MODELLING OF NITROGEN REMOVAL IN THE VADOSE ZONE

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ABSTRACT

Ammonium in secondary wastewater is removed in the vadose zone when wastewater is applied to spreading basins with alternate flooding and drying. The processes involved in the removal of ammonium nitrogen are adsorption of ammonium by the soil, oxidation of the adsorbed ammonium to nitrate by nitrifying bacteria in the subsequent drying period thus freeing adsorption sites in the soil for further ammonium adsorption, and reduction of nitrate to nitrogen gas by denitrifying bacteria during flooding.

The extent of nitrogen removal is governed by the rate of infiltration, the lengths of the flooding and drying periods, the adsorption capacity of the soil for ammonium and the rates of nitrification and denitrification. A model incorporating these processes has been developed, which can be used to explain why nitrogen removal does not take place in some wastewater rapid-infiltration systems, why nitrogen conversion stops after the nitrification state in some cases, and to calculate the extent of nitrogen removal as a function of soil type and operating conditions. The model shows that the approach to steady state after a change in operating conditions is reached only slowly.

The model parameters have been obtained experimentally under laboratory conditions. A case study of nitrogen removal from wastewater by rapid infiltration in Perth, Western Australia is discussed.

INTRODUCTION

Nitrogen removal by land treatment using the rapid infiltration system has been demonstrated in many existing field systems (e.g. Leach et al., 1980). Maximization of nitrogen removal has also been attempted at the Flushing Meadows project (Bouwer et al., 1980), where nitrogen removal from 30 to 65% was achieved, and even higher removal rates were obtained in column experiments when the average infiltration rate was reduced (Lance et al., 1976). The design for rapid infiltration system has incorporated some of the above findings, though it has been realized that nitrogen removal is dependent on soil type and operating conditions (USEPA 1981). The difficulty in translating our understanding of the nitrogen removal processes into design stems from the many variables that are involved, their complex relationships and especially the opposing effects these variables have on nitrogen removal.

In Perth, Western Australia, the Metropolitan Water Authority has since 1981 carried out a pilot investigation in recharging groundwater with secondary municipal wastewater using a rapid infiltration system at Canning Vale (Rule 1981). One million liters per day of wastewater is applied through six 40 m x 20 m basins located on fine to medium grain silica sand. The natural water table is about 9 m below the basins. Cycles of flooding and drying of the basins are used following the practice at the Flushing Meadows project. With cycles ranging from 9 days of flooding and 5 days of drying to 5 days of flooding and 9 days of drying no nitrogen removal was observed; only nitrification took place. Experiments using soil columns packed with sand from the recharge site also showed that no nitrogen was removed, and moreover substantial leaching of ammonium was observed (Mathew et al., 1982).

The above experience led us to develop a model that would bring together the contribution of all the variables in the processes leading to nitrogen removal in the vadose zone with cycles of wetting and drying, so that we could assess the operating conditions under which nitrogen could be removed, and hence explain why nitrogen removal did not take place in a particular case; and when nitrogen was removed, obtain the operating conditions that would optimize its removal.

This paper describes the development of the model, the assumptions and simplification used to obtain a solution to the model equations, and its application in predicitng nitrogen removal as a function of soil type and operating conditions.

MODEL FOR NITROGEN REMOVAL

A comprehensive model for the removal of ammonium (the major form of nitrogen in primary and secondary municipal wastewater) should include:

(a) Adsorption of ammonium by soil under changing soil moisture content incorporating the transport of ammonium in the soil solution due to convection and hydrodynamic dispersion, and the transfer of ammonium from the solution to the soil at a rate governed by the adsorption isotherm and the infiltration rate of the wastewater through the soil.

(b) Nitrification with a changing population of nitrifying bacteria which is dependent on the concentration of ammonium in the soil, soil pH and temperature, and the availability of oxygen as a function of depth below the soil surface.

(c) Leaching of nitrate from the soil to the solution, which is dependent on the water content of the soil during wastewater percolation, infiltration rate and the rate of hydrodynamic dispersion.

(d) Denitrification under changing populations of denitrifying bacteria; its rate is dependent on the availability of organic carbon to the denitrifiers.

We have mathematically formulated a model incorporating all the above factors, but it has been difficult to obtain the solution to the set of equations describing the model. We have found that a simplified model (i.e., disregarding factors which have small effects and making simplifying assumptions to restrict the values of certain variables) is adequate in providing answers that are useful for the management of nitrogen removal in a groundwater recharge scheme using treated wastewater (Mathew *et al.*, 1982).

The following assumptions and simplifications are used, based on batch and column experiments using a sandy loam (Pyrton): (i) nitrification takes place in the *top one meter* of soil only. In the field, nitrifiation is limited by the availability of oxygen, due to the decreasing oxygen availability with increasing depth. A depth of one meter has been chosen based on observation of air penetration in the sandy loam soil following the cessation of flooding. In heavier soils this depth may be considerably less. (ii) Nitrification follows Michaelis-Menten kinetics and proceeds uniformly along the one meter depth of the soil. The pH of the soil is between 6 and 7.5 and soil temperature is between 15 and 35° C ensuring a reasonable rate of bacterial activity. (iii) Hydrodynamic dispersion plays a minor role and soil ammonium equilibrium concentration is reached rapidly. As a consequence the concentration of ammonium down the soil is uniform. (iv) As the wetting front moves down the soil, resaturation is reached quickly. (v) Nitrate is leached rapidly and moves along with the wetting front. (vi) Denitrification is not limited by the availability of organic carbon in the first *four meters* of soil depth. It is considered that beyond a depth of four meters organic carbon would have been reduced to a concentration that will limit denitrification. The choice of depth is rather arbitrary, but takes into account depletion of organic carbon with depth due to its consumption by other bacteria.

The simplified model highlights two processes that basically determine the overall rate and hence efficiency of nitrogen removal: nitrification and denitrification. It is not difficult to understand why these two are the rate controlling processes since they are dependent on bacterial activity. Since the nitrifying and denitrifying bacteria are ubiquitous, the only requirement is an adequate capacity of the soil to adsorb ammonium. The minimum adsorption capacity that a soil must have can in fact be determined from the two rate controlling processes.

Nitrification

Following McLaren (1970) the oxidation of ammonium by bacteria can be expressed by:

$$K \ln (s/s_o) + (s - s_o) = k_a m_a t \qquad (1)$$

where K = saturation constant = 8 ppm (Ardakani et al., 1974);
s = ammonium concentration: s_o = initial concentration;
k_a = a constant which has to be determined experimentally;
m_a = average biomass of bacteria.

Denitrification

A zero order kinetics has been used based on published results and the results of our laboratory batch tests.

$$(s - s_o) = k_d t_d \qquad (2)$$

where s denotes nitrate concentraion, k_d the denitrification rate and t_d is the time of travel of the wastewater from the surface to the water table.

Model parameters

Parameters for the model are obtained from the literature and from laboratory experiments using Pyrton sandy loam (Mathew *et al.*, 1982).

m_a = 4.0 x 10^3 organisms/g of soil
k_a = 7.0 x 10^{-4} ppm g organism^{-1} day^{-1}
k_d = 4.0 ppm day^{-1}

Ammonium adsorption isotherm: s (ppm) = 1.34 c (ppm) + 19.4.

APPLICATION OF MODEL

Determination of optimum flooding and drying periods

Consider the Pyrton sandy loam which adsorbs 47 ppm N when in contact with wastewater containing 20 ppm ammonium-N. For a reduction in N of 30 ppm in the soil, a drying period of about 10 days is required (Equation 1). With a renewed adsorption capacity of 30 ppm the amount of wastewater that can be applied without ammonium reaching the groundwater is 2.25 m^3/m^2 of basin area.

The minimum time required to denitrify 30 ppm N is 7.5 days (Equation 2). The maximum infiltration rate to ensure a liquid residence time of at least 7.5 days over 4 m of travel is 0.22 m/day. With the amount of wastewater applied (2.25 m/day) the flooding period is 10.2 days, which is satisfactory since it is greater than 7.5 days.

Thus a flooding period of 10 days and a drying period of 11 days (a 3 week cycle) with an infiltration rate of 0.22 m/day can be used as initial trial values in a field operation.

Effect of infiltration rate

With a given soil the desired infiltration rate may not be achieved. If the soil hydraulic conductivity is too low, the site is not suitable. If the soil hydraulic conductivity is too high, clay incorporation into the soil (to a depth of 1 m say) is possible. The effect of increasing infiltration rate beyond the optimum is nitrate leaching to groundwater as illustrated in Figure 1.

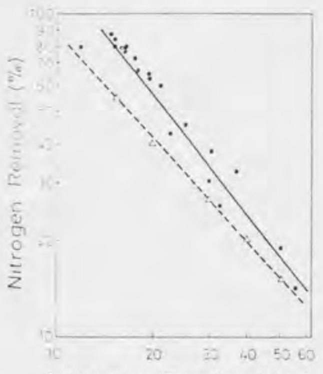

Figure 1. Effect of infiltration rate on nitrogen removal from sewage water by soil percolation. Solid line is the experimental curve of Lance et al (1976). Dotted line is obtained from the simplified model.

Minimum soil adsorption capacity

The effect of using shorter drying periods is shown in Table 1. Shorter drying periods result in a reduced renewed adsorption capacity. Consequently the flooding period must be short to prevent ammonium reaching the groundwater. The short flooding period is not sufficient in practice for anaerobic conditions to develop to allow denitrification at the desired rate. The results in Table 1 suggest that a renewed adsorption capacity of 20 ppm with an initial soil N concentration of 40 ppm is the minimum required. Our laboratory experiments indicate that a soil with a minimum cation exchange capacity of 5 meq/100 g is required.

TABLE 1

OPERATIONAL PARAMETERS FOR DIFFERENT RENEWED ADSORPTION CAPACITY VALUES

Operational parameters	Renewed adsorption capacity ppm *				
	50	40	30	20	10
1. Quantity treated per cycle m^3/m^2	3.75	3.00	2.25	1.50	0.75
2. Drying period, days	19	15	11	7.5	3.4
3. Time required for denitrification, days	11.4	9.1	6.8	4.5	2.2
4. Infiltration rate, m/day	0.35	0.44	0.59	0.88	1.82
5. Darcy velocity, m/day	0.15	0.19	0.25	0.37	0.77
6. Flooding period, days	25	16	9	4	0.97
7. Total period for a cycle, days	44	31	20	11.5	4.3

* Initial soil concentration = 100 ppm.

Approach to steady state

When starting the operation of recharge basins or changing operating conditions the model shows that steady state is reached only slowly. Table 2 shows that steady state is reached only after 7 cycles (140 days) when an operation with a flooding period of 9 days, drying period of 12 days and infiltration rate of 0.4 m/day is changed to flooding for 6 days, drying for 14 days and and infiltration rate of 0.35 m/day.

TABLE 2

NITROGEN REMOVAL PROCESSES LEADING TO STEADY STATE

Operational parameters	Flooding and Drying Cycle						
	I	II	III	IV	V	VI	VII
1. Adsorbed NH_4^+-N, ppm	45.2	41.5	36.0	35.4	34.5	34.2	34
2. Amount of NH_4^+-N to groundwater, g/m^2	0.7	1.5	0.25	0.1	[illegible]	0	
3. Soil NH_4^+-N at the end of drying, ppm	15.5	8.7	7.3	6.5	6.2	[illegible]	[illegible]
4. Amount nitrified, ppm	31.7	30	28.1	29.0	25.3	28.2	[illegible]
5. Amount of NO_3^--N to groundwater, g/m^2	13.5	12.[illegible]	11.6	11.3	11.0	11.2	[illegible]
6. Percentage N removal	44	66	72	73	73	76	[illegible]

DISCUSSION

The model, though involving many simplifying assumptions, provides a means of comparing nitrogen removal under different operation conditions. It explains why the silica sand at Canning Vale in Perth does not remove ammonium. This is because the sand has very little adsorption capacity. The high hydraulic conductivity keeps the sand aerobic and hence only nitrification occurs. The situation is similar to the rapid infiltration system in Boulder, Colorado (Smith *et al.*, 1979). In Flushing Meadows, where the soil has some capacity to adsorb ammonium, short flooding and drying periods resulted in nitrification only. In this case the ammonium adsorption capacity of the soil was not exhausted during flooding, and the ammonium was completely nitrified during the drying period. No ammonium therefore reached the groundwater, but the flooding period was too short for an aerobic condition to be developed.

Continuous flooding at the basin at Milton, Wisconsin (Benham-Blair 1979) resulted in ammonium ions contaminating groundwater, since the adsorption capacity of the soil was not renewed by nitrification.

Two weeks of flooding and two weeks of drying resulted in ammonium in groundwater after a period of time at the Flushing Meadows Project (Bouwer *et al.*, 1980). Then a shorter period of flooding with a reduced application rate reduced the ammonium contamination significantly. The reduced application of the wastewater, hence ammonium applied, became more equal to the amount of ammonium nitrified during the drying period. The experience at Flushing Meadows Project also shows that it took a long time for the overall process to reach steady state after a change of operating conditions (of the order of one year).

In column experiments using 1 m of Pyrton sandy loam on top of silica sand we found that nitrogen was removed with a series of flooding and drying. The rate of removal as a function of flow rate was less than indicated in Figure 1, since the wastewater was partly nitrified.

CONCLUSIONS

The removal of ammonium from treated wastewater by soil application using a rapid infiltration system involves adsorption, nitrification, leaching and denitrification, which interact in a complex manner. The use of a simple model has enabled us to understand the interctions between the processes to arrive at optimum operating conditions and to amend the soil for even greater nitrogen removal.

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