The increase in oxygen level was largely due to algae photosynthesis which produces oxygen.

3.2. Nitrate-Nitrogen

Higher effluent concentration than influents were often observed in HRP indicating that the rate of nitrification was higher than the rate of denitrification. A slight increase of nitrate was observed from an average influent concentration of 1.78 mg/l to an average effluent concentration of 1.85 mg/l. The small increase in nitrate than expected was probably attributed to short retention time, which was inadequate to allow nitrification process to take place adequately. The minimum retention time recommended for nitrification process in aquatic systems is 8 days (Metcalf and Eddy, 1995), but in this study the retention time of 5 days was used.

3.3. Organic-Nitrogen

The effluent organic nitrogen concentration ranged from 0.56 mg/l to 8.96 mg/l with an average value of 4.66 mg/l. This is equivalent to a decrease of 17.5% in organic nitrogen concentration from an average influent concentration of 5.65 mg/l, which was attributed to sedimentation process. Shin and Polprasert [35] and later Mayo *et al.* [38] observed that sedimentation of organic nitrogen contributes significantly to nitrogen removal in aquatic systems. The non-turbulence condition and short depth (about 0.6 m) in HRP possibly enhanced sedimentation of organic nitrogen. Another possible cause for the drop in organic nitrogen was mineralization process, which converts organic nitrogen to ammonia.

3.4. Ammonia-Nitrogen

Ammonia nitrogen decreased by 34.8% from an average influent concentration of 15.19 mg/l to an average effluent concentration of 9.90 mg/l. The reduction was attributed to uptake by micro organisms' (algae and bacteria), and nitrification processes. Ammonia volatilization was unlikely because volatilization is effective at pH above 9.4 [39], while in this system the pH ranged from 7.42 to 8.55. Uptake of ammonia is one of the potential factors reducing ammonia particularly because ammonia is a preferred source of nitrogen than nitrate [31] [40]. Nitrification was another cause of ammonia nitrogen removal since nitrate increased in HRP, which is evident that some ammonia were nitrified to nitrate and hence contributed to the observed decrease of ammonia nitrogen.

3.5. Total Nitrogen

Figure 3 shows the variation of influent and effluent of total nitrogen concentration in HRP. Total nitrogen was reduced by 31.7% from an average of 22.5 mg/l in the influent to an average of 15.37 mg/l in effluent of HRP. Significant reduction of total nitrogen was attributed to net loss of organic nitrogen due to sedimentation and uptake of ammonia by micro organisms. Some denitrification may occur even in aerobic conditions because autotrophic ammonia oxidizing bacteria, such as *Nitrosomonas europaea* and *Nitrosomonas eutropha*, can also denitrify aerobically under low oxygen concentrations [41].

3.6. Model Calibration and Simulation

Table 1 shows values of the constants and parameters obtained from the optimization process. The parameters were optimized by trial and error method, until the best fit between observed and predicted effluent was obtained. The optimized parameters from this study were compared with parameters obtained by other researchers. It was observed that most parameters were within the literature range and close to those obtained by other researchers.

The simulated and observed values for organic nitrogen and ammonia in high rate pond are shown in **Figure 4** and **Figure 5**, respectively. Generally model simulations followed the trend of observed data. The results show that the average percentage removal of total nitrogen between simulated and observed data from the system were close indicating that the model predicted well the nitrogen transformations in the system. It was also found that, the median percentage total nitrogen removal predicted by the model in high rate pond was 30.1%, which

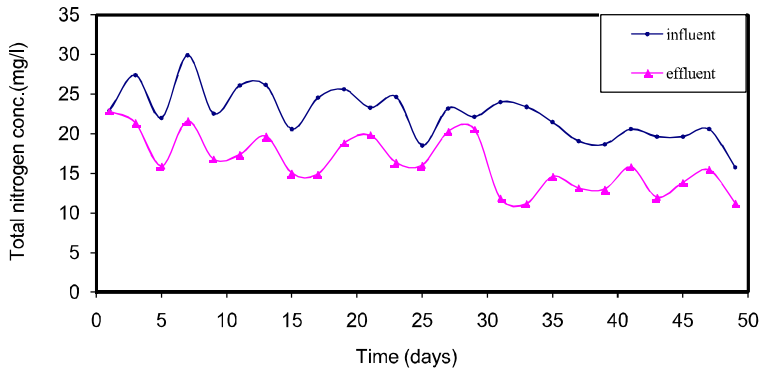


Figure 3. Variation of total nitrogen with time in HRP.

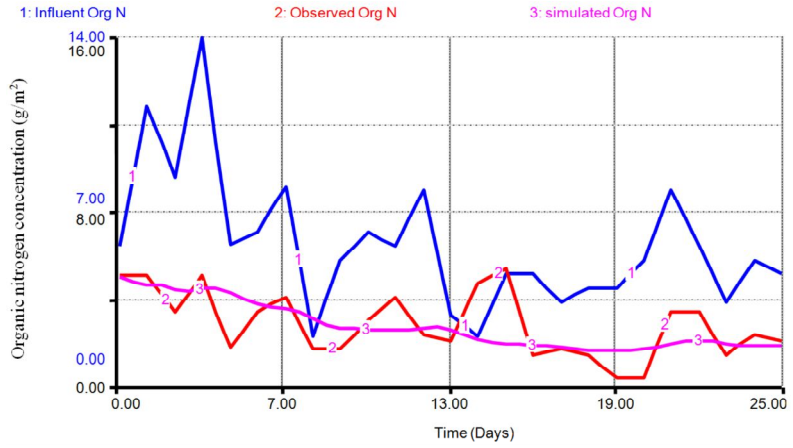


Figure 4. Variation of influent, observed and simulated organic nitrogen in HRP.

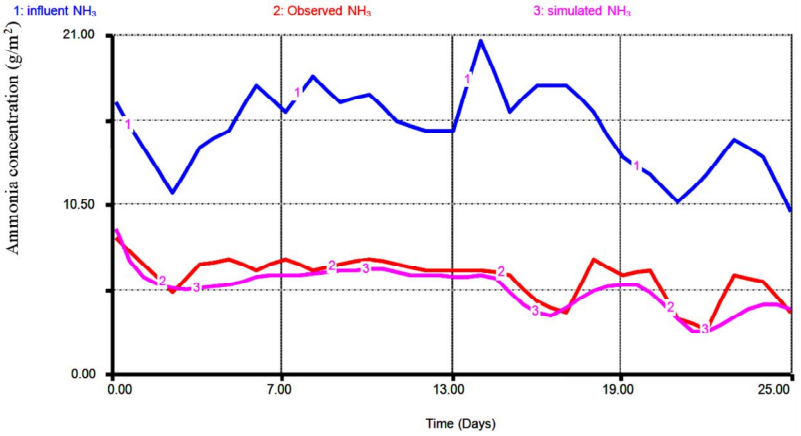


Figure 5. Variation of influent, observed and simulated ammonia nitrogen in HRP.

Table 1. Comparison of model parameter with values available in the literature.

Parameter	Description	Mutamba (2002)	This study	Source	Literature range
ρ_{s1}	Settling particle density (kg/m^3)	1025	1165	[36]	1050 - 1500
D_1	Settling particle diameter (m)	4 μm	1.2 μm	[42]	0.03 - 1 μm
$K_{N(1)}$	Nitrate uptake half saturation constant (mg/l)	3	36	Optimized	-
$K_{20(1)}$	Denitrification constant at 20˚C (d^{-1})	0.1	0.33	[34]	0 - 1.0
u_{N1}	Nitrosomonas growth rate (d^{-1})	1.5	1.25	[43]	0.33 - 2.21
Y_{n1}	Nitrosomonas yield coefficient (VSS/mgN)	0.5	1.12	[44]	0.03 - 1.3
K_{fa}	First order reaction constant (d ^{1})	336.6	336.6	[45]	336.6
$\mu_{max20(1)}$	Microorganism growth rate at 20˚C	0.1	0.18	[46]	0.18
Reg_rate 1	Ammonia regeneration rate (d ^{1})		0.08	Optimized	
Min_rate 1	Mineralization rate (d^{-1})	0.002	0.14	[30]	0.0005 to 0.143
θ_1	Microorganism growth temperature coefficient (d^{-1})	1.0	1.09	[36]	1.02 - 1.09
$K_{NH(1)}$	Ammonia half saturation constant (mg/l)	56	8	[47]	0.32 - 56
$K_{NO(1)}$	O_2 nitrosomonas half saturation coefficient (mg/l)	1.5	1.3	[44]	0.13 - 1.3

compares closely to those of observed values of 31.7%. Therefore, from the model results it can be concluded that the model sufficiently simulated nitrogen transformation mechanisms in the pilot plant.

Figure 6 shows that 0.24 gN/m^2·d of organic nitrogen settled to the bottom of HRP, but 0.15 gN/m^2·d of settled organic-nitrogen was regenerated back to water phase as ammonia due to decomposition of organic nitrogen. Therefore 0.09 gN/m^2·d of organic nitrogen was permanently removed as net sedimentation. About 0.95 gN/m^2·d of ammonia was transformed by nitrification process to nitrate while, denitrification and ammonia volatilization processes contributed to permanent removal in HRP by 0.87 gN/m^2·d, and 0.30 gN/m^2 d respectively. However, mineralization process and ammonia uptake by micro-organisms were 0.37 gN/m^2·d and 0.34 gN/m^{2}d, respectively.

Figure 7 summarizes the contribution of each nitrogen transformation mechanism in pond. It was evident that the dominant transformation mechanism in the HRP accounting for 29.5%, which is closer to 29% and 33.0% reported by [48] [49], respectively. Nitrification was largely favoured by photosynthetic oxygen production by algae as a result of adequate penetration of light in shallow depth HRP. The results also showed that denitrification was the second transformation route contributing 27.0%. In a similar ecological environment [49] observed that denitrification transformed 29.5% of the total nitrogen transformed in the system. Ammonia uptake by microorganisms was 10.5%, which is falls between a figure of 11% reported by [48] and 8% reported by [49]. Ammonia regeneration accounted for 4.7%, while mineralization, volatilization and sedimentation contributed 11.5%, 9.3% and 7.5% of total nitrogen transformed, respectively. The contribution of volatilization of ammonia was relatively low because of relatively low average pH of 7.6, which does not encourage ammonia stripping.

Further analysis revealed that, in HRP, denitrification process removed 27.4%, net sedimentation 2.8% and volatilization removed 9.5% of the total influent nitrogen. Permanent nitrogen removal from these systems was due to denitrification, net sedimentation and volatilization. Other processes transformed nitrogen into other forms having potential to pollute receiving waters. **Figure 8** shows percentage contribution for permanent ni-

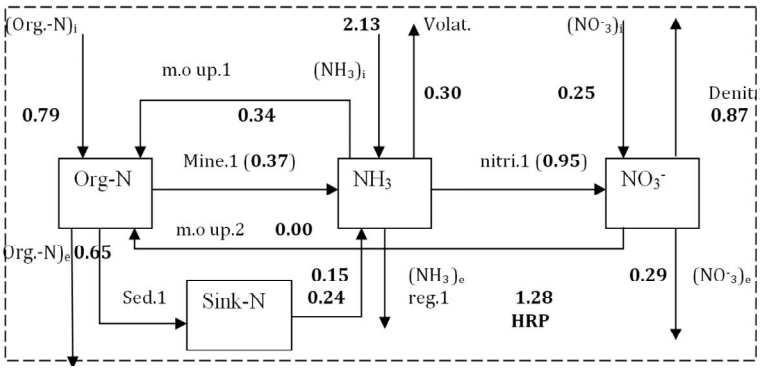


Figure 6. Mass balance diagram for Nitrogen transformation in high rate pond.

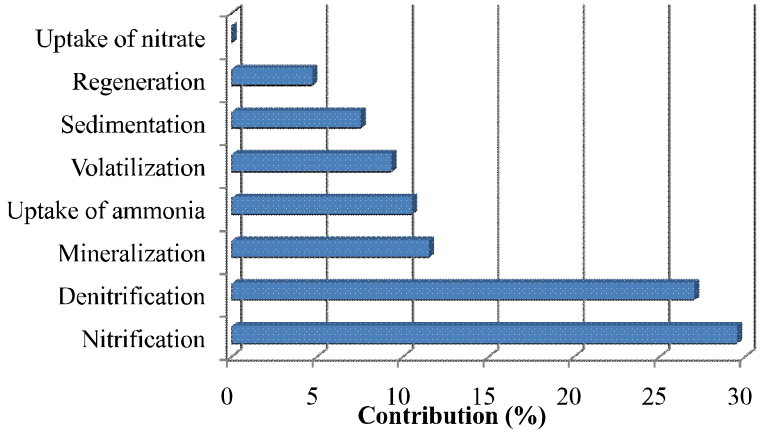


Figure 7. Contribution of various mechanisms on nitrogen transformation.

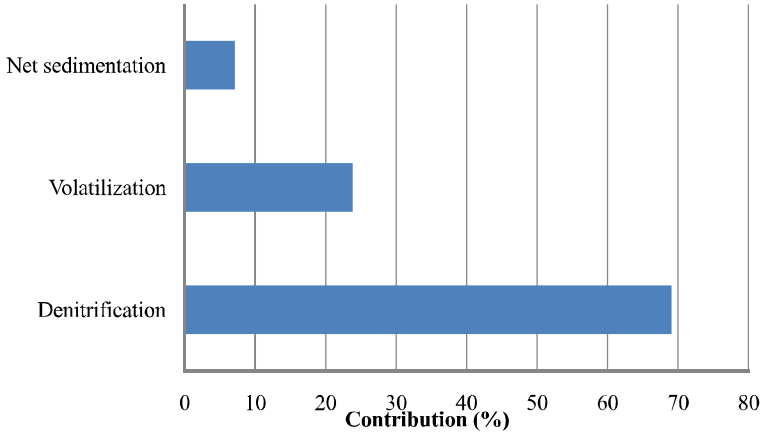


Figure 8. Major permanent nitrogen removal mechanisms and their contribution in HRP.

trogen removal mechanisms in HRP. The major nitrogen transformations which were permanent removal mechanisms from the HRP were denitrification, net sedimentation and volatilization. Denitrification process contributed 69.1%, net sedimentation 7.1% and volatilization contributed 23.8% of the total permanent removal mechanisms in HRP. The contribution of net sedimentation of 7.1% to the total permanent nitrogen removal is substantial bearing in mind that in field scale secondary facultative ponds and maturation ponds, the contribution of sedimentation is less than 3.3% [2]. Better sedimentation rate in high rate pond was probably contributed by its shallow depth and better quiescence condition as a result of its small surface area. It is worth mentioning that wind induced agitation is less effective in a small HRP water body of 10.2 m^2 compared to mid-pond surface areas of 1425 m^2 in maturation pond and 2100 m^2 in secondary facultative ponds.

3.7. Model Applications and Limitations

The developed model can be used to estimate the nitrogen removal in water hyacinth wetland. The ability of the model to simulate the observed trends of nitrogen transformation and removal processes and determine the permanent nitrogen removal in the system, proves that the model can be used as an operation and management tool for existing systems and to design similar systems. Given all input data such as ammonia, nitrate, organic nitrogen as well as daily mean temperatures, dissolved oxygen and pH, the design of a plant capable of achieving the desired nitrogen removal can be obtained by proper model simulation. However, there were small variations between model simulated with observed data, which was attributed to higher fluctuation of observed data due to short period of sample collection while the system was in the stage of stabilizing.

4. Conclusions

From these findings the following conclusions are made:

a) The dominant nitrogen transformation processes in HRP were nitrification and denitrification, which transformed 0.95 and 0.87 $gN/m^2 \cdot d$, respectively. These were followed by mineralization (0.37 $gN/m^2 \cdot d$), ammonia uptake by microorganisms (0.34 $gN/m^2 \cdot d$), volatilization (0.30 $gN/m^2 \cdot d$), sedimentation (0.24 $gN/m^2 \cdot d$), and regeneration (0.15 $gN/m^2 \cdot d$). Uptake of nitrate was not observed because of microorganisms' preference for ammonia, which was abundant.

b) The major nitrogen transformation mechanisms in high rate pond were denitrification, net sedimentation and volatilization, which accounted for 69.1%, 7.1% and 23.8% of the total permanent removal mechanisms in HRP.

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