WATER QUALITY

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Water Quality Improvement of Treated Wastewater by Soil Percolation

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SUMMARY

The processes involved in the removal of ammonium-nitrogen from treated wastewater by land application are described. A simple model has been developed that can be used to determine optimum operating conditions (flooding period, drying period, infiltration rate) and in the selection of soils that can best remove nitrogen. The model can be used to explain why certain recharge schemes have not worked. In Perth the model suggests the sandy soil should be amended by clay.

INTRODUCTION

The ability of soils to attenuate or remove substances from solutions percolating through them is well established (Greenland and Hayes, 1981). We can take advantage of this property of soils in the disposal of wastewater if it is done before the water reaches the water table. Satisfactory recharge of groundwater using treated wastewater is therefore theoretically possible and conceptually attractive in an arid region like Western Australia.

Proper management of the recharge operation is important since different soils possess different capacities for removing pollutants. An understanding of the processes involved in the removal of pollutants by soils is essential in arriving at a sound management strategy. In this paper the use of modelling in arriving at the strategy for the removal of ammonium from treated wastewater is illustrated. These consist of elucidating the processes of interactions between ammonium and soils leading to its removal (descriptive model), building a quantitative model and deducing optimum operating conditions for removing ammonium.

REMOVAL OF AMMONIUM BY SOIL

Ammonium (NH$_4^+$) is present in treated wastewater as the product of decomposition of organic-nitrogen (proteins, urea). In secondary-treated wastewater it is usually the major form of nitrogen in solution and a concentration of about 20 mg N/l is common. When discharged to open receiving water the ammonium is oxidised by micro-organisms to nitrate (NO$_3^-$) and represents an oxygen demand to the receiving water (1 mg N/l demands 4.6 mg O$_2$/l). In addition, it can cause algal bloom in the receiving water, whilst nitrate in drinking water can cause health problems.

When applied to soil via spreading basins the ammonium in the wastewater can be removed as follows. Being positively charged it is removed in the soil via a cation-exchange mechanism displacing other cations held on the soil's cation exchange sites. Application of the wastewater (flooding of a recharge basin) can be carried out until the cation-exchange capacity of the soil is exhausted. Upon drying (drying the recharge basin) soil nitrifying bacteria oxidise the captured ammonium into nitrate, utilizing oxygen from the air; thus releasing cation-exchange sites for further ammonium removal during a following application of wastewater. In the following flooding period not only ammonium in the percolating water is removed, but an anaerobic condition is created that enables soil denitrifying bacteria to convert nitrate to nitrogen gas, provided that an organic-carbon source is available to the heterotrophic bacteria (1 mg N requires approximately 2 mg TOC). Nitrifying and denitrifying bacteria are ubiquitous in domestic wastewater and soils.

Alternate flooding and drying of recharge basins can therefore be employed for the removal of ammonium nitrogen. The overall series of processes can be summarized diagramatically as shown in Figure 1.

![Diagram of ammonium nitrogen removal by alternate flooding and drying of recharge basins](image)

Figure 1 Diagramatic representation of ammonium nitrogen removal by alternate flooding and drying of recharge basins

The Flushing Meadows Project (Bouwer et al, 1980) and the 23rd Avenue Rapid Infiltration Project (Bouwer and Rice, 1980) in Phoenix, Arizona are examples where ammonium is removed by alternate flooding and drying of recharge basins.

Although alternate flooding and drying is a necessary requirement for the removal of ammonium from wastewater by soil, it is not a sufficient condition. A number of other conditions must be
fumbl. The soil must have a reasonable capacity for adsorbing ammonium. This capacity is related to the clay content of the soil and the mineralogy of the clay. A certain minimum adsorption capacity is required and must be determined as part of the quantification (modelling) of the ammonium removal process. Too much clay in the soil is known to be undesirable, since the soil’s hydraulic conductivity becomes too low.

The rate of nitrification in soils is dependent on the number of nitrifying bacteria and the concentration of ammonium in soil. A sufficiently long drying period should be allowed so that a high percentage of exchange sites is freed to further remove ammonium in the following flooding. Too long a drying period, however, decreases the average application rate and requires a larger land area. An optimum length for drying needs to be determined.

Three processes occur simultaneously during flooding: ammonium adsorption from solution to soil, leaching of nitrate and denitrification. These processes are rate dependent processes, though their rates are quite different. Nitrate leaching is the fastest process, followed by ammonium adsorption and finally denitrification is the slowest. Infiltration rate and length of the flooding period are important variables during flooding. Too high an infiltration rate leaches nitrate to groundwater, on the other hand too low an infiltration rate requires a larger land area. An optimum application rate needs to be determined. Prolonged flooding enhances the extent of denitrification, but ammonium may leach to the groundwater if the capacity of the soil for adsorbing it is meanwhile exceeded.

A model (Figure 2) can be used to obtain the operating conditions to maximize the amount of ammonium-nitrogen removed.

<table>
<thead>
<tr>
<th>Flooding Time</th>
<th>Model for Ammonium Removal by Alternate Infiltration Rate and Drying of Recharge Basins</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drying Time</td>
<td>Amount of Nitrogen Removed</td>
</tr>
<tr>
<td>Infiltration Rate</td>
<td>(Clay Amendment of Soil)</td>
</tr>
</tbody>
</table>

**Figure 2 Variables affecting ammonium removal by soil**

3 **MODEL FOR AMMONIUM REMOVAL BY SOIL**

A comprehensive model for ammonium removal should include:

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

(b) Nitrification under changing populations of nitrifying bacteria (again due to flooding and drying) which is dependent on concentration of ammonium in soil, soil pH and temperature, and availability of oxygen as a function of depth below the soil surface.

(c) Leaching of nitrate from soil to solution, which is dependent on the soil moisture content; transport of nitrate in soil solution is a function of infiltration rate and rate of hydrodynamic dispersion.

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

Although it is possible to mathematically formulate a model incorporating all the above factors, it is 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 management of a groundwater recharge scheme using treated wastewater (Mathew, Newman and Ho, 1982).

The following assumptions and simplifications are used:

(a) Nitrification takes place in the top one metre of soil only. In the field nitrification is limited by the availability of oxygen, due to decreasing oxygen availability with increasing depth and the corresponding decreased nitrification rate. A depth of one metre has been chosen based on observation of air penetration in a sandy loam soil following the cessation of flooding. In tighter soils this depth may be considerably less.

(b) Nitrification follows Michaelis-Menten kinetics and proceeds uniformly along the one metre 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.

(c) As a consequence of assumption (a), renewed soil adsorption capacity for ammonium is only available in the top one metre of the soil. It is assumed that the concentration of ammonium down the soil is uniform (i.e. hydrodynamic dispersion is neglected and soil ammonium equilibrium concentration is reached fairly rapidly).

(d) As the wetting front moves down the soil, all the air is displaced and soil particles are in contact with incoming flow, i.e. saturation is reached quickly.

(e) Nitrate is leached rapidly and moves along with the wetting front.

(f) Denitrification follows zero order kinetics, and is not limited by organic carbon availability in the first four metres of soil depth. It is considered that beyond a depth of four metres organic carbon would have been reduced to a concentration that will limit denitrification. The choice of the depth is rather arbitrary, but takes into account depletion of organic carbon with depth due to its consumption by other bacteria.
Although the above assumptions mean the model does not fully describe the overall process completely, it is not far from the real world situation, as the assumptions have been made from observation of batch and column experiments using a soil from the Upper Swan Valley (Pyrton Sandy Loam) to derive the model parameters.

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

1 Nitrification

Ammonium is used by nitrifying bacteria for growth, maintenance and waste metabolism. The total rate of immobilization of ammonium by the bacteria for these processes can be expressed as (McLaren, 1970)

\[ \frac{dS}{dt} = A \frac{dm}{dt} \cdot a \cdot S + k_{d} \cdot S \]

(1)

where
- \( S \) = ammonium concentration.
- \( t \) = time.
- \( m \) = biomass of bacteria.
- \( A \) = proportionality constant (reciprocal to growth yield) equal to ammonium oxidised per unit weight of biomass synthesized.
- \( a \) = ammonium oxidised per unit biomass per unit time for maintenance.
- \( k_{d} \) = rate constant for waste metabolism.

The terms \( dm/dt \) and \( a \) can be expressed in terms of the Monod equation (Ardaiani et al., 1974)

\[ \frac{dm}{dt} = \frac{\gamma_{m} \cdot S}{K_{1} + S} \text{ and } a = \frac{\alpha}{K_{2} + S} \]

(2)

where
- \( \gamma_{m} \) = maximum specific growth rate.
- \( \alpha \) = maximum value of \( a \).

In both cases the maximum value occurred when ammonium availability is not a limiting factor. Assuming \( K_{1} \) and \( K_{2} \) are not much different in their numerical values and close to \( K \), equation (1) becomes

\[ \frac{dS}{dt} = (A_{m} + \alpha + k_{d}) \cdot S \]

(3)

Under a given environmental condition it can be assumed that the bacteria establish an optimum population, with an average of \( m_{a} \). Integrating equation (3) gives

\[ K \cdot \ln \left( \frac{S}{S_{0}} \right) + (S - S_{0}) = K_{a} \cdot m_{a} \cdot t \]

(4)

where
- \( S_{0} \) = initial ammonium concentration
- \( k_{d} = (A_{m} + \alpha + k_{d}) \) = a constant which has to be determined experimentally.

2 Denitrification

Although Michaelis-Menten kinetics and first order kinetics have been suggested for denitrification, a zero order kinetics has been found to fit the results of published information and laboratory results just as well.

\[ \frac{dS}{dt} = k_{d} \]

(5)

where \( k_{d} \) = denitrification rate.

Hence \( S_{0} = S = k_{d} \cdot t \)

3.3 Model Parameters

Parameters for the simplified model are obtained from the literature and from laboratory experiments using Pyrton Sandy Loam, Bassendean and Spearwood sands of the Swan Coastal Plain, Western Australia (Mathew, Newman and Ho, 1982) and presented below.

3.3.1 Nitrification

\( K = 8 \) ppm (Ardaiani, 1974).
\( m_{a} = 4.0 \times 10^{3} \) organisms/g of soil.
\( k_{d} = 7.0 \times 10^{-4} \) ppm g organism\(^{-1}\) day\(^{-1}\).

3.3.2 Denitrification

\( k_{d} = 4.0 \) ppm/day

3.3.3 Ammonium adsorption by soils

The relationship between cation exchange capacity and clay content, and hydraulic conductivity and clay content is shown in Figure 3. The relationship between ammonium concentration in soil in equilibrium with 20 mg/l of ammonium nitrogen in solution and cation exchange capacity is shown in Figure 4.

3.3.4 Soil properties

Bulk density = 1,500 kg/m\(^3\).
Porosity = 0.42

Figure 3 Cation exchange capacity and hydraulic conductivity with respect to percentage clay in Spearwood sand

4 APPLICATION OF MODEL

4.1 Flooding and Drying Periods

The optimum flooding and drying periods for a given wastewater and soil is primarily determined by the rate of nitrification and denitrification.
Consider a soil that has an adsorption capacity of 47 ppm ammonium-N when in contact with wastewater containing 20 mg/l ammonium-N (Pyrtton Sandy Loam). The rate of nitrification with the initial ammonium concentration is 3 ppm/day (Equation 4). For a reduction in ammonium nitrogen of 30 ppm in the soil, a drying period of 10 days is required.

During each flooding period the soil can adsorb a further 30 ppm (renewed adsorption capacity). The amount of wastewater that can be applied without ammonium leaching to the groundwater is thus (50 x 1,500)/20 = 2,250 l/m² of basin area.

With a denitrification rate of 4 ppm/day, the time required to denitrify 30 ppm of nitrate-nitrogen is 30/4 = 7.5 days (Equation 6). The maximum infiltration rate to ensure a liquid residence time of at least 7.5 days over four metres of travel is (4/7.5) 0.42 = 0.22 m/day.

The amount of wastewater applied is 2,250 l/m² (see above), thus the flooding period is (2,250/1,000)/0.22 = 10.5 days, which is satisfactory since it is greater than 7.5 days.

A flooding period of 10 days and a drying period of 11 days (a 3 week cycle) with a flooding rate of 0.22 m/day are indicated by the simplified model. These periods can be used as initial trial values in a field operation.

4.2 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 is possible. Allowance must, however, be made for reduction in infiltration rate due to solids build-up in the base of a recharge basin. With repeated flooding and drying an equilibrium infiltration rate will eventually be reached.

The effect of increasing infiltration rate beyond the optimum is usually nitrate leaching to groundwater, as shown by Figure 5.

Figure 4 Relation between cation exchange capacity and (1) adsorption equilibrium distribution coefficient and (ii) concentration in soil in equilibrium with 20 ppm NH₄-N in solution

Figure 5 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.

4.3 Minimum soil adsorption capacity

The effect of using shorter drying periods is shown in Table I.

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Table I

OPERATIONAL PARAMETERS FOR DIFFERENT RENEWED ADSORPTION CAPACITY VALUES

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<th>Operational parameters</th>
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<tr>
<td>1. Quantity treated per cycle of operation, l/m²</td>
<td>3750 3000 2250 1500 750</td>
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<td>2. Drying period, days</td>
<td>19 15 11 7.3 5.6</td>
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<td>3. Time required for denitrification, days</td>
<td>11.4 9.1 6.8 4.5 2.2</td>
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<td>4. Infiltration rate, m/day</td>
<td>0.35 0.44 0.59 0.88 1.82</td>
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<td>5. Darcy velocity, m/day</td>
<td>0.15 0.19 0.25 0.37 0.77</td>
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<td>6. Flooding period, days</td>
<td>25 16 9 4 0.97</td>
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<td>7. Total period for a cycle, days</td>
<td>44 31 20 11 3.4</td>
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Shorter drying periods result in reduced nitrification and hence lower renewed adsorption capacity. Consequently only shorter flooding periods are required. Although the simplified model allows short flooding periods, in practice anaerobic conditions may not develop fully to allow denitrification to proceed at the desired rate. It is considered that a renewed soil adsorption capacity of 20 ppm for ammonium is the minimum required for satisfactory operation, so that too short flooding and drying periods are avoided.

The least adsorption capacity a soil must have for ammonium-nitrogen is therefore 20 ppm, provided
that this capacity is renewed each time. The rate of nitrification with a lower initial ammonium concentration is, however, also lowered. The figures in Table 1 have been calculated based on an initial ammonium-nitrogen in the soil of 100 ppm. Only soil with an initial ammonium-nitrogen concentration of 40 ppm is considered to be suitable for the removal of ammonium by flooding and drying. Figure 4 shows that the cation-exchange capacity (CEC) of the soil should be at least 4 meq/100g. Amendment of Spearwood soil with 10% Pyrton loam, for example, will give this desired CEC (Figure 3), though its hydraulic conductivity may be too high. Too much clay, on the other hand, is not desirable since the hydraulic conductivity of the soil may fall below 1 m/day and there may be difficulty with clogging. A Pyrton loam-Spearwood Sand mixture with a clay content of about 22% gives an optimum mixture of high CEC and high hydraulic conductivity.

4.4 Approach to Steady State

When starting the operation of recharge basins or changing operating conditions (length of flooding and drying periods), steady state is reached only slowly. Table II shows that steady state is reached only after seven cycles of flooding and drying (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 an infiltration rate of 0.35 m/day.

5 DISCUSSION

The model described above, though involving many simplifying assumptions, provides a means of predicting the effects of changing operating conditions on the removal of ammonium-nitrogen from wastewater by land application. The model explains why Bassendean sand does not remove ammonium in a laboratory column (Figure 6) or at the MMA Canning Vale Pilot Recharge Site when operated based on the flooding and drying cycle of the Flushing Meadows Recharge Project. This is because the sand has very little CEC and too high an hydraulic conductivity.

The model can also explain the performance of field operations of ammonium removal or non-removal at major sites where wastewater is applied onto soil, even though we do not have information on the CEC of the soils.

In Flushing Meadows, it was found that with short frequent cycles of two days flooding and five days drying, no removal of nitrogen was achieved as only ammonium was oxidised and leached out as nitrate (Bouwer et al., 1980). Similarly, in the fieldwork carried out by the University of Colorado (Smith et al., 1979) one day flooding and two and a half days drying only produced nitrification. The explanation derived from the simplified model is that the soil is always kept aerobic due to the short flooding period and hence continuous nitrification only is possible. With the flooding rate being high all the nitrate is leached out during flooding.

In both cases quoted above no ammonium was found to be leached out. From the simplified model it is seen that during the flooding period the soil adsorption capacity is not exhausted, and the ammonium applied in a flooding period is nitrified before the next flooding event. Thus the absence of ammonium in groundwater is almost certainly because nitrification takes place continuously and goes further to completion than if interrupted by a denitrification phase. Hence the soil is acting like a trickling filter for the continuous conversion of ammonium to nitrate.

Continuous flooding of the basin at Milton, Wisconsin (Benham-Blair and Affiliates Inc., 1979) resulted in ammonium ions contaminating groundwater. In this case the adsorption capacity of the soil apparently was not being renewed by nitrification. Nitrification can only take place in aerobic conditions which occur in the drying period. Hence as the adsorption capacity of the soil is exhausted the ammonium find its way to the ground water.

Two weeks of flooding and two weeks of drying resulted in leaching of ammonium after a period of time (Bouwer, 1980). A shorter period for flooding with a reduced rate of flooding resulted in reduction of ammonium leaching. The model indicates that the ammonium applied during flooding is more than the renewed adsorption capacity of the soil and suggests that the drying period should be long enough to ensure the renewed adsorption capacity is sufficient to cope with the flooding period.

The experience at the Flushing Meadows Project also shows that it takes a long time for the overall process to reach steady state after a change of operating conditions (of the order of one year).

<table>
<thead>
<tr>
<th>TABLE II NITROGEN REMOVAL PROCESSES LEADING TO STEADY STATE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operational parameters</td>
</tr>
<tr>
<td>------------------------</td>
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<tr>
<td></td>
</tr>
<tr>
<td>1. Adsorbed NH₄⁺ N</td>
</tr>
<tr>
<td>Concentration, ppm</td>
</tr>
<tr>
<td>2. Amount of NH₄⁺ N</td>
</tr>
<tr>
<td>leached out, g/m²</td>
</tr>
<tr>
<td>3. Concentration of</td>
</tr>
<tr>
<td>NH₄⁺ N at the end of</td>
</tr>
<tr>
<td>drying, ppm</td>
</tr>
<tr>
<td>4. Amount nitrified, ppm</td>
</tr>
<tr>
<td>5. Amount of NO₃⁻ N</td>
</tr>
<tr>
<td>leached out, g/m²</td>
</tr>
<tr>
<td>6. Total quantity of N</td>
</tr>
<tr>
<td>leached out, g/m²</td>
</tr>
<tr>
<td>7. Percentage N removal</td>
</tr>
</tbody>
</table>
The model can be used to select soils that can be used to amend sandy soils of the Swan Coastal Plain so that they are useful in removing ammonium. This has led us to investigate the use of bauxite processing residue (red mud) as the amending agent.

There is a lot of room for improvement in the model, and at present we are refining it for soil adsorption. Many pollutants are removed by soil adsorption, thus the study should throw light on the attenuation of these pollutants by soils.

6 CONCLUSIONS

The removal of ammonium from treated wastewater by soil application involves several processes (adsorption, nitrification, leaching, denitrification) which interact in a complex manner. The use of a simple model to help understand the interactions between the processes, and in arriving at optimum operating conditions have been illustrated.

The simple model used can be greatly refined with further research. However, it has been shown that even a simple model can aid in the management of ammonium removal and this can be extended to the removal of other pollutants by soil.

7 ACKNOWLEDGEMENT

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8 REFERENCES


