

KINETICS AND DESIGN OF RZ TREATMENT SYSTEM

4.1 Introduction

The subsurface RZTS are used for the removal of various constituents in wastewater. The major constituents removed include organic content, nutrients, heavy metals, suspended solids, and pathogens. The removal mechanisms are complex due to the contribution of interrelated processes occurring within the subsurface environment. The dominating processes of constituent removal include settling, adsorption, straining, ammonification, nitrification, denitrification, precipitation, decomposition, and plant uptake. The simplified design approach adopted for most of the RZTS is based on plug flow conditions with first order reaction kinetics. The RZTS treatment option has not been tried to a greater extent for the removal of nutrients for tropical conditions. Also the studies have not been focused to understand dominant mechanisms occurring in the wetlands for the removal of the nutrients and to develop design model for the removal of nutrients. The objective of present study is to understand the nutrient removal mechanisms within a subsurface wetland and hence the discussion is more focused on the processes, which contribute to nutrient removal. The experimentation work was carried out at laboratory and field scale set-ups. The data was obtained on influent and effluent characteristics for subsurface system. The data was analyzed and efficiency of the system for nutrient removal in wastewater was determined. The experiments conducted and the results obtained are discussed in the earlier chapter.

It is essential to know the relative contribution of various dominating nutrient removal mechanisms. An engineering insight into the dynamic behavior of the system is

useful to specify the design criteria for the system. Each of these processes is governed by various parameters. The interrelation between the various processes needs to be developed. The evaluation of the various parameters involved in these expressions shall be of help to identify the dominating mechanism of nutrient removal. The modeling of the system is required to be carried out by incorporating the mathematical expressions describing the phenomenon occurring in the system. The mathematical expressions are based on the various conceptual models of reaction kinetics. The model thus developed has unknown parameters and are required to be estimated.

The optimal parameter set best describing the relationship between observed and model predicted values should be obtained. These evaluated parameters indicate the possible dominant mechanisms of nutrient removal. The model study is also used to simulate various combinations of the processes in the system.

The present study is carried out in two parts viz. model development and application of the model. The models developed are based on lumped parameter and distributed parameter approaches using the data obtained from laboratory scale study. The predicted and observed (field data) nutrient concentrations are compared in the application part of the study. Thus over all objective of this study is to develop a simulation model that can be used as planning tool for the design of RZTS for the effective control and treatment of pollution that may cause because of nutrients viz. nitrogen and phosphorus.

4.2 Review of Kinetic Studies for Nutrient Removal in RZTS

The RZTS have been applied for the purification of wastewater with a focus on organic and nutrient content removal. The increasing application of RZ for the treatment of wastewater under different environmental conditions is a stimulant for the development of better reaction kinetics models aiding the design process. The models adopted for design of RZ are based on rules of thumb, input-output data alone (regression equations), first-order kinetics, Monod kinetics and dynamic compartmental models.

Wood (1995) and Kadlec and Knight (1996) set the rules of thumb based on observations from a wide range of systems, climatic conditions and wastewater types. But there exists a large variation in the design parameters and hence is useful for extensive calculation to check the design.

Rousseau et al., (2004) have discussed the regression models developed and used by various researchers in detail. Regression models are based on only input-output data and work as black box models thereby lumping complex CW system into only two or three parameters. It is an over simplification of the model.

Kadlec and Knight (1996), and Kadlec (1997) adopted an ideal plug flow behavior predicting an exponential profile between inlet and outlet concentrations.

Shepherd et al., (2001) presented a time dependent retardation model for COD removal. They assumed that removal rates decrease during the course of time, because easily biodegradable substances are removed first and fast leaving a solution with less biodegradable constituents and hence with slower removal kinetics.

Rousseau et al., (2001) have summarized the application of first order reaction kinetics for modeling BOD, TSS, TN and TP. The first order rate constants for horizontal SSF CWs have also been mentioned.

Mitchell and McNevin (2001) advocated the use of Monod type design model, which represents first-order rate reactions for relatively low concentrations but zero-order rate reactions for high concentrations.

Kemp and George (1997) found Monod type model better than the first-order model to represent ammonia removal based on experimental conditions in a pilot scale horizontal SSF CWs for domestic wastewater. Wynn and Liehr (2001) presented a mechanistic compartmental simulation model of a horizontal SSF CWs. Kallner and Wittgren (2001) adopted first-order reaction kinetics to model each of nitrogen transformations processes viz., ammonification, nitrification and denitrification.

4.3 Scope of Proposed Work

The review of literature on reaction kinetics/design models shows the use of various kinds of models. The models based on first reaction rate kinetics are popular and most widely used for variety of field and pilot scale studies. The reaction rate parameters evaluated from these studies exhibited wide variability in their values. The determination of reaction parameters for a given wetland treatment system is required to decide/set design criteria for given environment. The pilot/laboratory scale studies conducted are used to determine the reaction rate parameters by following best fit criteria. The design criteria developed was based on thumb rules, first order models and Monod type kinetics. But none of these models are universally applicable. These are system/environment specific. Thus it would be important to test other reaction kinetic models to assess their usefulness and applicability.

In the present study two types of models are developed. In the first model the processes occurring within RZTS are represented in a lumped parameter. The conditions within the RZTS are assumed to be plug flow, complete mix or dispersed. The parameter/s of the models, which are based on these conditions, are referred as lumped parameter/s. In the second model, the various processes contributing nitrogen removal are considered in the mathematical formulations with a view that the model predicted results represent the actual conditions better if more number of processes for the system are defined and included. But incorporation of more process increases complexity of the problem. Hence simple reaction kinetic is adopted to define the processes within the system. The parameters involved in these models are determined using laboratory and field scale studies conducted at an average temperature of 27⁰C.

The proposed work based on the above discussions is given below.

1. To develop and assess the feasibility/applicability of lumped parameter models based on different reaction kinetic models for laboratory scale studies.

2. To estimate the reaction parameters involved in these lumped parameter models.
3. To develop a distributed parameter model by incorporating the basic N transformations processes and other N - removal mechanisms.
4. To evaluate the reaction rate parameters involved in the distributed parameter model.
5. To assess the performance of lumped parameter and distributed parameter models to predict the various forms of nitrogen using the results obtained during field scale studies.

4.4 Lumped Parameter Model

In the present study, it is proposed to apply lumped parameter model for predicting various forms of nitrogen. The reaction kinetics to be adopted in this model is based on plug flow, complete mix, and dispersed flow conditions. Numerous processes are involved in the RZ bed for the removal of various pollutants. The efforts taken in order to develop models so far do not satisfy the complexities of such processes. This necessitates the use of lumped parameter models for the kinetic study. The well known kinetic models and their equations are described as follows.

4.4.1 Plug Flow First Order Kinetic Model

$$\frac{dC}{dt} = -k_b C$$

$$C = C_o \times e^{-k_b t} \dots\dots\dots(4.1)$$

where, C = nutrient concentration (mg/L); C_o = initial nutrient concentration (mg/L); t = time in days and K_b = first order reaction rate parameter (d⁻¹).

The reaction parameter to be optimized for best fit with observed nutrient concentrations is K_b.

4.4.2 Complete Mix Kinetic Model

$$\frac{C}{C_o} = \frac{1}{(1+kt)} \dots\dots\dots(4.2)$$

where, C = effluent concentration (mg/L); C_o = influent concentration (mg/L);

t = time (d) and k = rate parameter (d^{-1}).

4.4.3 Plug Flow Reactor with Axial Dispersion and Reaction

$$\frac{C}{C_o} = \frac{4a \exp(1/2d)}{(1+a)^2 \exp(a/2d) - (1-a)^2 \exp(-a/2d)} \dots\dots\dots(4.3)$$

where, C = effluent concentration (mg/L); C_o = influent concentration (mg/L)

$$a = \sqrt{1 + 4K t_o d}$$

d = Dispersion factor = D/uL ; D = Axial dispersion coefficient (m^2/d);

u = Fluid velocity (m/d); L = Characteristic length (m);

K = First order reaction rate constant (d^{-1}) and t_o = Detention time (d).

4.5 Application of the Model, Results and Discussion

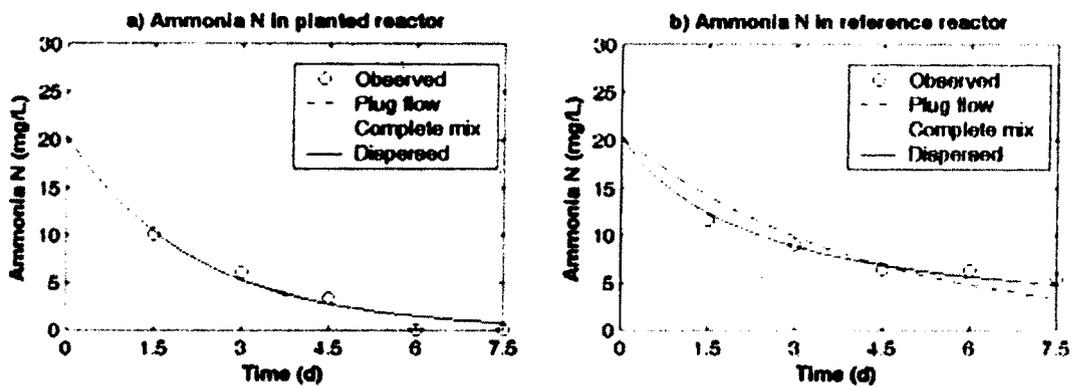
The results observed over lab scale studies for various parameters with planted and reference lab scale set-ups were used to determine best fitting reaction kinetic model. The best fitting model was determined based on the residual errors observed with the data. The reaction parameters involved in the adopted models were estimated using non-linear least square analysis. Table 4.1 shows comparison of these rate parameters estimated for

abovementioned models. The observed values and model predicted values are shown in the Figs. 4.1 to 4.4 for NH₄-N, TKN, TN and P in both planted and reference reactors.

Table: 4.1: Comparison of Rate Constants for Various Kinetic Models

S. No.	Parameter	Initial concentration (mg/L)	Plug Flow		Complete Mix		Dispersed		
			K	RE	K	RE	K	d	RE
Planted reactor									
1	NH ₄ -N	20.32	0.44	3.53	0.99	19.06	0.448	0.001	3.54
2	TKN	24.56	0.353	10.4	0.721	25.5	0.355	0.002	10.45
3	TN	29.04	0.246	52.9	0.429	86.4	0.247	0.003	53.05
4	P	11.30	0.03	0.3	0.032	0.3	0.03	0.003	0.267
Reference reactor									
1	NH ₄ -N	20.32	0.24	14.26	0.43	1.74	0.431	1753.7	1.745
2	TKN	24.56	0.135	19.1	0.199	9.7	0.199	4457.8	9.69
3	TN	29.04	0.093	30.8	0.124	20.0	0.124	4459	20.03
4	P	11.30	0.004	0.3	0.004	0.3	0.004	0.743	0.34

It can be seen from these results that the nutrient concentrations are better predicted for plug flow conditions and complete mix conditions in the planted reactor, and reference reactor respectively. The complete mix conditions may not be prevailing in the planted bed because of varied adsorption and uptake sites existing within the planted bed. It is also discussed earlier that in such kind of the reactor there is simultaneous presence of oxic as well non oxic zone. The transformations taking place may vary depending on the presence of pollutant in the respective zone. Thus the pollutant may exist with varied concentration not following complete mix condition in the planted bed.



**Fig. 4.1: Performance of Models for $\text{NH}_4\text{-N}$ removal in a) Planted Reactor;
b) Reference Reactor**

Also the voids present within the planted bed should have been fully occupied by the root and rhizome sections. This may effectively reduce the space availability for complete mixing to occur. This would also reduce available space for pollutant to disperse for given volume and HRT of the reactor. The dispersion model nearly predicts the nutrient values for plug flow and complete mix conditions for planted and reference reactor respectively. The dispersion coefficients observed are very small and hence dispersion should be occurring at minimum rate in the planted bed reactor. However the dispersion coefficients observed in reference reactor are high indicating more dispersion in this reactor. The complete mix conditions and more dispersion could have occurred in the reference reactor because of continuous channels connecting voids. As discussed earlier the porosity of the reference reactor would be more as compared to planted bed for a given volume because of absence of plant components. Also this would increase space for the given volume and HRT causing more dispersion of particles. Thus in general for the reference reactor, even if the volume and aspect ratio is same as that of planted bed, more dispersion is favored as compared to that in planted bed.

The observed values and model predicted values are shown in the Figs. 4.4 for total phosphorous in both planted and reference reactors. It shows that all the models have predicted the same values of phosphorous. The reaction rate constant is small (0.03 d^{-1}) and hence the predictions have not differed by large extent.

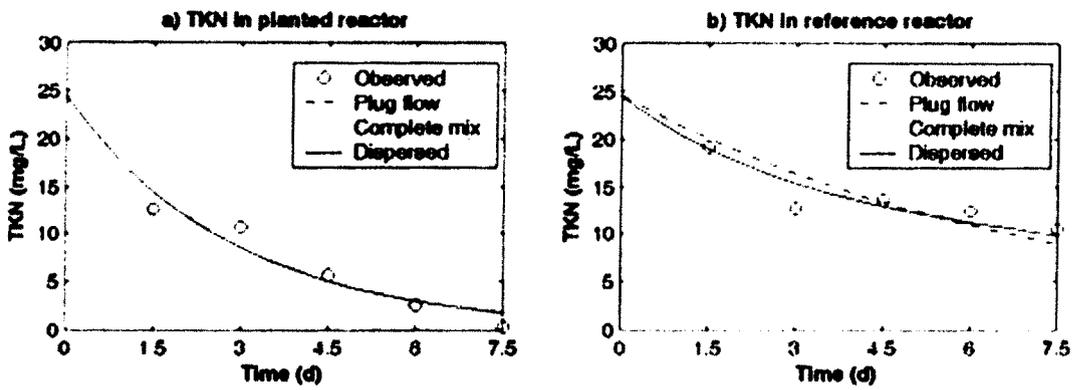


Fig. 4.2: Performance of Models for TKN Removal in a) Planted Reactor; b) Reference Reactor

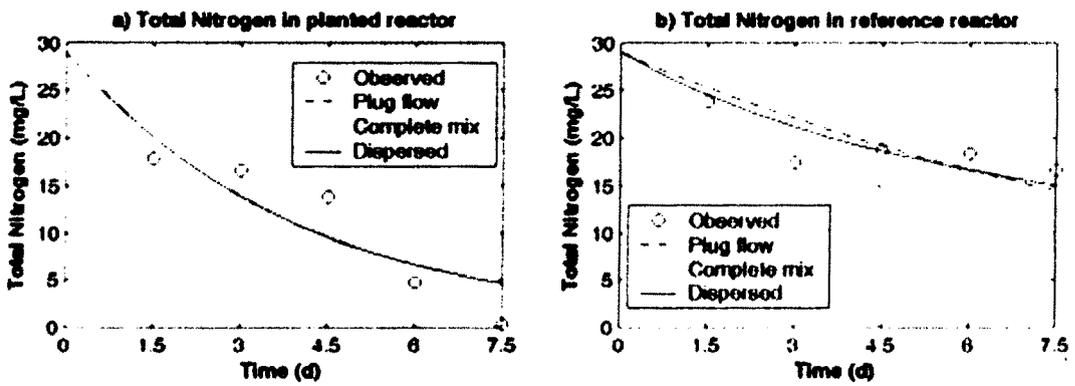


Fig. 4.3: Performance of Models for Total Nitrogen removal in a) Planted Reactor; b) Reference reactor

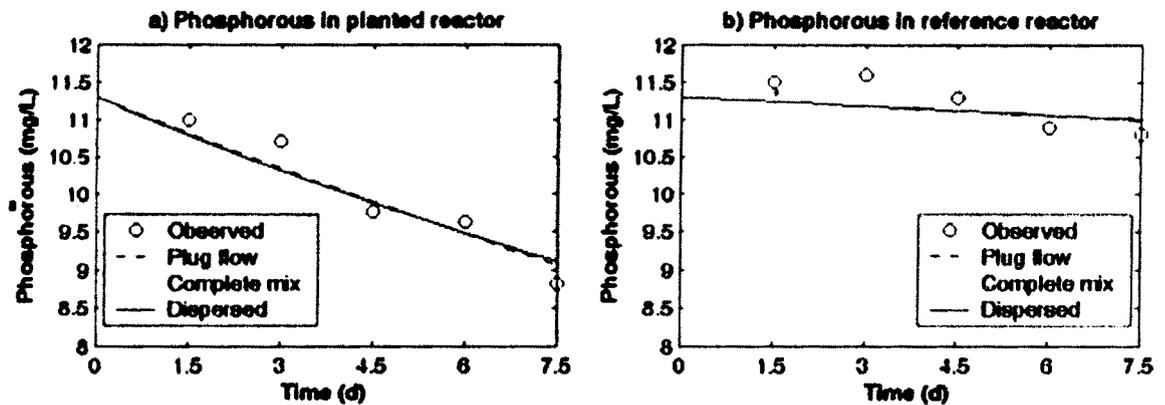


Fig. 4.4: Performance of models for Phosphorous removal in a) Planted reactor; b) Reference reactor

4.6 Distributed Parameter Model

The lumped parameter model does not indicate the relative effect of various mechanisms occurring within a system for N removal. It represents the net removal of N forms. In order to study/identify dominating mechanism/processes distributed parameter model is useful.

4.6.1 Processes for Nitrogen Transformations

The processes considered in the present model for N transformations are ammonification, nitrification, adsorption, plant uptake and denitrification. The schematic diagram of these processes is shown in Fig. 4.5.

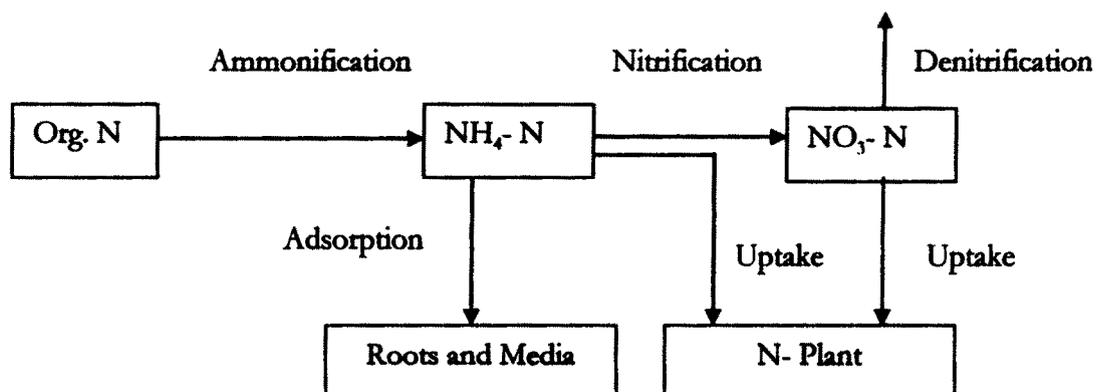


Fig. 4.5: Schematic Representation of Nitrogen Transformation and Removal Mechanisms

The various processes involved in the nitrogen transformations are discussed as follows.

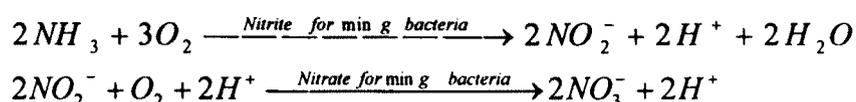
1. Ammonification-

The dead bodies of plants, animal, and animal excreta ultimately reach the soil where they are acted upon by saprophytic bacteria. These ammonifying bacteria like *Bacillus vulgaris*, *B. ramosas*, *B. mesentericus* decompose proteins of dead plants and animals to convert them into ammonia and ammonium salts. The process is called ammonification.

The microorganisms usually liberate nitrogen that is in excess of their requirements as ammonia. In addition to CO_2 and NH_3 , they produce a variety of intermediate products like alcohols, organic acids and sometimes also aldehydes and ketones depending upon environmental condition and the amount of soluble nitrogenous compounds present in plant residue. The quantity of these substances in plant residue is very small except in fresh green materials like green manures and similar other substances. The process of ammonification is modeled using first order kinetics represented by equation 4.1.

2. Nitrification

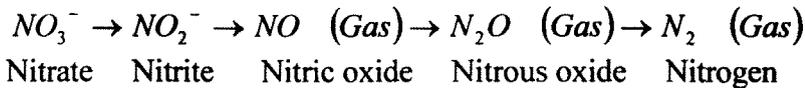
The ammonia thus formed is oxidized to nitrite by nitrosomonas. The nitrite, on further oxidation by nitrobacter, forms nitrate. The process is called nitrification. Plants for synthesis of amino acids and proteins reuse the nitrates thus formed.



3. Denitrification

It is the process by which nitrate is reduced to free nitrogen. The soil also contains denitrifying bacteria like pseudomonas, which carry out the process. The free nitrogen i.e. molecular nitrogen thus released is returned to the atmosphere completing the nitrogen cycle.

Denitrification is a form of anaerobic bacterial respiration process during which nitrogen oxides, principally nitrite and nitrate, are sequentially reduced through NO and N₂O to N₂. The denitrifiers convert nitrate in a sequence of reactions to molecular nitrogen, a gas. Denitrification follows the following sequence of reactions.



Thus during the reaction nitrogen compounds act as terminal electron acceptors instead of oxygen during respiration. Commonly therefore not exclusively denitrification occurs when O₂ becomes limited for aerobic respiration.

The common denitrifying bacteria are *Thiobascillus denitrificans*, *Micrococcus denitrificans*, and *Pseudomonas aeruginosa*. Thus there is variety of species from different genera known to be involved in denitrification. Some bacteria are capable of full transformation of NO₃⁻ to molecular gas, e.g. *paracoccus denitrificans*. Many other bacteria, however, are only capable of catalyzing particular stage in reaction. Therefore denitrification involves a mixed community of microorganisms with complementary metabolisms.

4. Plant uptake:

Inorganic nitrogen in the form of ammonia, and nitrates is absorbed by green plants and converted into nitrogenous organic compounds. Nitrates are first converted into ammonia that combines with organic acids to form amino acids. Amino acids are used in the synthesis of proteins, enzymes, chlorophyll, and nucleic acid etc. Thus nitrates formed are utilized by plants for the synthesis of amino acids from which ultimately proteins are formed.

5. Adsorption:

The NH₄-N can be removed through a mechanism of adsorption. The adsorption sites are provided by the medium and roots.

4.6.2 Model Development

The organic nitrogen is converted into NH₄-N through the process of ammonification and can be modeled using first order reaction kinetics.

$$\frac{dN_o}{dt} = -K_o N_o \dots\dots\dots (4.4)$$

where, N_o = Organic nitrogen (mg/L), K_o = ammonification rate constant (d⁻¹)

The transformation of NH₄-N into nitrates takes place by nitrification. The concentration of ammonia at any time is represented as the net effect of ammonification, nitrification, plant uptake and adsorption. The rate of change of NH₄-N by adopting first order reaction kinetics for all these processes is given by equation 4.5.

$$\frac{dN_a}{dt} = K_o N_o - K_a N_a - K_{pa} N_a - K_{ad} N_a \dots\dots\dots (4.5)$$

Where, N_o = concentration of NH₄-N (mg/L), K_a = nitrification rate constant (d⁻¹),

K_{pa} = plant uptake rate (d⁻¹), K_{ad} = adsorption rate (d⁻¹).

The nitrate content within the plant increases by plant uptake. The nitrification process increases and denitrification process reduces the nitrogen content from the wastewater. These processes can be modeled as:

$$\frac{dN_n}{dt} = K_a N_a - K_d N_n - K_{pn} N_n \dots\dots\dots (4.6)$$

Where, N_n = concentration of NO₃-N (mg/L), K_d = denitrification rate constant (d⁻¹), K_{pn} = plant uptake rate for NO₃ (d⁻¹)

The analytical form of the equations 4.4 to 4.6 can be represented respectively as

$$N_o = N_{io} \exp(-K_o t) \dots\dots\dots (4.7)$$

$$N_a = N_{ia} \exp(-K_a t) + \frac{K_o N_{io}}{(K_a - K_o)} [\exp(-K_o t) - \exp(-K_a t)] \dots\dots\dots (4.8)$$

$$N_n = N_m \exp(-K_N t) + \frac{K_a N_{ia}}{(K_N - K_a)} [\exp(-K_a t) - \exp(-K_N t)]$$

$$+ \frac{K_a K_o N_{io}}{(K_a - K_o)} \left[\frac{\exp(-K_o t) - \exp(-K_N t)}{K_N - K_o} - \frac{\exp(-K_a t) - \exp(-K_N t)}{K_N - K_a} \right] \dots\dots\dots (4.9)$$

Where, N_{io} = initial concentration of organic -N (mg/L),
 N_{ia} = initial concentration of $\text{NH}_4\text{-N}$ (mg/L), N_m = initial concentration of $\text{NO}_3\text{-N}$ (mg/L),
 $K_A = K_a + K_{pa} + K_{ad}$, and $K_N = K_d + K_{pm}$.

The unknown reaction rate parameters involved in the equations 4.4 to 4.9 are estimated using the inverse approach. The data obtained from laboratory scale studies conducted on planted reactor with synthetic wastewater as influent is used in the modeling process. An inverse algorithm based on nonlinear least square module is developed in Matlab to estimate the parameters. The sequential approach is adopted in the calibration process. The ammonification parameter (K_o in equation 4.4) is determined using the organic nitrogen data. The calibrated K_o is then used to determine K_a , K_{pa} , and K_{ad} (equation 4.5) for the $\text{NH}_4\text{-N}$ data. Finally, K_d and K_{pm} (equation 4.6) were estimated by using earlier estimated values of other parameters. The calibrated parameters were formally optimized and are given in the Table 4.2 and Table 4.3 for planted and reference reactors respectively.

The observed and simulated concentrations of organic, ammonia, kjeldahl and nitrate nitrogen for planted and reference reactor are shown in Fig. 4.6 and Fig. 4.7 respectively. The simulated concentrations are computed using the parameters estimated during the calibration process.

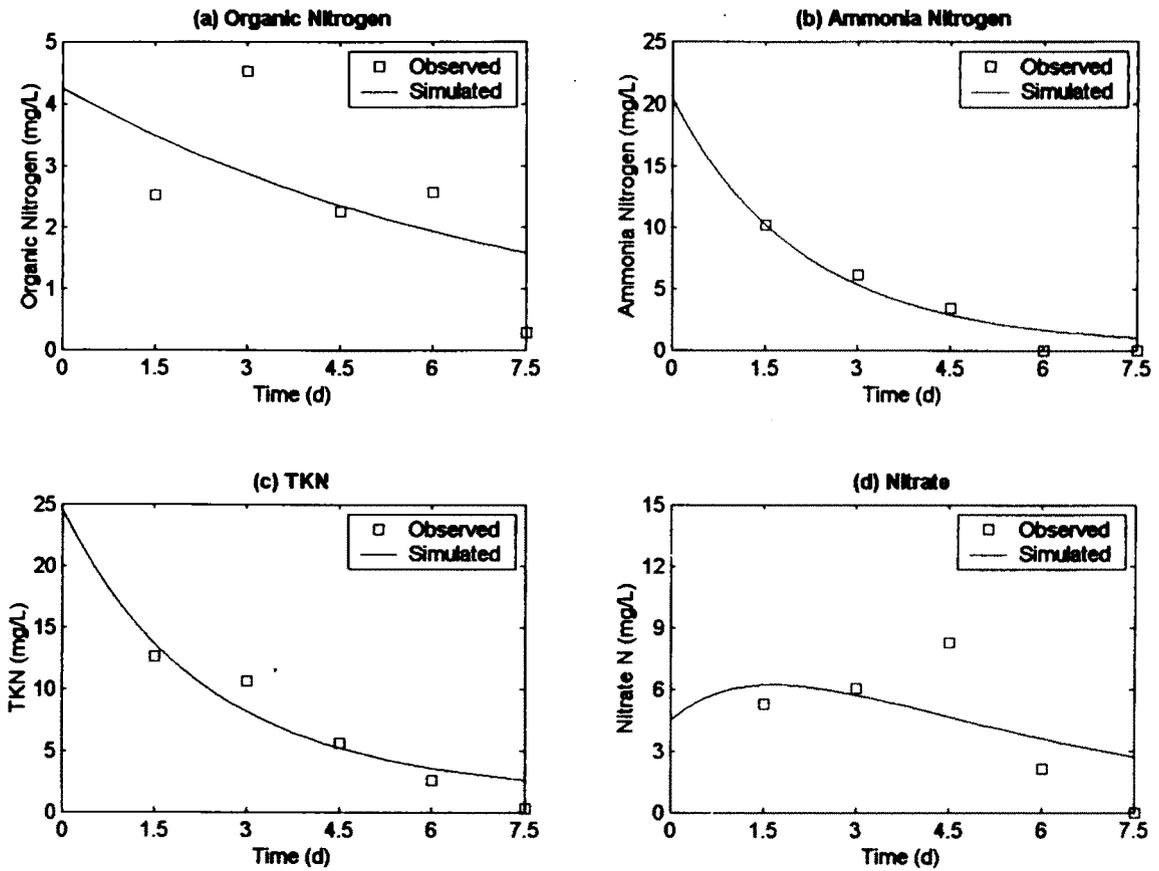


Fig. 4.6: Observed and Simulated Concentrations of a) Organic Nitrogen; b) Ammonia Nitrogen; c) TKN; d) Nitrate for Planted Reactor

Table 4.2: Reaction Rate Parameters in Distributed Parameter Model for Planted Reactor

Parameter	Notation	Value (d^{-1})
Ammonification rate	K_o	0.1315
Nitrification rate	K_a	0.2534
Plant uptake rate for NH_4-N .	K_{pa}	0.2450
Denitrification rate	K_d	0.2613
Plant uptake rate for NO_3	K_{pn}	0.3112

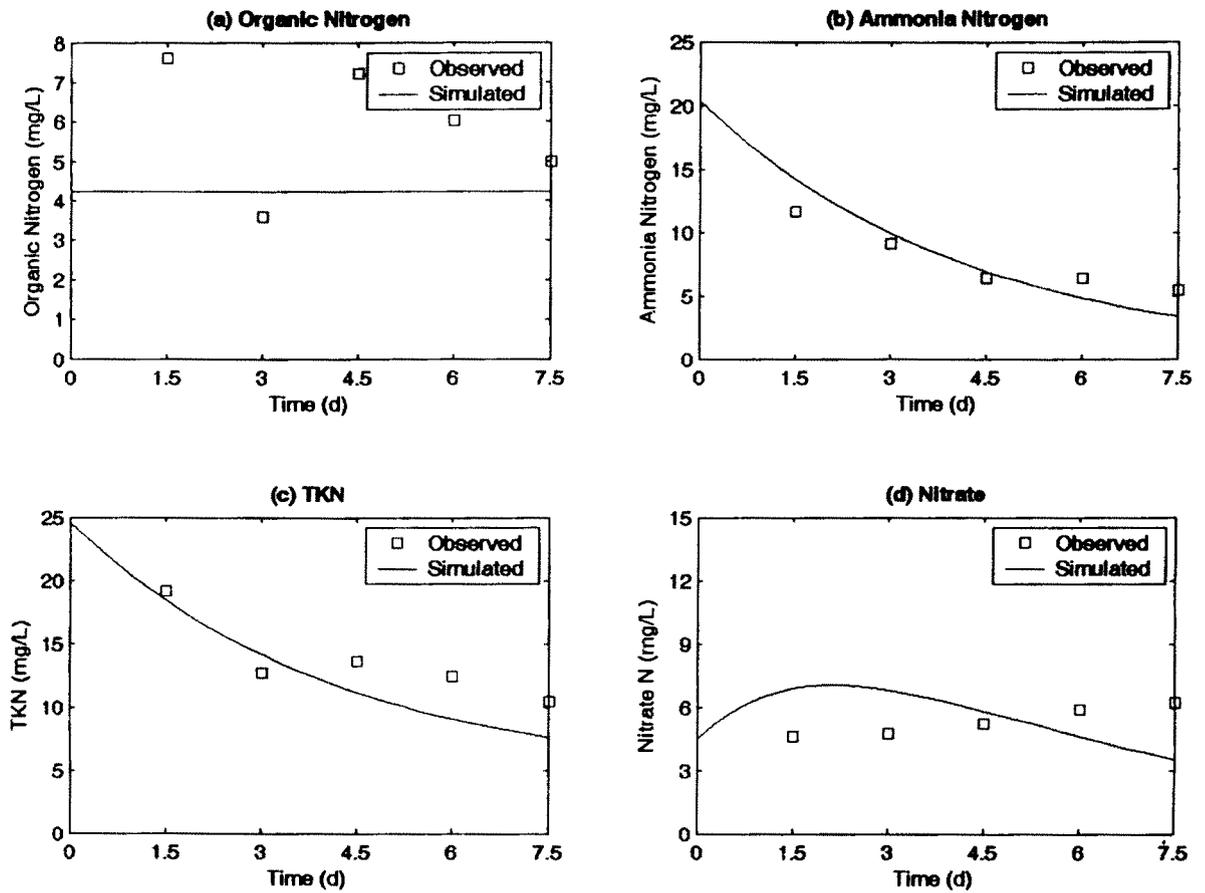


Fig. 4.7: Observed and Simulated Concentrations of a) Organic Nitrogen; b) Ammonia Nitrogen; c) TKN; d) Nitrate for Reference Reactor

Table 4.3: Reaction Rate Parameters in Distributed Parameter Model for Reference Reactor

Parameter	Notation	Value (d^{-1})
Ammonification rate	K_o	0.00
Nitrification rate	K_a	0.2399
Denitrification rate	K_d	0.4193

4.7 Application of Models to Field Scale Studies

The lumped parameter and distributed parameter models are applied to predict the nitrogen concentrations in effluents from the field scale experiments. The nitrogen concentration in the septic tank effluent is used as initial concentration and the effluent concentrations are predicted for various hydraulic retention times. The model predicted results and actual concentrations observed in the field are given in Tables 4.4. Also the distributed parameter model is applied to predict N concentrations in effluent from field scale experiments. The model predicted results and actual values are presented in Table 4.5.

Table 4.4: Comparison of Predicted and Measured Nutrient Values Using Lumped Parameter Model

HRT (d)	NH ₄ -N (mg/L)		TKN (mg/L)		TN (mg/L)		TP (mg/L)	
	Obs.	Pred.	Obs.	Pred.	Obs.	Pred.	Obs.	Pred.
1.5	17.92	12.30	23.56	16.09	30.28	22.76	17.35	20.30
3.0	11.2	5.38	13.44	8.16	20.4	13.92	14.33	17.53
4.5	9.52	3.49	10.08	5.84	17.83	11.03	12.52	17.92
6.0	7.28	1.76	7.84	3.37	17.56	7.68	9.54	17.04
7.5	7.92	1.13	8.5	2.47	17.15	6.22	8.87	15.44

Table 4.5: Comparison of Predicted and Measured Nitrogen Values Using Distributed Parameter Model

HRT (d)	Organic N (mg/L)		NH ₄ -N (mg/L)		TKN (mg/L)		NO ₃ -N (mg/L)		TN (mg/L)	
	Obs.	Pred.	Obs.	Pred.	Obs.	Pred.	Obs.	Pred.	Obs.	Pred.
1.50	2.64	2.89	20.92	11.71	23.56	14.60	6.72	7.37	30.28	21.97
3.00	2.24	2.27	11.20	5.06	13.44	7.33	6.96	5.82	20.40	13.14
4.50	0.56	1.82	9.52	3.21	10.08	5.03	7.75	5.55	17.83	10.57
6.00	0.56	1.53	7.28	1.73	7.84	3.25	9.72	4.17	17.56	7.42
7.50	0.58	1.61	7.92	1.27	8.50	2.88	8.65	3.82	17.15	6.70

Obs.: Observed; Pred.: Predicted

The comparative results for $\text{NH}_4\text{-N}$, TKN and TN show that there is no much of a difference between the predicted values by lumped parameter and distributed parameter models. The processes considered in the distributed parameter model were assumed to follow first order reaction kinetics. Hence the final predictions do not differ much. But an insight into the contributions by the various processes for nitrogen removal can be had from the distributed parameter model. The organic and nitrate nitrogen predictions by distributed model are better.

The variation between the predicted and observed values may be attributed to the characteristics of wastewater. The model parameters used for prediction were determined from the laboratory scale study with synthetic wastewater. The results show that the reaction rates are high in synthetic wastewater when compared to septic tank effluent for nitrogen. It is due to the fact that the nitrogen available for reaction in septic tank effluent is in complex form and hence the reaction rates are lower in field study. Thus the predicted values are lower than the observed. But the reaction rates are higher in septic tank effluent than in synthetic wastewater for phosphorous. The higher rates should have occurred due to sedimentation of particulate P in the septic tank effluent. In order to compare the extent of variation, the reaction rates are computed by calibrating lumped parameter model using field values. The average values of reaction rate parameters computed for various HRTs are used for comparison. The relative comparison is given in the Table 4.6.

Table 4.6: Comparison of Reaction Rate Parameters

Form of nutrient	Reaction rate parameter K (d^{-1})	
	Planted reactor	
	Field	Laboratory
$\text{NH}_4\text{-N}$	0.1765	0.440
TKN	0.1834	0.353
TN	0.1065	0.246
TP	0.1139	0.03

The rate parameters for nitrogen are 2 to 2.5 times higher in laboratory studies than in field scale studies for planted reactor.

4.8 Typical Design of RZTS for Nutrient Removal

Data:

A Residential Complex of Population: 500 Persons

Sewage Contribution: 120 L/capita.day

Plant Efficiency: 60%

Septic Tank Effluent TN Concentration: 40 mg/L

Temperature Coefficient, θ : 1.02 – 1.06

Derived data from this study:

$K_{20} = 0.0708 \text{ d}^{-1}$

dw: Depth of bed, m, 0.3 to 0.45 m typically

η : Porosity, 0.39 for grit media

K_s : Hydraulic conductivity, 5529.60 m/d for grit media

Effluent flow rate = 0.9 x Influent flow rate

Nitrogen Loading Rate: should not exceed 20 kg/ha.day

Phosphorus Loading Rate: should not exceed 15 kg/ha.day

Type of vegetation: *Typha Latifolia*

Type of bed media: Grit (Stone chips)

Coefficient of uniformity, C_u : 2.04

Step I: Determination of temperature corrected N removal rate constant

$$\begin{aligned}K_T &= K_{20} \times \theta^{T-20} \\K_{27} &= 0.0708 \times 1.06^{27-20} \\&= 0.1065\end{aligned}$$

Step II: Determination of Surface Area of RZTS for N removal

$$A = \frac{Q(\ln N_o - \ln N_e)}{k \times dw \times \eta \times F}$$

Where,

A: Net surface area, ha

Q: Average flow rate, m³/day

N_o: Influent N concentration, mg/L

N_e: Effluent N concentration, mg/L

K: Overall N removal rate constant, corrected for temperature, d⁻¹

d_w: Depth of bed, m

η: Effective Porosity of bed expressed as decimal

F: Conversion factor, 10,000 m²/ha

The quantity of sewage to be treated per day = 500 x 120 = 60000 L/day i.e. 60m³/day

$$Q_{ave} = \frac{60 + (0.9 \times 60)}{2} = 57 \text{ m}^3 / \text{day}$$

$$\therefore A = \frac{57(\ln 40 - \ln 16)}{0.1065 \times 0.45 \times 0.39 \times 10000}$$

$$= 0.2794 \text{ ha}$$

Step III: Determination of detention time for N removal

$$\text{Detention Time}(t) = \frac{A \times d_w \times \eta}{Q}$$

$$\begin{aligned} t &= \frac{2794 \times 0.45 \times 0.39}{57} \\ &= 8.60 \text{ days} \\ &= 9 \text{ days (say)} \end{aligned}$$

Step IV: Check for nutrient loading rate

$$\text{Nutrient loading Rate (NLR)} = \frac{N_o \times d_w \times \eta \times F_1}{t \times F_2}$$

$$\text{Nutrient loading Rate (NLR)} = \frac{40 \times 0.45 \times 0.39 \times 0.001}{9 \times 10^{-4}}$$

$$= 7.8 \text{ kg/ha.day} < 20 \text{ kg/ha.day (o.k.)}$$

Step V: Check for hydraulic considerations and determination of cross sectional area by Darcy's law

$$\text{Cross sectional area } (A_c) = \frac{Q}{K_s \times s}$$

Where,

K_s : Hydraulic Conductivity, 5529.60 m/d for grit media (Multiply the measured value by a safety factor of 10% to account for roots growth)

s : Slope, expressed as decimal, 0.01 typically

$$\text{Cross sectional area } (A_c) = \frac{57}{5529.60 \times 0.10 \times 0.01}$$

$$= 10.3081 \text{ m}^2$$

Therefore, based on depth of 0.45m, width (b) can be chosen as 23.0 m and based on designed surface area; length (l) comes to be 121.47 m. For convenience the length can be divided in two equal halves.

Hence, provide two RZ beds of 60.75 x 23 x 0.45m in series, with separate inlet and outlet chamber.

NOTE:

In this study, it could be deduced from field observations that, 20% - 55% P – removal can be obtained with loading rate 15 kg/ha.day at HRT of 6 – 7.5 days. Hence in the present design case designed HRT is sufficient for the said P – removal. The separate consideration is not given in the design for P - removal. The typical details of the RZ bed are shown in Annexure -II