

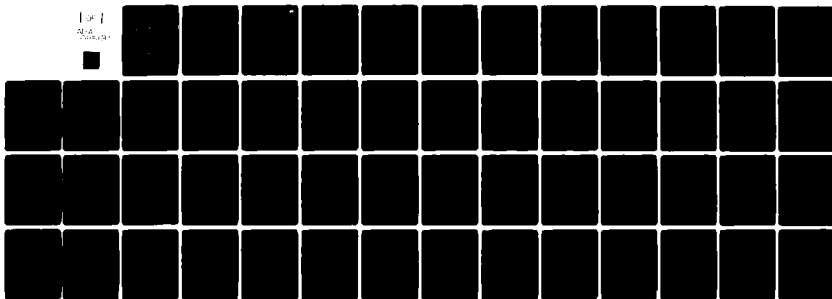
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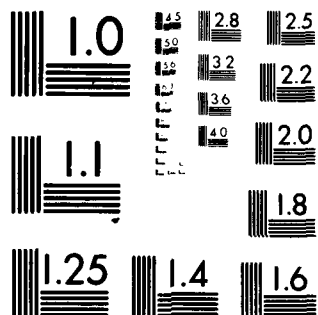
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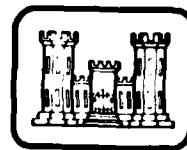
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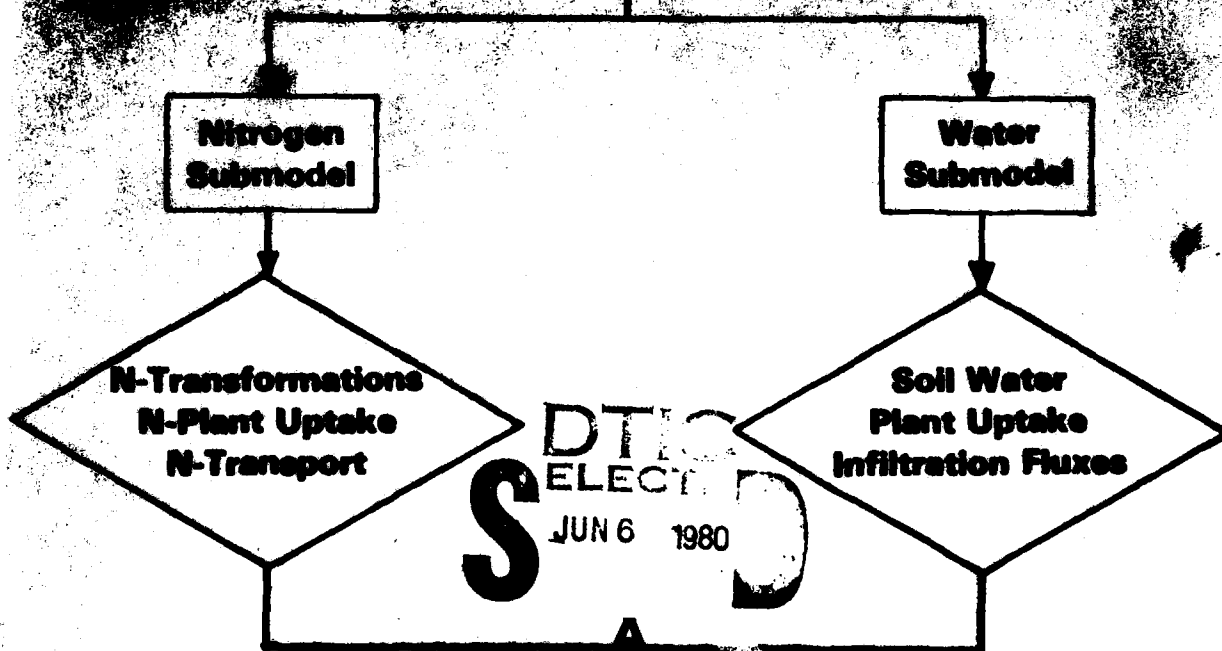
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Simplified model for prediction of nitrogen behavior in land treatment of wastewater

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**Water Content
Conc. of N Species
Plant Uptake with
Time and Soil Depth**

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CRREL Report 80-12



Simplified model for prediction of nitrogen behavior in land treatment of wastewater

H.M. Selim and I.K. Iskandar

April 1980

Submitted
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Prepared for
DIRECTORATE OF CIVIL WORKS
OFFICE, CHIEF OF ENGINEERS

By
UNITED STATES ARMY
CORPS OF ENGINEERS
COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
HANOVER, NEW HAMPSHIRE, U.S.A.

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10 CRREL-87-12

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER CRREL Report 80-12	2. GOVT ACCESSION NO. AD-A085191	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) SIMPLIFIED MODEL FOR PREDICTION OF NITROGEN BEHAVIOR IN LAND TREATMENT OF WASTEWATER		5. TYPE OF REPORT & PERIOD COVERED
7. AUTHOR(s) H.M. Selim and I.K. Iskandar		6. PERFORMING ORG. REPORT NUMBER
9. PERFORMING ORGANIZATION NAME AND ADDRESS Louisiana State University, Baton Rouge, Louisiana, and U.S. Army Cold Regions Research and Engineering Laboratory Hanover, New Hampshire 03755		8. CONTRACT OR GRANT NUMBER(s) 1256
11. CONTROLLING OFFICE NAME AND ADDRESS Directorate of Civil Works Office, Chief of Engineers Washington, D.C. 20314		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS CWIS 31633, 31297 and 31442
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		12. REPORT DATE 11 Apr 1980
		13. NUMBER OF PAGES 53
		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Land treatment Models Nitrogen cycle Wastewater treatment		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) A simplified model for simulation of nitrogen transformations and transport in land treatment of wastewater is presented. The purpose of the model is to predict the behavior of $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ in the soil profile in land treatment systems. The program is based on the solution of the transient soil water flow equation simultaneously with the equations describing the transformation, transport, and plant uptake of nitrogen in the soil. The program is valid for uniform as well as multilayered soil profiles and can be adapted to incorporate various nitrogen transformation mechanisms and boundary conditions. The model can be used as a tool to predict the fate of nitrogen in land treatment systems. Model sensitivity to changes in the rate of nitrification, ammonium ion exchange, and rate of plant uptake of nitrogen is also described. Description of the computer program, the program listing, and an example of input data and a two-week computer simulation of output data are presented.		

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PREFACE

This report was prepared by Dr. H.M. Selim, Assistant Professor, Department of Agronomy, Louisiana State University, Baton Rouge, Louisiana, and Dr. I.K. Iskandar, Research Chemist, Earth Sciences Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory.

The study was conducted as a part of the U.S. Army Corps of Engineers Civil Works Research and Investigation Project under the following work units: CWIS 31633, *Optimization of Automated Procedures for Design and Management of Land Treatment Systems*, CWIS 31297, *Nitrogen Transformation in Land Treatment*, and CWIS 31442, *Mathematical Modeling in Land Treatment*.

This report was technically reviewed by Dr. R.S. Mansell of the University of Florida and Dr. M. Mehran of the University of California-Davis.

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CONTENTS

	Page
Abstract	i
Preface	ii
Introduction.....	1
The model	1
Modeling objectives.....	1
Main features.....	1
General description.....	2
Water flow equations and boundary conditions.....	2
Soil surface boundary conditions.....	3
Bottom boundary conditions.....	3
Nitrogen transformations and transport equations and boundary conditions.....	4
Water and nitrogen uptake by plants.....	6
Method of model solution.....	7
Model sensitivity.....	8
Description of the computer program.....	17
Input data section.....	17
Source program.....	17
Subroutine IDIST.....	19
Subroutine IDIST2.....	19
Subroutine ROOTS.....	19
Subroutine INDTDZ.....	19
Subroutine WATER.....	19
Subroutine WPROP.....	19
Subroutine AMONIA.....	20
Subroutine NITRAT.....	20
Functions ZZ1, ZZ2, ZZ3	20
Subroutine OUTPUT.....	20
Subroutine TRIDM.....	20
Literature cited.....	20
Appendix A. Program listing.....	23
Appendix B. Example of input and output.....	45

ILLUSTRATIONS

Figure

1. Diagram of the simplified nitrogen model showing the water and the nitrogen submodels.....	2
2. Schematic diagram of a multilayer soil profile.....	4
3. Schematic diagram of the nitrogen transformation processes considered in the nitrogen submodel.....	5
4. Simulated soil water suction distributions in a Windsor soil for one week following application of 5 cm of wastewater.....	9
5. Simulated $\text{NH}_4\text{-N}$ distributions for one week following wastewater application.....	10

	Page
Figure	
6. Simulated $\text{NO}_3\text{-N}$ distributions for one week following wastewater application.....	10
7. Cumulative $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ uptake with time.....	10
8-12 Simulated concentration distributions of $\text{NO}_3\text{-N}$ in the soil profile where weekly application of 5 cm of wastewater was maintained with differing parameters.....	11-12
13. Nitrification rate coefficient.....	12
14-16 Simulated concentration distributions of $\text{NO}_3\text{-N}$ in the soil profile where weekly application of 5 cm of wastewater was maintained with differing parameters.....	13-14
17-18 Simulated concentration distribution of $\text{NO}_3\text{-N}$ in the soil profile with differing parameters.....	14-15
19. Cumulative N uptake with time.....	15
20. Simulated concentration distributions of $\text{NO}_3\text{-N}$ in the soil profile where 5 cm of wastewater was applied every $\frac{1}{2}$ week.....	15
21. Same as Figure 20 except for weekly application of 10 cm of wastewater.....	15
22. Simulated concentration distributions of $\text{NO}_3\text{-N}$ in the soil profile where weekly application of 5 cm of wastewater was maintained.....	16
23. Cumulative N uptake with time where weekly application of 5 cm of wastewater was maintained for a period of 9 weeks.....	16
24. Detailed flow chart of simplified nitrogen model.....	18

SIMPLIFIED MODEL FOR PREDICTION OF NITROGEN BEHAVIOR IN LAND TREATMENT OF WASTEWATER

H.M. Selim and I.K. Iskandar

INTRODUCTION

In land treatment, nitrogen is almost always the factor limiting the rate of wastewater application. Excessive nitrate nitrogen concentration in groundwater is of great health concern due to its association with infant methemoglobinemia (blue baby syndrome) and eutrophication of natural waters. Consideration of land treatment as an alternative to advanced waste treatment has been hampered by the lack of scientific data on the fate of N that would allow efficient and cost-effective design of systems without incurring health risks.

The N behavior in land treatment is affected by numerous physical, chemical and biological processes and environmental conditions. Iskandar and Selim (1978) evaluated existing models for prediction of $\text{NO}_3\text{-N}$ in percolate water in land treatment. They concluded that several models developed to describe one or more processes in agricultural regimes can be adapted for land treatment. However, existing large models being used for prediction of N transformation and transport in agricultural land must be modified and simplified for use under land treatment conditions. The fact that nitrogen is applied in small amounts repeatedly (most often weekly) in land treatment, in contrast to normal agricultural fertilizing practice, should produce significant differences in the nitrogen transformation processes. Also, the soils under land treatment are most often near or above field capacity so that the water flow pattern as well as N transformation processes will vary significantly from those of an agricultural regime.

The objectives of this report are to describe a simplified model for prediction of nitrogen behavior in slow and rapid infiltration land treatment systems.

Model development, computer program listing and documentation and sensitivity analysis of model parameters are included. Validation of the developed model will be the subject of a later report.

THE MODEL

Modeling objectives

The objectives of developing a dynamic nitrogen model were to

1. Develop a computer model for N behavior to simulate the physical, chemical and biological processes in slow and rapid infiltration systems.
2. Enable prediction of $\text{NO}_3\text{-N}$ concentration in soil solution and leachate with time and space.
3. Assist in estimating the application rate and schedule of water and nitrogen to a land treatment system.
4. Improve land treatment management techniques for better renovation of wastewater and less detrimental impact on the environment.
5. Point out the area(s) of research need, based on model sensitivity analysis and availability of information in the literature.

Main features

The main feature of the computer program is that it is valid for uniform as well as multilayered or stratified soil profiles. In addition, the program is flexible and is designed to incorporate the following (input) conditions as desired:

1. Rate of wastewater application.
2. Duration of wastewater application.
3. Depth of individual soil layers.

4. Concentration of ammonium and nitrate in the wastewater.
5. Wastewater application cycle, i.e. scheduling.
6. Soil water properties and nitrogen transformation mechanisms for individual soil layers.
7. Plant root distribution and growth in the soil.
8. Rate of nitrogen uptake by plants.
9. Evapotranspiration rate.
10. Initial distribution of water and nitrogen species in the soil profile.

General description

Figure 1 shows a block diagram of the simplified model presented in this report. The model is formed of two main submodels. The first is a water flow submodel which describes wastewater infiltration, water movement in the soil profile, and rate of plant uptake of water with soil depth and time. The second is a nitrogen submodel which describes the transport and transformations of N species in the soil as well as nitrogen uptake by plants. The model also includes several subroutines which account for initial and boundary conditions, plant root distribution in the soil, soil water

properties, and nitrogen transformation processes (ion exchange, nitrification and denitrification). A detailed flow chart of the model and description of all subroutines are presented in a later section.

Water flow equations and boundary conditions

In order to describe the nitrogen transformation and transport in saturated-unsaturated soil profiles under transient flow conditions, the following water flow equation (Childs 1969) must be solved:

$$\frac{\partial \theta}{\partial t} = \left(\frac{\partial}{\partial z} \right) [K(h) \frac{\partial h}{\partial z}] - \frac{\partial K(h)}{\partial z} - A(z, \theta) \quad (1)$$

where

θ = soil water content (cm^3/cm^3)

h = soil water pressure head (cm)

$K(h)$ = soil hydraulic conductivity (cm/h)

$A(z, \theta)$ = rate of water extraction ($\text{cm}^3/\text{h cm}^2$)

t = time (h)

z = depth in the soil (cm).

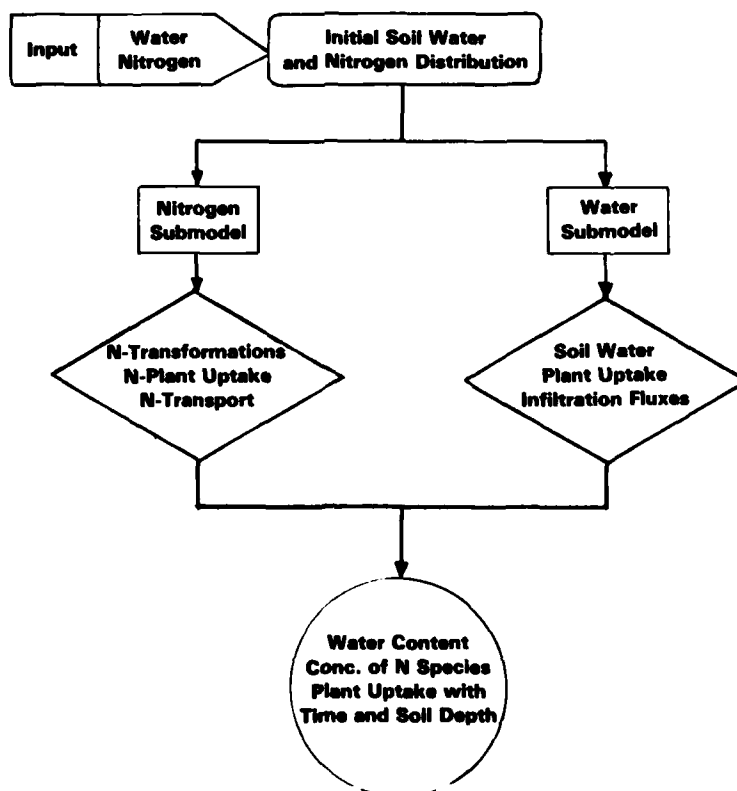


Figure 1. Diagram of the simplified nitrogen model showing the water and the nitrogen submodels.

Equation 1 is commonly known as the h -form of the water flow equation. This equation was chosen over the diffusivity form (Selim 1978), since it allows not only for saturated-unsaturated flow but it also allows soil stratification or layering of the soil profile. In solving eq 1, the left-hand term must be transformed such that

$$\partial\theta/\partial t = (\partial\theta/\partial h) (\partial h/\partial t) = \text{Cap}(h) \partial h/\partial t \quad (2)$$

where $\text{Cap}(h)$ is the soil water capacity term (cm^{-1}) which is determined using the appropriate soil water characteristic relationship (θ vs h).

In solving eq 1 for multilayered soil profiles, the soil water hydraulic conductivity $K(h)$ and the soil water capacity $\text{Cap}(h)$ must be provided for each soil layer. In addition, the soil water initial and boundary conditions must be specified. The initial condition is dictated by the initial distribution of θ or h in the soil profile at some assumed (starting) time. The boundary conditions at the soil surface and at some depth L below the soil surface must be provided.

Soil surface boundary conditions

Two soil surface boundary conditions are normally encountered under field conditions: 1) the water head boundary condition and 2) the water flux boundary condition.

Water head boundary condition

This condition is used when water ponding, of some height h above the soil surface, is encountered. The height h may be considered as a variable with time, i.e. $h(t)$, in order to allow for fluctuations during wastewater application and rainfall:

$$h = h_0(t), \quad \text{at} \quad z = 0 \quad (3)$$

This boundary condition is also used when the soil surface is under suction, i.e. the water content at the surface is below saturation. In such case, $h(t)$ is negative and is a measure of the soil water suction (negative pressure) at the soil surface.

Water flux boundary condition

This condition is imposed when a constant or time-dependent flux (or intensity) $q(t)$ of wastewater (or rainfall) is applied at the soil surface. It also allows for evaporation between rainfall or irrigation events. This condition can be written as

$$q(t) = -K(h) \partial h/\partial z + K(h), \quad \text{at} \quad z = 0 \quad (4)$$

Bottom boundary conditions

At some depth L below the soil surface, three boundary conditions may be encountered: 1) an impervious barrier, 2) a soil profile extending to great depth, and 3) a groundwater table.

Impervious barrier

This boundary condition is used when an impermeable layer (e.g. a heavy clay layer) is encountered at some soil depth. Water flow across such a barrier is negligible. The boundary condition for an impervious barrier may be expressed as

$$-K(h) \partial h/\partial z + K(h) = 0, \quad \text{at} \quad z = L. \quad (5)$$

Soil profile extends to a great depth

In this case, the soil profile is regarded as a semi-infinite medium. Thus, it is assumed that at great depth the change in soil water suction is zero:

$$\partial h/\partial z = 0, \quad z \rightarrow \infty. \quad (6)$$

Such a boundary condition may be used if the soil profile is well-drained and of significant depth.

Groundwater table

If a water table is encountered at some depth L in the soil profile, the water content θ is maintained at saturation θ_s at all times. Therefore,

$$\theta = \theta_s, \quad z = L, \quad t > 0. \quad (7)$$

Furthermore, the soil water suction or pressure head is

$$h = 0, \quad z = L, \quad t > 0 \quad (8)$$

In addition to the above-mentioned boundary conditions, other conditions are needed in order to describe the water flow at the interface between soil layers in multilayered or stratified soil profiles. For example, we may consider a soil profile consisting of three soil layers: I, II, and III. The length of each soil layer is indicated by L_1 , L_2 , and L_3 (see Fig. 2). The appropriate boundary conditions at the interface between two soil layers are (Selim 1978).

$$h_I = h_{II}, \quad z = L_1, \quad t > 0, \quad (9)$$

$$h_{II} = h_{III}, \quad z = L_1 + L_2, \quad t > 0, \quad (10)$$

where h_I , h_{II} and h_{III} are the pressure heads in layers I, II, and III, respectively. These boundary conditions

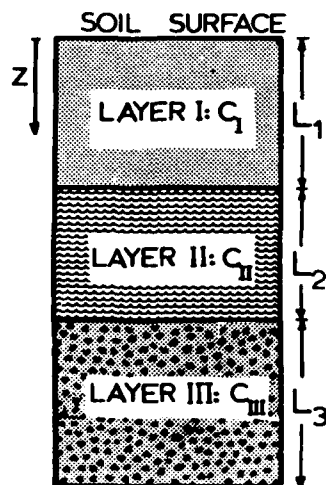


Figure 2. Schematic diagram of a multilayered soil profile.

are necessary in order to maintain the continuity of the pressure head h at the boundary interfaces.

Nitrogen transformations and transport equations and boundary conditions

In the development of this simplified model, three major approximations have been made. The first simplification is that the nitrification process was considered as a single step, i.e. $\text{NH}_4^+ \rightarrow \text{NO}_3^-$ rather than a two-step process ($\text{NH}_4^+ \rightarrow \text{NO}_2^- \rightarrow \text{NO}_3^-$). Such an assumption is considered adequate, since NO_2^- in most soils under neutral pH conditions is rapidly oxidized to NO_3^- . The second major simplification is that the organic-N phase was not incorporated in the model. It was assumed that the net change (over a short period of time) in organic-N content is small and the rate of nitrogen mineralization as well as immobilization are extremely slow. The third simplification is that oxygen diffusion in the soil profile was not incorporated. Therefore, denitrification of nitrate in the soil was assumed to be a function of the degree of soil water saturation only.

The nitrogen transformation processes considered were: nitrification of NH_4^+ to NO_3^- , denitrification of NO_3^- , and ion exchange of NH_4^+ (see Fig. 3). The ion-exchange process was assumed to be instantaneous, whereas nitrification and denitrification processes were of the first-order kinetic type (Selim et al. 1976 and Selim and Iskandar 1978). A distribution coefficient

K_D (cm^3/g) was used to describe the instantaneous (reversible) ammonium release from exchange sites to soil solution. The first-order kinetic rate coefficients associated with the nitrification and denitrification processes were k_1 and k_2 (h^{-1}), respectively. The assumptions that these nitrogen transformation processes follow first-order kinetic reaction were based on studies by McLaren (1970, 1971), Mehran and Taji (1974), and Hagin and Amberger (1974).

Soil environmental conditions such as soil suction, aeration, temperature, organic matter content, and pH have significant effects on the various nitrogen transformation mechanisms. In order to incorporate these factors, the rate coefficients were expressed (Selim et al. 1976) as

$$k_1 = \bar{k}_1 f_1, \quad (11)$$

$$k_2 = \bar{k}_2 f_2, \quad (12)$$

where $\bar{k}_1$ and $\bar{k}_2$ are considered constants for each individual soil layer and f_1 and f_2 are empirical functions which describe the influence of the previously mentioned environmental conditions on nitrification and denitrification, respectively.

The transport of $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ in the soil solution occurs as a result of molecular diffusion, mechanical dispersion, and convection or mass flow. Molecular diffusion results from the random thermal movement of molecules, whereas mechanical dispersion results from the velocity distribution of water in the soil pore space. For all soil layers, a single dispersion coefficient D is commonly used which combines mechanical dispersion and diffusion. Therefore, the convective-dispersive equations governing $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ transport may be expressed (Misra et al. 1974, Davidson et al. 1977, and Selim and Iskandar 1978) as

$$\begin{aligned} \partial(\theta C)/\partial t = & (\partial/\partial z) (\theta D \partial C/\partial z) - \partial(\nu C)/\partial z \\ & - \theta k_1 C - \rho \partial S/\partial t - q_{\text{NH}_4} \end{aligned} \quad (13)$$

$$\begin{aligned} \partial(\theta Y)/\partial t = & (\partial/\partial z) (\theta D \partial Y/\partial z) - \partial(\nu Y)/\partial z \\ & + \theta k_1 C - \theta k_2 Y - q_{\text{NO}_3} \end{aligned} \quad (14)$$

where C = concentration of $\text{NH}_4\text{-N}$ in soil solution ($\mu\text{g}/\text{cm}^3$)

Y = concentration of $\text{NO}_3\text{-N}$ in soil solution ($\mu\text{g}/\text{cm}^3$)

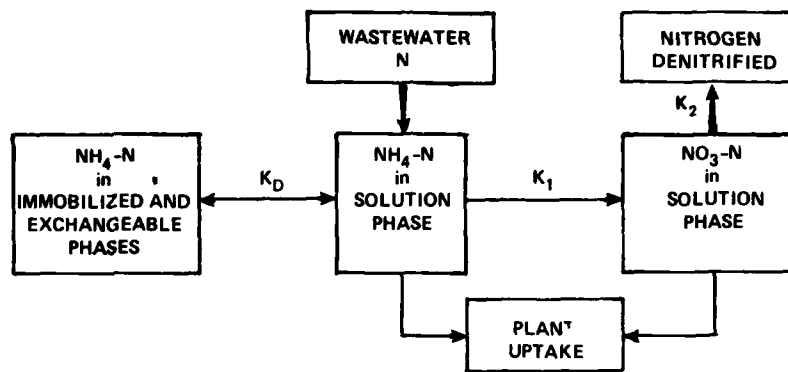


Figure 3. Schematic diagram of the nitrogen transformation processes considered in the nitrogen submodel.

D = solute dispersion coefficient (cm^2/h)

ν = soil water flux (cm/h)

S = amount of NH_4 in the exchangeable phase per gram of soil ($\mu\text{g}/\text{g}$)

ρ = soil bulk density (g/cm^3)

k_1 and k_2 = kinetic rate coefficients for nitrification and denitrification (h^{-1}), respectively

q_{NH_4} and q_{NO_3} = rates of plant uptake of NH_4 -N and NO_3 -N per unit soil volume ($\mu\text{g}/\text{cm}^3 \text{ h}$), respectively.

The first two terms on the right-hand side of eq 13 and 14 account for solute transport, and are usually called the dispersion and mass flow terms, respectively. The third and fourth terms of eq 13 account for nitrification and ion exchange, respectively, of NH_4 -N. Similarly, the third and fourth terms of eq 14 represent the nitrification and denitrification processes, respectively. The ion exchange process governing NH_4 -N adsorption-desorption was assumed to be of the linear Freundlich type, i.e.

$$S = K_D C, \text{ or } \partial S / \partial t = K_D \partial C / \partial t, \quad (15)$$

where K_D , commonly called the distribution coefficient (cm^3/g), represents the ratio between the amount of NH_4 -N adsorbed and its concentration in the soil solution.

Rearrangements of eq 13 and incorporation of eq 15 yield the following simplified equation for ammonium transport and transformation:

$$R \partial C / \partial t = D \partial^2 C / \partial z^2 - (V/\theta) \partial C / \partial z - k_1 C - (q_{\text{NH}_4}/\theta) \quad (16)$$

where R is the retardation factor for ammonium exchange:

$$R = 1 + \rho K_D / \theta. \quad (17a)$$

and V is expressed as

$$V = \nu - D \partial \theta / \partial z. \quad (17b)$$

Similarly, eq 14 after rearrangements yields the following equation for nitrate transport and transformations:

$$\partial Y / \partial t = D \partial^2 Y / \partial z^2 - (V/\theta) \partial Y / \partial z + k_1 C - k_2 Y - (q_{\text{NO}_3}/\theta). \quad (18)$$

It should be noted that in the case of multilayered soil profiles, soil water and nitrogen transformation parameters (e.g. ρ , $K(h)$, K_D , k_1 , k_2 , etc.) must be provided for each individual soil layer.

To solve the ammonium and nitrate transport and transformation equations, eq 16 and 18, the initial and boundary conditions must be specified. During wastewater application, the soil surface boundary conditions for eq 16 and 18, respectively, are:

$$\nu C_s = -\theta D \partial C / \partial z + \nu C, \quad z = 0, \quad t < T, \quad (19)$$

and

$$\nu Y_s = -\theta D \partial Y / \partial z + \nu Y, \quad z = 0, \quad t < T, \quad (20)$$

where

C_s and Y_s = $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ concentrations in applied wastewater, respectively ($\mu\text{g N/ml}$)
 $\nu = q(t)$, flux or intensity of wastewater application (cm/h)
 T = duration of wastewater application (h).

The above equations, eq 19 and 20, are commonly called the dispersive-convective boundary conditions which can also be applied to describe rainfall events. In such a case, the intensity and duration of rainfall (ν and T) must be specified and C_s and Y_s in rainwater may be considered zero.

Following the termination of a wastewater application or rainfall event ($t > T$), the surface boundary conditions become

$$\partial C / \partial z = 0, \quad z = 0, \quad t > T \quad (21)$$

and

$$\partial Y / \partial z = 0, \quad z = 0, \quad t > T \quad (22)$$

Furthermore, the boundary condition at the bottom of the soil profile ($z = L$) is

$$\partial C / \partial z = 0, \quad z = L, \quad t > 0 \quad (23)$$

$$\partial Y / \partial z = 0, \quad z = L, \quad t > 0 \quad (24)$$

In addition, the boundary conditions at the boundary interface between two soil layers (see Fig. 2) may be written as

$$C_I = C_{II} \text{ and } Y_I = Y_{II}, \quad z = L_1, \quad t > 0 \quad (25)$$

$$C_{II} = C_{III} \text{ and } Y_{II} = Y_{III}, \quad z = L_1 + L_2, \quad t > 0 \quad (26)$$

where the subscripts I, II, and III refer to the first, second, and third soil layers, respectively. Similar to the equations for water flow, eq 25 and 26 above are needed in order to maintain the continuity of $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ concentrations at the boundary interface.

Water and nitrogen uptake by plants

Plant uptake of water and nitrogen from the soil root zone is an important factor in the renovation of wastewater applied to soil. Recent studies have shown that in a slow infiltration land treatment system, a major portion of applied wastewater nitrogen (up to 70%) was taken up by plants (Iskandar et al. 1976). Therefore in modeling the fate of nitrogen in soil, it is important to incorporate a plant uptake model that provides accurate predictions of the rate of plant uptake during the growing season. However, as Nye and Tinker (1977) pointed out, the major difficulties in modeling of plant uptake are the lack of quantitative measurements on the root development and distribution as well as the inaccuracy of soil physical measurements.

At present there are two approaches for modeling plant root uptake of water and nutrients in soils: 1) a "microscopic" approach where the water and nutrient flux to a single root is considered (Nye and Marriot 1969, Claassen and Barber 1976), and 2) a "macroscopic" approach where the root system as a whole is considered (Molz and Remson 1970, Davidson et al. 1977, Selim and Iskandar 1978). In this simplified model the macroscopic approach is used to describe the water as well as the nitrogen uptake by plant roots. The extraction or sink term $A(z, \theta)$ for water uptake (eq 1) is represented as

$$A(z, \theta) = T R(z) K(h) / \int_0^Z R(z) K(h) dz \quad (27)$$

where Z is the maximum depth of the root zone in the soil (cm) and T the evapotranspiration rate per unit area of soil surface (cm/h). The term $R(z)$ is the root distribution as a function of depth in the soil profile. Specifically the root distribution $R(z)$ is the length of roots (cm) as a function of soil depth and time. Equation 27 was proposed by Molz and Remson (1970) and was successfully used in predicting the water uptake when the evapotranspiration rate T was met. Such conditions are satisfied when high soil water contents (low suctions) are maintained in the soil root zone, such as in land treatment-slow infiltration systems.

The terms q_{NH_4} and q_{NO_3} in eq 16 and 18 account for the rate of uptake of $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$, respectively. Here the Michaelis-Menten approach was used to determine the rate of N uptake as a function of root density and concentration of ammonium and nitrate in the soil solution. Therefore the rate of N uptake may be expressed as:

$$q_{\text{NH}_4} = I_{\text{max}} C / [K_m + (C + Y)] \quad (28)$$

$$q_{\text{NO}_3} = I_{\text{max}} Y / [K_m + (C + Y)] \quad (29)$$

In eq 28 and 29, I_{max} is the maximum rate of N uptake per unit root length ($\mu\text{g/h cm}$) when the concentration of nitrogen in the soil solution is extremely high, and the term K_m is the Michaelis constant ($\mu\text{g/ml}$) which is the concentration of N at $1/2 I_{\text{max}}$. Both I_{max} and K_m are determined by measuring N uptake in solution cultures having different nitrogen concentrations (Claassen and Barber 1976). In this model the values of I_{max} and K_m were considered similar for both ammonium and nitrate uptake*.

Method of model solution

The water and nitrogen equations (eq 1, 16 and 18) are nonlinear partial differential equations and cannot be solved analytically. Therefore, these equations, subject to the above described initial and boundary conditions, were solved using numerical analysis techniques. The method of solution was by explicit-implicit finite difference approximation (Menrici 1962, Varga 1962, and Carnahan et al. 1969). This method was successfully used by Selim (1978) for transient water and solute movement in multilayered soil profiles. Finite difference approximations provide distributions of soil water content, water suction, $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ concentrations at incremental distances Δz in the soil profile, and discrete time steps Δt . In finite difference form, a variable such as h is expressed as $h_i^n = h(z, t) = h(i\Delta z, n\Delta t)$ where $i = 1, 2, 3, \dots, I$, and $n = 1, 2, \dots$. Therefore, the finite difference approximation for the water flow equation (eq 1) is

$$\begin{aligned} \text{Cap}(h_i^{n+1/2}) [h_i^{n+1} - h_i^n] &= \gamma K(h_{i+1/2}^{n+1/2}) [h_{i+1}^{n+1} - h_{i-1}^{n+1}] \\ &\quad - \gamma K(h_{i-1/2}^{n+1/2}) [h_i^{n+1} - h_{i-1}^{n+1}] \\ &\quad + \gamma K(h_{i+1/2}^{n+1/2}) [h_{i+1}^n - h_i^n] \\ &\quad - \gamma K(h_{i-1/2}^{n+1/2}) [h_i^n - h_{i-1}^n] \\ &\quad - \beta [K(h_{i+1/2}^n) + K(h_{i-1/2}^n)] - \Delta t A_i^n \end{aligned} \quad (30)$$

where $\gamma = \Delta t / 2(\Delta z)^2$ and $\beta = \Delta t / \Delta z$. Similarly, finite difference approximations for the equation governing

$\text{NH}_4\text{-N}$ transport and transformation (eq 16) may be expressed as

$$\begin{aligned} R_i^{n+1} [C_i^{n+1} - C_i^n] &= \gamma D [C_{i+1}^{n+1} - 2C_i^{n+1} + C_{i-1}^{n+1}] \\ &\quad + \gamma D [C_{i+1}^n - 2C_i^n + C_{i-1}^n] \\ &\quad - (V/\theta)_i^{n+1} \beta [C_{i+1}^{n+1} - C_i^{n+1}] \\ &\quad - \Delta t k_1 C_i^n - \Delta t (q_{\text{NH}_4}/\theta)_i^n \end{aligned} \quad (31)$$

and the finite difference approximation for $\text{NO}_3\text{-N}$ (eq 18) is

$$\begin{aligned} Y_i^{n+1} - Y_i^n &= \gamma D [Y_{i+1}^{n+1} - 2Y_i^{n+1} + Y_{i-1}^{n+1}] \\ &\quad + \gamma D [Y_{i+1}^n - 2Y_i^n + Y_{i-1}^n] \\ &\quad - (V/\theta)_i^{n+1} \beta [Y_{i+1}^{n+1} - Y_i^{n+1}] \\ &\quad + \Delta t k_1 C_i^n - \Delta t k_2 Y_i^n - \Delta t (q_{\text{NO}_3}/\theta)_i^n \end{aligned} \quad (32)$$

Equations 30, 31, and 32 are nonlinear since $\text{Cap}(h_i^{n+1/2})$ and $K(h_i^{n+1/2})$ are dependent on $h_i^{n+1/2}$ for which solutions are being sought. The iteration method described by Remson et al. (1971) is usually used to predict $h^{n+1/2}$ using h^n . Selim and Kirkham (1973) showed that solution of the water flow equation can be approximated satisfactorily using h^n when smaller values of Δt than required for stable solution are used. This simplifies the computation considerably since the system of equations becomes linear. Accordingly, the approximations, $K(h_i^{n+1/2}) = K(h_i^n)$ and $\text{Cap}(h_i^{n+1/2}) = \text{Cap}(h_i^n)$, were made.

Incorporation of initial and boundary conditions in their finite difference forms and rearrangement of eq 30, 31, and 32 yield three linear systems of equations. Rearranging the finite difference form of water flow equation (eq 30) yields

$$d_i^n h_{i-1}^{n+1} + e_i^n h_i^{n+1} + g_i^n h_{i+1}^{n+1} = w_i^n \quad (33)$$

where

$$\begin{aligned} d_i^n &= -\gamma K(h_{i-1/2}^n) \\ e_i^n &= \text{Cap}(h_i^n) + \gamma [K(h_{i+1/2}^n) + K(h_{i-1/2}^n)] \\ g_i^n &= -\gamma K(h_{i+1/2}^n) \\ w_i^n &= \text{Cap}(h_i^n) h_i^n + \gamma K(h_{i-1/2}^n) h_{i-1}^n \\ &\quad - \gamma [K(h_{i+1/2}^n) + K(h_{i-1/2}^n)] h_i^n \\ &\quad + \gamma K(h_{i+1/2}^n) h_{i+1}^n \end{aligned}$$

*S.A. Barber, Department of Agronomy, Purdue University, personal communication 1979.

$$-\beta [K(h_{i+1/2}^n) + K(h_{i-1/2}^n)] - \Delta t A_i^n.$$

By including the initial and boundary conditions in their finite difference forms, eq 33 can be written in matrix-vector notation as

$$B \vec{h}^{n+1} = \vec{w} \quad (34)$$

where B is a tridiagonal real matrix and $\vec{h}$ and $\vec{w}$ denote the associated real column vectors (the arrows indicate vectors). The matrix B may be written as

$$B \equiv \begin{bmatrix} e_1^n g_1^n & & & & \\ d_2^n e_2^n g_2^n & & & & \\ & d_3^n e_3^n g_3^n & & & \\ & & \dots & & \\ & & & \dots & \\ & & & & d_{l-1}^n e_{l-1}^n g_{l-1}^n \\ & & & & d_l^n e_l^n g_l^n \end{bmatrix} \quad (35)$$

The coefficients of the main diagonal of the matrix B , in absolute values, are greater than the raw sum of the off-diagonal coefficients. Hence, the matrix B is strictly diagonally dominant (Varga 1962, p. 23). Therefore the matrix is nonsingular, and there exists a solution $\vec{h}^{n+1}$ for the matrix vector equation (eq 34) that is unique. The tridiagonal system of equations was solved by an adaptation of the Gaussian algorithm as described by Henrici (1962, p. 352). The second and third systems of eq 31 and 32 for $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ transport and transformation, respectively, were solved similarly.

It is obvious from eq 16 and 18 that nitrogen transport is dependent on θ and ν , both of which are variable under transient flow conditions. Thus, in order to describe nitrogen transport for transient conditions, the water flow equation (eq 1) must be solved prior to the nitrogen transformation and transport equations. Therefore, for any time step, $n+1$, where all variables are assumed to be known at time step n , eq 30, 31, and 32 are solved sequentially until a desired time t is reached.

MODEL SENSITIVITY

In order to provide a complete sensitivity analysis of model parameters, it is essential to investigate each parameter separately. This is usually achieved by first studying the influence of each parameter on model results for a wide range of values, with all other parameters remaining unchanged. Second, when two or

more parameters prove to be more significant compared to other model parameters, such two or more parameters are investigated simultaneously for a range of values. For the model presented here a complete sensitivity analysis was not attempted since a large number of model parameters were involved. Therefore, it was decided to study only selected parameters which were chosen for sensitivity analysis. These parameters are 1) the rate of nitrification (k_1), 2) the distribution coefficient (K_D) for $\text{NH}_4\text{-N}$ ion-exchange, and 3) rate of plant uptake ($I_{\max}$). The influence of different nitrogen transformation parameters for individual soil layers and the rate of denitrification were not investigated. Moreover, soil water properties, schedule of wastewater application and $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ concentrations in the wastewater remained unchanged for all cases studied.

The simultaneous transport, transformation, and plant uptake of nitrogen and water were simulated using the model presented here. Input soil and water parameters, initial and boundary conditions, etc., were similar to those of the CRREL research experimental facilities. Wastewater was assumed to contain 25 $\mu\text{g}/\text{ml}$ of $\text{NH}_4\text{-N}$ and zero nitrate content. The schedule of application was 0.5 or 1 week and the total amount of wastewater applied was 5 cm per each application. The soil parameters chosen were for a Windsor sandy loam soil having three distinct soil layers. Chemical characteristics of this soil are presented elsewhere (Iskandar et al. 1979, Iskandar and Nakano 1978). The total length of the soil profile was assumed to be 150 cm and the thicknesses of the first, second and third layers were 15, 30 and 105 cm, respectively. A water table (zero water pressure head) was assumed at the bottom (150 cm depth) of the soil profile. The soil water properties for each soil layer were described by the following mathematical expressions:

$$\theta(h) = \theta_s / [1 + (-h/a)^b] \quad (36)$$

$$K(\theta) = \eta \exp(\alpha\theta). \quad (37)$$

The parameters for each soil layer were obtained by "best fit" of experimental data (Iskandar and Nakano 1978). The values of a and b were 100 and 1 for the first layer, 40 and 1 for the second layer, and 30 and 1 for the third layer, respectively. The values for parameters η and α were 9.6×10^{-4} and 27.63 for the first layer, 2.2×10^{-4} and 30.7 for the second layer, and 2.1×10^{-4} and 38.87 for the third layer, respectively. The values for water content at saturation θ_s were 0.44, 0.42 and 0.34 (cm^3/cm^3) for the first, second and third layers, respectively. Furthermore, the values for

soil bulk density ρ were 1.41 for the first layer, 1.59 for the second layer, and 1.55 g/cm³ for the third layer.

Several nitrogen transformation rate coefficients and uptake rates were chosen in order to illustrate the significance of these processes on the fate of wastewater nitrogen in land treatment systems. The rate of nitrification $\bar{k}_1$ ranged from 0.025 to 0.5 h⁻¹ whereas $\bar{k}_2$ was maintained constant at 0.01 h⁻¹. For the nitrification kinetic reaction, the function f_1 (eq 1) which describes the dependence of the reaction on soil environmental conditions remained unchanged and was expressed as a function of pressure head (Hagin and Amberger 1974):

$$f_1 = \begin{cases} 0 & h > -10 \text{ cm} \\ 0.005 (-h-10) & h > -50 \text{ cm} \\ 0.2+0.006 (-h-40) & h > -100 \text{ cm} \\ 0.5+0.0015 (-h-100) & h > -433 \text{ cm} \\ 1.0-0.002 (-h-433) & h < -433 \text{ cm.} \end{cases}$$

The denitrification function f_2 (eq 12) was considered as a function of the degree of water saturation in the soil:

$$f_2 = \begin{cases} 0 & \text{for } (\theta/\theta_s) < 0.8 \\ (\theta-0.8\theta_s)/0.1\theta_s & \text{for } 0.8 < \theta/\theta_s < 0.9 \\ 1 & \text{for } \theta/\theta_s > 0.9 \end{cases}$$

where θ_s is soil water content at saturation (cm³/cm³). Furthermore, the value of the coefficient K_D for the ammonium exchange ranged from 0.05 to 1.5 cm³/g. All these parameters, for the cases shown here, were similar for all three soil layers.

The root distribution $R(z)$ used in the sensitivity analysis was in the form of an exponential expression:

$$R(z) = 226 \exp (-0.1 z)$$

This exponential function provides a sharp decrease of the root distribution (or density) with soil depth z . In this case, 77.8% of the roots were actually observed to be in the top 15 cm, 17.2% in the 15- to 30-cm soil depth and only 5% of the roots in the 30- to 60-cm soil depth. This mathematical expression for root distribution was obtained from field measurements of root length with depth (Iskandar unpublished data 1979). It represents a two-year-old mixture of reed canary-grass and tall fescue grass irrigated with 5 cm of wastewater weekly. Furthermore, a value of 1.0 ppm for the Michaelis constant K_m was chosen for all cases presented here. Values of $I_{\max}$ ranged from 0.0005 to 0.0015 $\mu\text{g N/h cm}$ of roots.

In order to illustrate the capabilities of this model, simulated water content and nitrogen distributions in

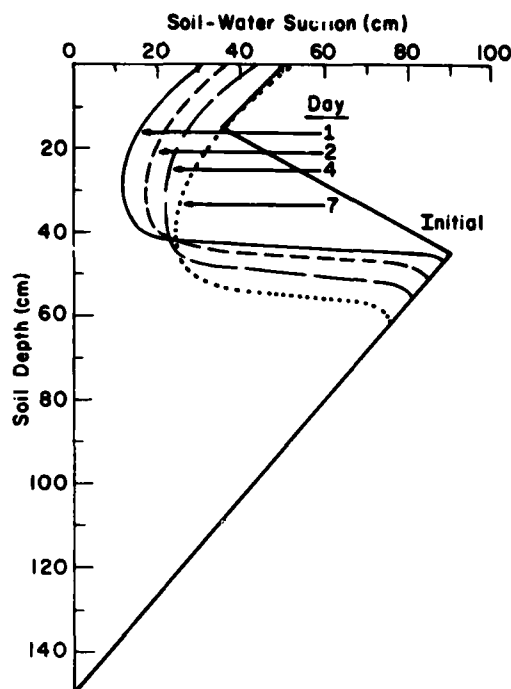


Figure 4. Simulated soil water suction distributions in a Windsor soil for one week following application of 5 cm of wastewater

the soil are presented in Figures 4, 5 and 6 for one week following the application of 5 cm of wastewater. In this case the rate coefficients for nitrification $\bar{k}_1$ were taken as 0.1 h⁻¹ and K_D as 0.25 cm³/g. Following the application of 5 cm of wastewater, which contained 25 ppm of NH₄-N, we see that NH₄-N concentration in the soil solution decreased drastically with time. This disappearance of NH₄-N was due to its conversion to NO₃-N through nitrification and to uptake by plants. The NO₃-N distributions shown in Figure 6 show that the maximum peak concentration occurred on day 1. This is primarily due to the initial NO₃-N in the soil profile. Furthermore, the initial peak, which was located at the 15-cm depth, penetrated to a depth of 35 cm during the first day. Downward movements of the nitrate peak to lower soil depths continued with time at a decreasing rate. This slow movement of nitrate in the soil profile was due to the continuing decrease of soil water flow during water redistribution, i.e. following the infiltration of applied wastewater. Meanwhile, the nitrate concentration of the leachate ($z = 150$ cm) continued to increase with time.

Figure 7 shows the cumulative nitrogen uptake by plants with time during weekly application of wastewater. Simulated results show that NH₄-N uptake was much greater than that for NO₃-N at all times. This

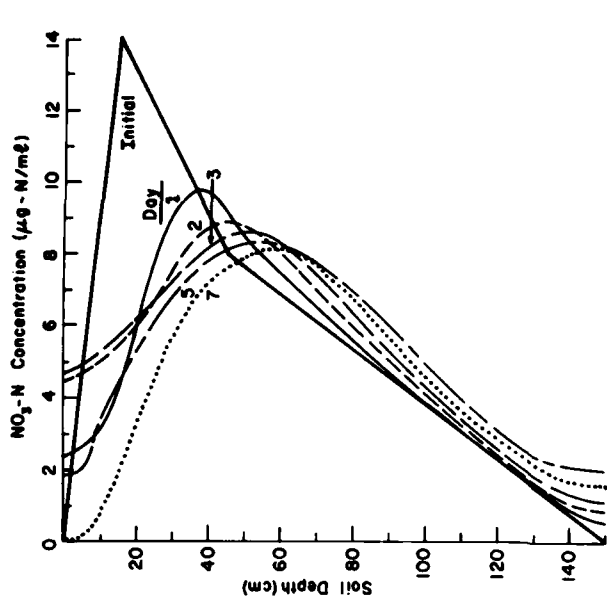


Figure 6. Simulated $\text{NO}_3\text{-N}$ distributions for one week following wastewater application and for $\bar{k}_1 = 0.1 \text{ h}^{-1}$, $K_D = 0.25 \text{ cm}^3/\text{g}$ and $I_{\text{max}} = 0.001 \text{ µg N/h cm}$.

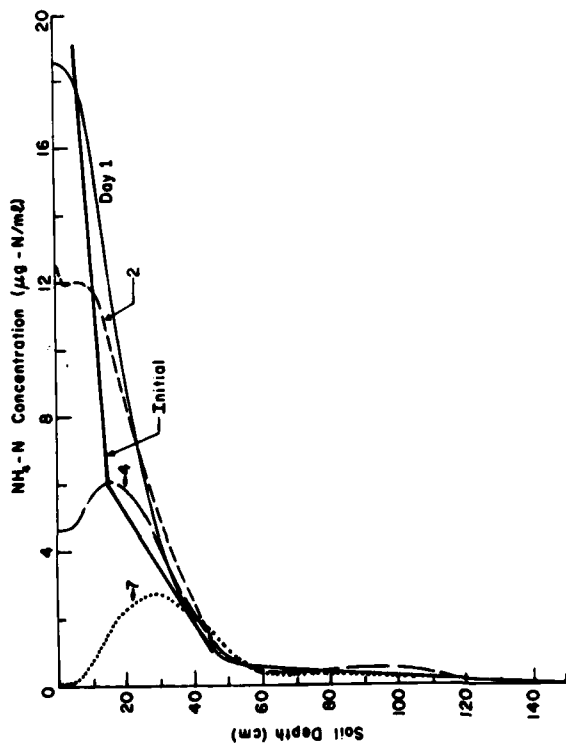


Figure 5. Simulated $\text{NH}_4\text{-N}$ distributions for one week following wastewater application and for $\bar{k}_1 = 0.1 \text{ h}^{-1}$, $K_D = 0.25 \text{ cm}^3/\text{g}$ and $I_{\text{max}} = 0.001 \text{ µg N/h cm}$.

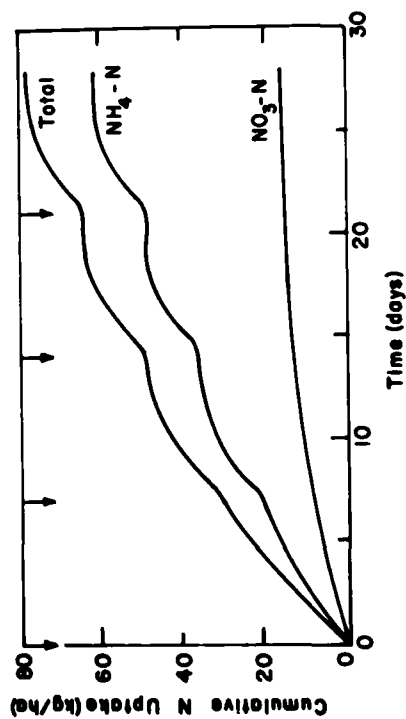


Figure 7. Cumulative $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ uptake with time for $I_{\text{max}} = 0.001 \text{ µg N/h cm}$. Arrows indicate wastewater applications events.

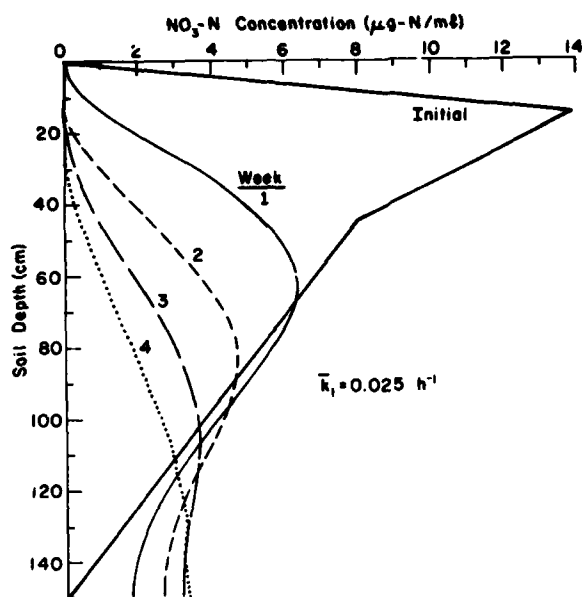


Figure 8. Simulated concentration distributions of $\text{NO}_3\text{-N}$ in the soil profile where weekly application of 5 cm of wastewater was maintained. Model parameters were $k_1 = 0.025 \text{ h}^{-1}$, $K_D = 0.25 \text{ cm}^3/\text{g}$ and $I_{\text{max}} = 0.001 \text{ } \mu\text{g N/h cm}$.

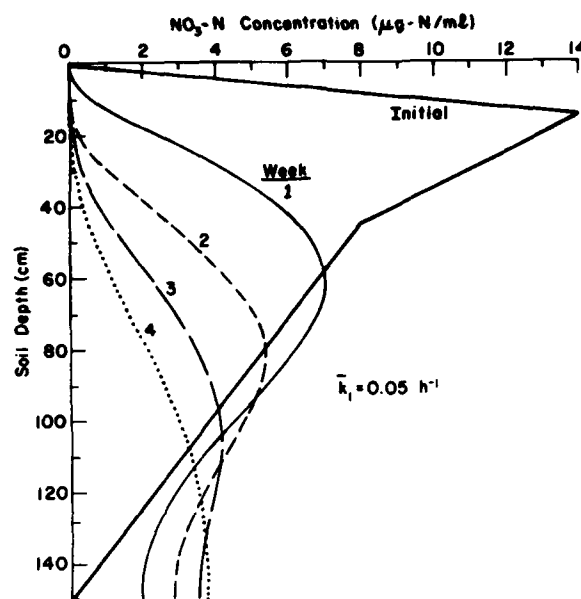


Figure 9. Simulated concentration distributions of $\text{NO}_3\text{-N}$ in the soil profile where weekly application of 5 cm of wastewater was maintained. Model parameters were $k_1 = 0.05 \text{ h}^{-1}$, $K_D = 0.25 \text{ cm}^3/\text{g}$ and $I_{\text{max}} = 0.001 \text{ } \mu\text{g N/h cm}$.

is due to the low concentration of $\text{NO}_3\text{-N}$ in the top portion of the soil profile for an extended period of time. In contrast, the $\text{NH}_4\text{-N}$ remained at shallow soil depth due to ion-exchange which resulted in higher $\text{NH}_4\text{-N}$ uptake. It should be noted that in the simulation, 77.8% of plant roots were in the top 15 cm of the soil profile.

Figures 8-12 show the influence of changing the nitrification rate coefficients k_1 on the nitrate distribution in the soil profile during weekly application of wastewater. In the cases considered, the values of k_1 range from 0.025 to 0.5 h^{-1} , whereas K_D and I_{max} remained constant ($K_D = 0.25 \text{ cm}^3/\text{g}$ and $I_{\text{max}} = 0.001 \text{ } \mu\text{g N/h cm}$). The simulated results show that as the rate of nitrification increased, the maximum peak concentration also increased at the end of the weekly wastewater applications. These increases in peak concentrations were obviously due to the imposed increase in faster conversion of $\text{NH}_4\text{-N}$ to $\text{NO}_3\text{-N}$ in the soil. Furthermore, maximum peak concentrations were located at shallower soil depths as k_1 increased. The location of the peak closer to the soil surface coincides with that for $\text{NH}_4\text{-N}$. The simulated results also show that the rate of nitrification directly influences the effluent concentration (at $z = 150 \text{ cm}$). As expected, the effluent $\text{NO}_3\text{-N}$ concentration (at any particular time) increased

as the rate of nitrification increased.

Figure 13 shows the effect of changing the rate of nitrification on the total amounts of $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ in the soil profile during weekly wastewater application. These simulated results were obtained by integrating the nitrogen concentration profiles shown in Figures 8-12. As expected, as the rate of $\text{NH}_4\text{-N}$ conversion to $\text{NO}_3\text{-N}$ increased, the total amount of $\text{NH}_4\text{-N}$ in the soil profile decreased and the total amount of $\text{NO}_3\text{-N}$ in the soil profile increased. It should also be emphasized here that the relationship between N in the soil profile and k_1 (Fig. 13) is a nonlinear one. This is clearly shown by the leveling of the curves for k_1 greater than 0.2 h^{-1} . Such leveling of the curves indicates that, for the cases considered, the influence of k_1 on the fate of nitrogen is negligible for $k_1 > 0.2 \text{ h}^{-1}$. Therefore, it is expected that beyond such k_1 values, other factors which affect the amount of $\text{NH}_4\text{-N}$ in the soil profile (such as the rate of N uptake, the ion-exchange of $\text{NH}_4\text{-N}$, and the amount of weekly wastewater applied) will influence the $\text{NO}_3\text{-N}$ in the soil profile. For example, if the amount of weekly wastewater were 50 rather than 25 ppm, it would be reasonable to expect that the leveling will be at a higher k_1 value than 0.2 h^{-1} . The opposite would be true for a reduced rate of plant uptake.

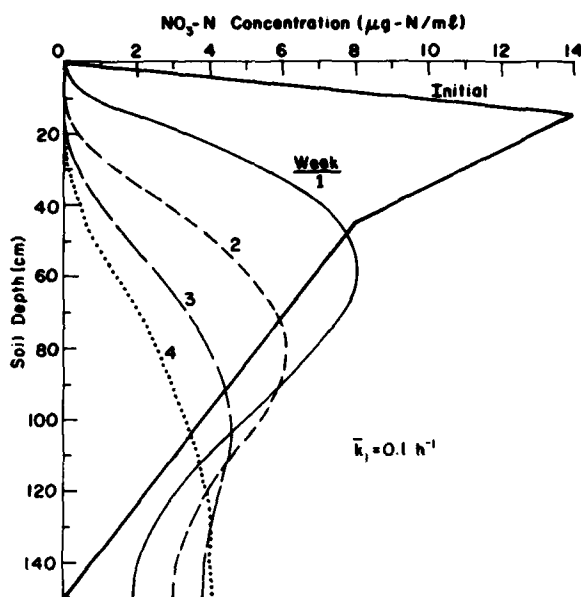


Figure 10. Simulated concentration distributions of $\text{NO}_3\text{-N}$ in the soil profile where weekly application of 5 cm of wastewater was maintained. Model parameters were $k_1 = 0.1 \text{ h}^{-1}$, $K_D = 0.25 \text{ cm}^3/\text{g}$ and $l_{\text{max}} = 0.001 \text{ } \mu\text{g N/h cm}$.

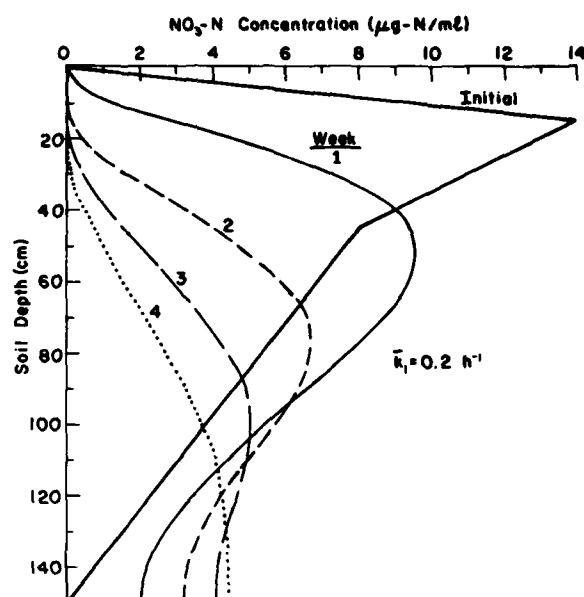


Figure 11. Simulated concentration distributions of $\text{NO}_3\text{-N}$ in the soil profile where weekly application of 5 cm of wastewater was maintained. Model parameters were $k_1 = 0.2 \text{ h}^{-1}$, $K_D = 0.25 \text{ cm}^3/\text{g}$ and $l_{\text{max}} = 0.001 \text{ } \mu\text{g N/h cm}$.

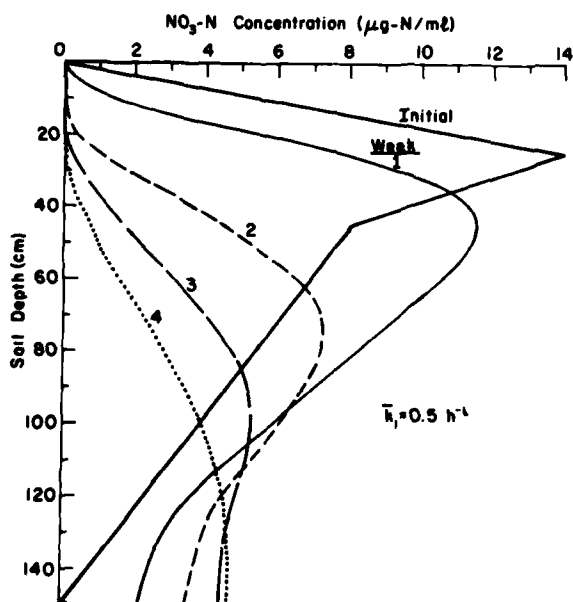


Figure 12. Simulated concentration distributions of $\text{NO}_3\text{-N}$ in the soil profile where weekly application of 5 cm of wastewater was maintained. Model parameters were $k_1 = 0.5 \text{ h}^{-1}$, $K_D = 0.05 \text{ cm}^3/\text{g}$ and $l_{\text{max}} = 0.001 \text{ } \mu\text{g N/h cm}$.

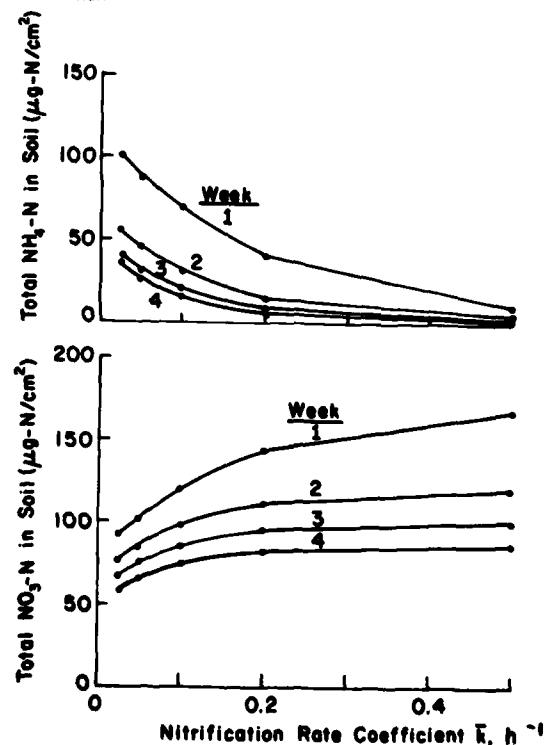


Figure 13. Nitrification rate coefficient k_1 vs total $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ in the soil profile.

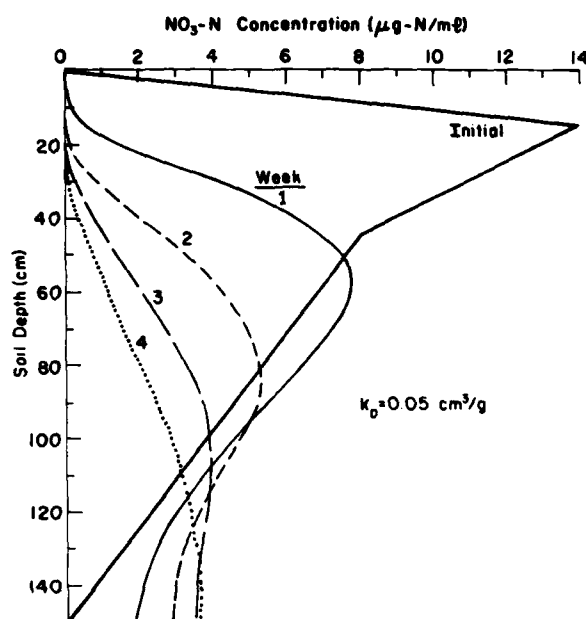


Figure 14. Simulated concentration distributions of $\text{NO}_3\text{-N}$ in the soil profile where weekly application of 5 cm of wastewater was maintained. Model parameters were $\bar{k}_1 = 0.1 \text{ h}^{-1}$, $K_D = 0.05 \text{ cm}^3/\text{g}$ and $I_{\max} = 0.001 \text{ } \mu\text{g N/h cm}$.

The influence of a range of K_D values on the fate of wastewater nitrogen is shown in Figures 14–16. The K_D values considered ranged from 0.05 to $1.5 \text{ cm}^3/\text{g}$ which simulates a wide range of soils having different cation exchange capacities. The $\bar{k}_1$ and $I_{\max}$ values remained constant ($\bar{k}_1 = 0.1 \text{ h}^{-1}$ and $I_{\max} = 0.001 \text{ } \mu\text{g-N/cm h}$) for these cases. For small values of K_D (Fig. 14), the nitrate concentration profiles showed a rapid movement in the soil profile. Such rapid nitrate leaching is a direct result of low $\text{NH}_4\text{-N}$ retardation in the soil profile. In contrast, for larger K_D values (Fig. 15 and 16), the retardation of $\text{NH}_4\text{-N}$ to transport in the soil profile was greater, resulting in slower movement of $\text{NO}_3\text{-N}$ in the soil profile. This slow movement of nitrate nitrogen is illustrated by the location of the peaks at shallow soil depths as well as higher peak concentrations.

The effect of $I_{\max}$, the maximum rate of N uptake, on the fate of nitrogen in the soil profile as well as the cumulative N uptake are shown in Figures 17–19. Here the range of $I_{\max}$ was from 0.005 to $0.0015 \text{ } \mu\text{g-N/h cm}$ of root length. All other parameters were constant: $\bar{k}_1 = 0.1 \text{ h}^{-1}$ and $K_D = 0.25 \text{ cm}^3/\text{g}$. As expected, for small values of $I_{\max}$ (Fig. 17), the $\text{NO}_3\text{-N}$ distributions show significantly higher concentrations than for large

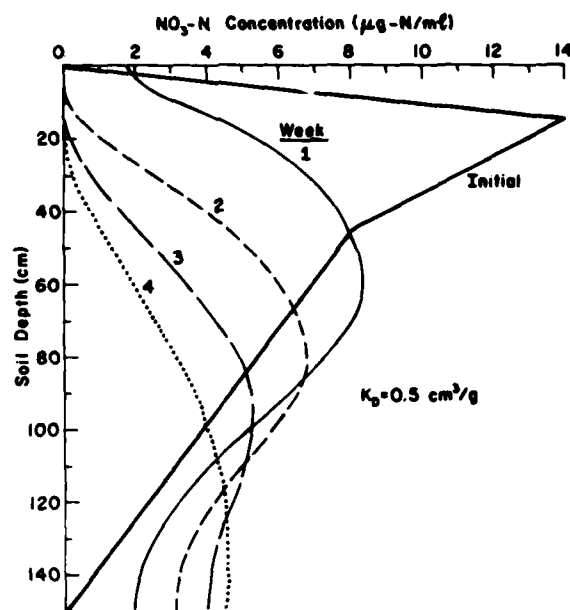


Figure 15. Simulated concentration distributions of $\text{NO}_3\text{-N}$ in the soil profile where weekly application of 5 cm of wastewater was maintained. Model parameters were $\bar{k}_1 = 0.1 \text{ h}^{-1}$, $K_D = 0.5 \text{ cm}^3/\text{g}$ and $I_{\max} = 0.001 \text{ } \mu\text{g N/h cm}$.

$I_{\max}$ values. Differences in concentration distributions are clearly shown in the upper portion of the soil profile. For $I_{\max} = 0.0015 \text{ } \mu\text{g N/h cm}$, plant uptake resulted in considerable depletion of the $\text{NO}_3\text{-N}$ in the root zone (0–30 cm). In contrast, considerable amounts of $\text{NO}_3\text{-N}$ remained in the top soil profile for the case $I_{\max} = 0.0005 \text{ } \mu\text{g-N/h cm}$. The cumulative nitrogen uptake patterns for different values (Fig. 19) show that for $I_{\max} = 0.005$ the uptake with time was linear. Such a linear relationship indicates a constant rate of nitrogen uptake with time. For this case, the maximum rate of nitrogen uptake was met, indicating an abundance of nitrogen in the soil root zone at all times. However, for large values of $I_{\max}$ the amount of nitrogen in the root zone was limited as indicated by the nonlinear uptake patterns for $I_{\max}$ of 0.001 and $0.0015 \text{ } \mu\text{g-N/h cm}$. Immediately following each weekly application, the simulated results also show a rapid increase in the nitrogen uptake as a result of the newly added nitrogen in the wastewater. However, three to four days after application of wastewater, when the nitrogen concentration in the root zone becomes small, the rate of uptake decreases drastically with time. This change of the rate of uptake with time is clearly illustrated in Figure 19 by the sudden increase followed by a leveling of the

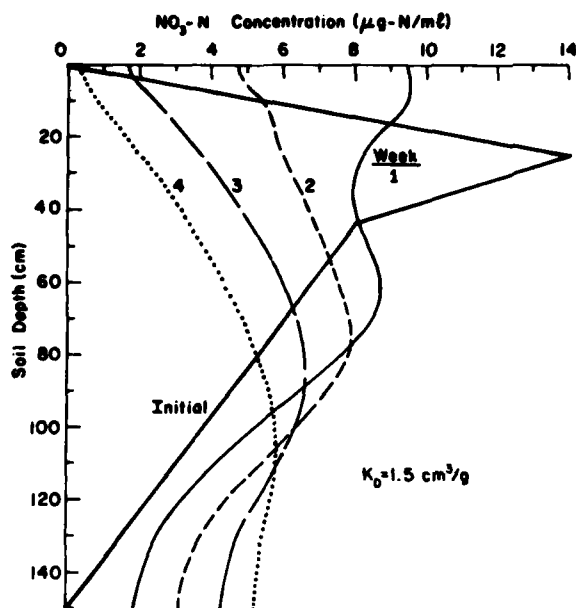


Figure 16. Simulated concentration distributions of $\text{NO}_3\text{-N}$ in the soil profile where weekly application of 5 cm of wastewater was maintained. Model parameters were $\bar{k}_1 = 0.1 \text{ h}^{-1}$, $K_D = 1.5 \text{ cm}^3/\text{g}$ and $I_{\max} = 0.001 \mu\text{g N/h cm}$.

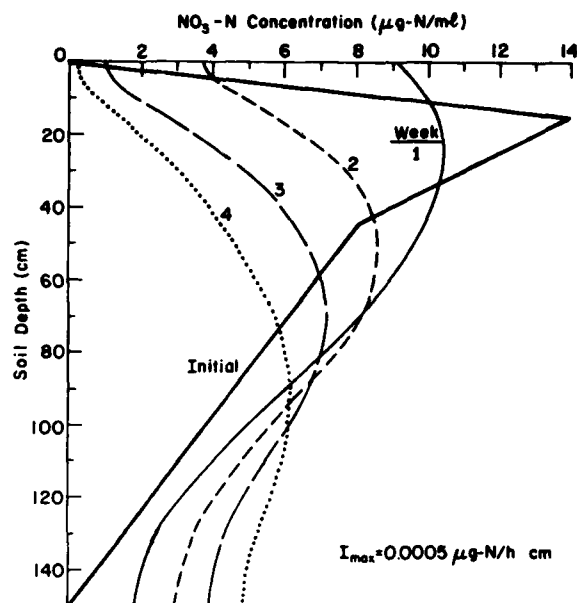


Figure 17. Simulated concentration distribution of $\text{NO}_3\text{-N}$ in the soil profile where $\bar{k}_1 = 0.1 \text{ h}^{-1}$, $K_D = 0.25 \text{ cm}^3/\text{g}$ and $I_{\max} = 0.0005 \mu\text{g N/h cm}$.

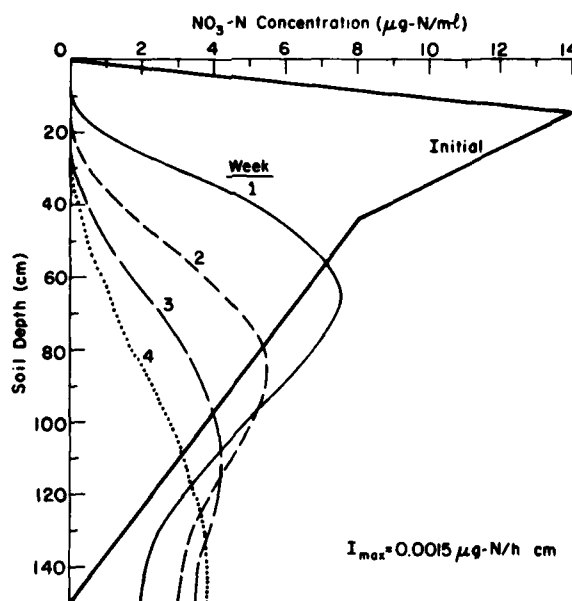


Figure 18. Simulated concentration distribution of $\text{NO}_3\text{-N}$ in the soil profile where $\bar{k}_1 = 0.1 \text{ h}^{-1}$, $K_D = 0.25 \text{ cm}^3/\text{g}$ and $I_{\max} = 0.0015 \mu\text{g N/h cm}$.

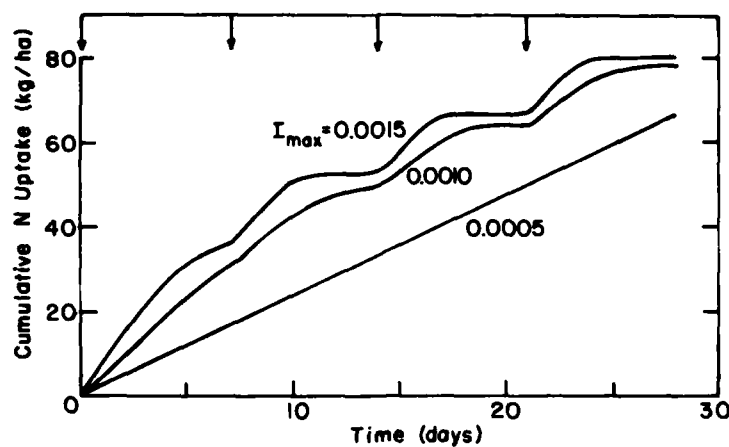


Figure 19. Cumulative N uptake with time for I_{max} of 0.0005, 0.0010 and 0.0015 $\mu\text{g N/h cm}$.

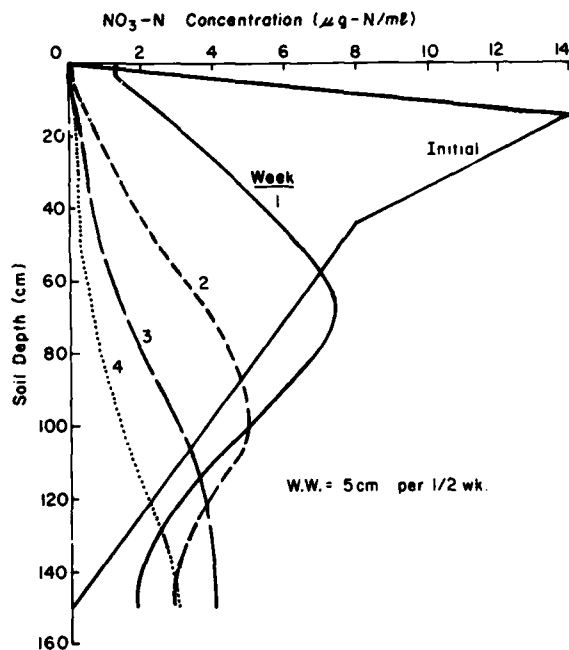


Figure 20. Simulated concentration distributions of $\text{NO}_3\text{-N}$ in the soil profile where 5 cm of wastewater was applied every $\frac{1}{2}$ week. Model parameters were the same as those used for Figure 10.

cumulative nitrogen profile during each application of wastewater. Obviously maximum nitrogen uptake was not met for the cases with I_{max} of 0.001 and 0.0015 $\mu\text{g N/h cm}$

Figures 20 and 21 show the influence of the amounts and scheduling of wastewater application on nitrate distributions in the soil profile. Figure 20 shows $\text{NO}_3\text{-N}$

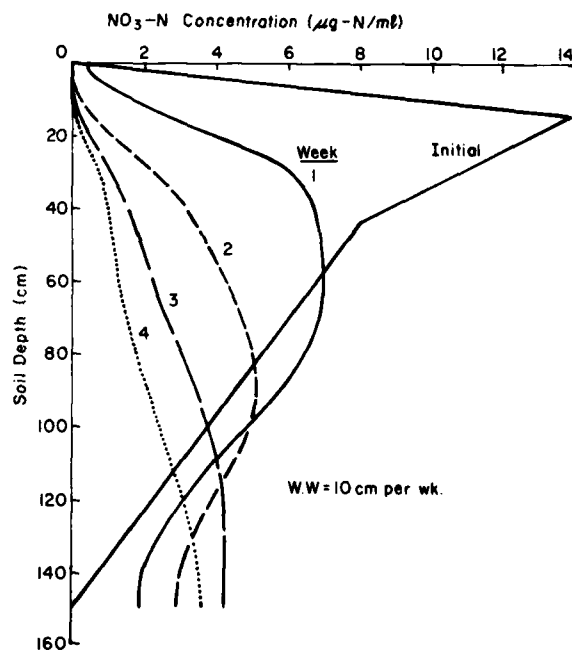


Figure 21. Same as Figure 20 except for weekly application of 10 cm of wastewater.

distribution in the soil where 5 cm of wastewater was applied every 3.5 days, i.e. twice weekly. This rate is twice the application rate considered in previous cases where only a 5-cm wastewater application was maintained every week. Figure 21 is for a different case where 10 cm of wastewater is applied in one application every week. All other parameters, for the purpose of

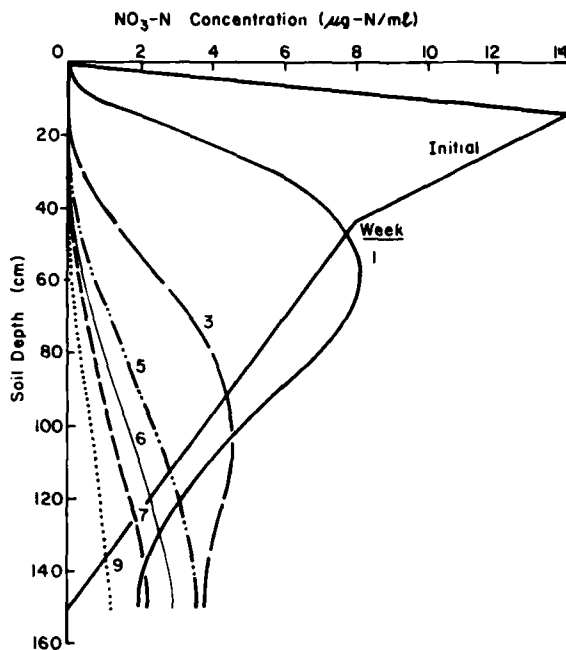


Figure 22. Simulated concentration distributions of $\text{NO}_3\text{-N}$ in the soil profile where weekly application of 5 cm of wastewater was maintained. Model parameters were the same as those used for Figure 10.

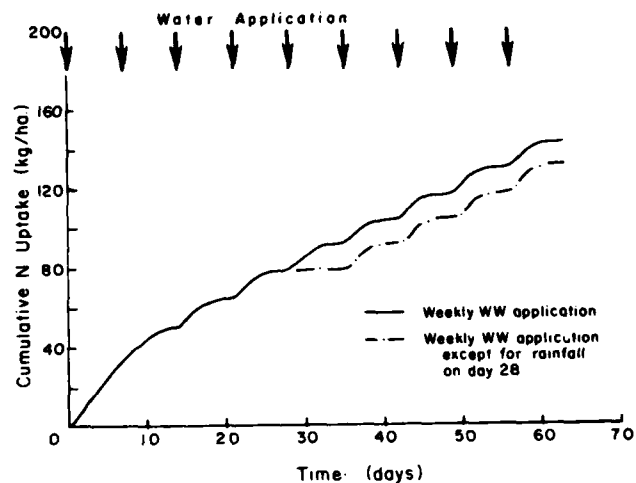


Figure 23. Cumulative N uptake with time where weekly application of 5 cm of wastewater was maintained for a period of 9 weeks. Dashed line is for a case where 5 cm of water (or simulated rainfall), rather than wastewater, was applied on the fifth week (day 28).

comparison, are the same as those used for Figure 10. Comparison of Figures 10 and 20 shows that increasing the schedule of application to 5 cm/ $\frac{1}{2}$ week, rather than one week, resulted in more leaching of the nitrate nitrogen from the soil profile. In addition, peak concentrations were at lower soil depths when the wastewater was applied twice weekly. Comparison of Figures 20 and 21 shows that the total $\text{NO}_3\text{-N}$ in the soil was applied once every week than for 5 cm every $\frac{1}{2}$ week. Increased total $\text{NO}_3\text{-N}$ in the soil profile (shown in Fig. 21) was probably due to increased depth of penetration of $\text{NO}_3\text{-N}$ in the soil for the 10 cm/week application rate.

The influence of rainfall events on $\text{NO}_3\text{-N}$ distributions in the soil profile is shown in Figures 22 and 23. Here, we compare a case where 5 cm of wastewater is applied weekly for a total period of 9 weeks to another case where in the fifth week (day 28) 5 cm of water or simulated rainfall containing no $\text{NO}_3\text{-N}$ or $\text{NH}_4\text{-N}$ is applied. Figure 22 shows that the results of $\text{NO}_3\text{-N}$ distributions in the soil for the two cases were identical

for the time of simulation considered. This was not surprising since the top portion of the soil profile contained very little $\text{NO}_3\text{-N}$ at the end of the fourth week. As a result, the effect of the simulated rainfall event on the fifth week was in limiting the amount of N uptake during that time. This is clearly illustrated in Figure 23, where after the fifth week the cumulative N uptake was approximately 125 kg N/ha higher for the case where weekly wastewater was maintained. Moreover, there was a leveling of N uptake during the fifth week for the case where 5 cm of water (or rainfall) was applied on day 28. This difference in the cumulative N uptake between the two cases is equivalent to the total amount of N applied in one wastewater application. These results, therefore, further support the concept that intermittent rainfall, for the cases studied, directly influences the plant uptake rather than $\text{NO}_3\text{-N}$ distribution in the soil profile. If, however, considerable amounts of $\text{NO}_3\text{-N}$ are present in the upper portion of the soil profile prior to application of water or simulated rainfall, profiles of $\text{NO}_3\text{-N}$ vs soil depth different from that shown in Figure 22 would be obtained.

DESCRIPTION OF THE COMPUTER PROGRAM

The computer program that we developed to predict the water and nitrogen transport, transformation, and uptake by plants in the soil profile in land treatment systems is written in FORTRAN language and consists of a SOURCE (or MAIN) program, 10 subroutine programs, three FUNCTION programs, and an input data section. The names of the subroutines are IDIST, IDIST2, ROOTS, INDIDZ, WATER, WPROP, AMONIA, NITRAT, OUTPUT and TRIDM. The names of the function programs are ZZ1, ZZ2, and ZZ3. In addition, the program uses subroutine QSF which is a standard integration subroutine available from the IBM System 360 Scientific Subroutine Package (1970). This subroutine is on file in the CRREL computer system.

Input data section

Unless otherwise stated, the format for the input data is 8F10.3 (see FORMAT 100 in the SOURCE program). The input data which must be provided by the user are as follows:

1. The first record (card) of the data set contains:
 DTT = initial approximation of Δt
 DZZ = initial approximation of Δz (cm)
2. The second record of the data set contains:
 SFLUX = flux v of wastewater application (cm/h)
 ET = evapotranspiration rate T (cm/h)
 QM = $I_{\max}$ of the Michaelis-Menten equation for nitrogen uptake ($\mu\text{g/h cm}$ of root length)
 QK = Michaelis constant K_m ($\mu\text{g/ml}$)
 CSNH₄ = concentration of NH₄-N in the wastewater C_s ($\mu\text{g-N/ml}$)
 CSNO₃ = concentration of NO₃-N in the wastewater Y_s ($\mu\text{g-N/ml}$)
 DISP = solute dispersion coefficient D (cm^2/h)
3. The third record of the input data set contains:
 CL = total length (cm) of the soil profile L
 CL1 = soil depth (cm) to the first soil layer L_1 (see Fig. 1)
 CL2 = soil depth (cm) to the second soil layer $L_1 + L_2$ (see Fig. 1).
4. The fourth record contains soil water parameters for the first soil layer (see *Sensitivity Analysis*). The format used here is E10.4, 6F10.5 (see FORMAT 500 in SOURCE program):
 AC1 = η of eq 37
 BC1 = α of eq 37
 AT1 = a of eq 36
 BT1 = b of eq 36
5. This record is similar to the one above except for the second soil layer.
6. This record is similar to the one above except for the third soil layer.

7. This record contains the soil bulk density (g/cm^3) and saturated water content (cm^3/cm^3) for each soil layer:
 ROU1 = ρ_1 , bulk density of the first soil layer
 THS1 = $(\theta_s)_1$, saturated water content of the first soil layer
 ROU2 = ρ_2 , bulk density of the second soil layer
 THS2 = $(\theta_s)_2$, saturated water content of the second soil layer
 ROU3 = ρ_3 , bulk density of the third soil layer
 THS3 = $(\theta_s)_3$, saturated soil water content of the third soil layer.
8. This record contains the nitrogen parameters for the first soil layers:
 REX1 = $(K_D)_1$, ammonium distribution coefficient (cm^3/g) for the first soil layer.
 RNIT1 = $(k_1)_1$, nitrification rate coefficient (h^{-1}) for the first soil layer.
 RDNIT1 = $(k_2)_1$, denitrification rate coefficient (h^{-1}) for the first soil layer.
9. This record is similar to the one above except for the second soil layer.
10. This record is similar to the one above except for the third soil layer.
11. This record contains:
 TINF = T , duration (h) of wastewater (or rainfall) application
 TCYC = duration of wastewater cycle in hours
 NCYC = number of cycles desired.
12. This record contains:
 TWRITE = time (h) at which output data are requested.

Source program

The main functions of the SOURCE (or main) program are prescribing the DIMENSION statements, reading the input data, and setting up the entire sequence of the program. A detailed flow chart of the SOURCE program is shown in Figure 24.

The DIMENSION statements are introduced in COMMON blocks and are labeled L1 to L18. The array size of most variables is set to be 310. This array size may be changed by the user depending on the depth of the soil profile (L) as well as the incremental distances Δz .

The source program also reads the input parameters and provides the output for these parameters.

The following variables are used in the source program:

- C = NH₄-N concentration of soil solution C ($\mu\text{g-N/ml}$), dimension = NP1.
- Y = NO₃-N concentration in soil solution Y ($\mu\text{g-N/ml}$), dimension = NP1.
- H = soil water pressure head h (cm), dimension = NP1.

TH = soil water content θ (cm^3/cm^3),
 dimension = NP1.
 CON = soil water hydraulic conductivity
 $K(\theta)$ (cm/h), dimension = NP1.
 CAP = soil water capacity $\text{Cap}(h)$ (cm^{-1}),
 dimension = NP1.
 RDIST = root density distribution $R(z)$ (cm),
 dimension = NX
 AA, BB, CC, R = dummy variables which are used
 in solving the matrix-vector equa-
 tions for water, $\text{NH}_4\text{-N}$, and NO_3
 -N , dimension = N
 XXX = soil depths (cm) for which initial
 distributions are provided, dimen-
 sion = NIN
 C1 = initial distribution of pressure head
 (cm) dimension = NIN
 C2 = initial distribution of water content
 (cm^3/cm^3) dimension = NIN
 C3 = initial distribution of $\text{NH}_4\text{-N}$,
 ($\mu\text{g-N/ml}$) dimension = NIN
 C4 = initial distribution of $\text{NO}_3\text{-N}$,
 ($\mu\text{g-N/ml}$), dimension = NIN.

Subroutine IDIST

This subroutine is labeled the "Initial Distribution Program" in the program listing (Appendix A). This subroutine uses the initial input distributions, i.e. initial conditions, at any number of soil depths. In order to calculate the pressure head, water content, $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ concentration distributions at incremental distances DT (CM) for the entire soil profile the calculations are carried out by linear interpolation using the input data points.

In this subroutine it is not necessary to provide initial water content distributions corresponding to the soil suction for the various soil depths (in input data). Conversion from suction or pressure head to water content is carried out in subroutine WPROP. However, the user must provide some value (zero is recommended) for all input data points.

It should be emphasized here that, if input data for pressure heads, $\text{NH}_4\text{-N}$, etc., are not provided for the same soil locations (depths), the user must use subroutine IDIST2.

Subroutine IDIST2

This subroutine is labeled the "Initial Distribution Program Number 2" in the program listing. This subroutine is similar to subroutine IDIST except that it allows the calculation of initial distribution regardless of locations (soil depths) at which measurements are provided. Therefore, this subroutine must be used if initial distributions of all variables (pressure head, $\text{NH}_4\text{-N}$, etc.) are not available at common soil depths.

In this subroutine each variable is treated separately. In addition the number of data points, locations and values of each variable must be supplied in the main program.

Subroutine ROOTS

This subroutine is labeled the "Root Distribution Program" in the program listing. The subroutine provides the root distribution in the soil profile. This root distribution can be expressed as a function of time as well as soil depth in the profile. This is provided as a mathematical expression. In the example below, an exponential decay function of root length with soil depth is used for all times. If desired, the user can express the root distribution as a function of soil depth as well as time.

Subroutine INDTDZ

This subroutine is labeled the "Program for Adjusting Zone of Infiltration" in the program listing. The subroutine may be used only if the water flux in the soil profile is extremely small. In such a case it is reasonable to be mainly concerned with the top portion of the soil profile during the initial stages of wastewater application or rainfall. Such an assumption is applicable if water redistribution continues for several days with no new wastewater application or rainfall. In this program an initial length of 30 cm (root zone) is assumed ($N = 30$) in the main program. This length is automatically increased during wastewater application. At the termination of infiltration the total length of the profile is incorporated.

It is important to emphasize here that the use of such a subroutine is not essential. However, its use saves a considerable amount of computer time especially during simulation of infiltration when DT is smallest. If this feature is not desirable, the user may ignore it by replacing $N = 30$ by $N = \text{CL/DZ} + 0.01$ in the main program and deleting all call INDTDZ statements.

Subroutine WATER

This subroutine is labeled the "Water Flow Program" in the program listing. The subroutine provides the solution for the water flow equation for a homogeneous or a layered soil profile. The method of solution is based on the finite difference approximations discussed previously. The bottom boundary condition is incorporated in the solution and is applicable for a water table boundary or a semi-infinite (i.e. deep) soil profile. The surface boundary condition (flux type) is provided from main program.

Subroutine WPROP

This subroutine is labeled the "Soil-Water Properties Program" in the program listing. The subroutine

provides the soil-water properties for each soil layer in the soil profile, namely the hydraulic conductivity as a function of water content or suction and the water content-suction relationship. From the latter, the water capacity term is calculated. In this example (see *Sensitivity Analysis*) mathematical expressions are used to describe these relationships. This subroutine is called by subroutine WATER for every time step.

Subroutine AMONIA

This subroutine is labeled the "Ammonium Transport and Transformation Program" in the program listing. The subroutine provides the solution to the ammonium transport and transformation equation under transient flow conditions. It also calculates the ammonium uptake by plant roots. The method of solution is the finite difference approximation method. The rate of nitrification and denitrification and the distribution coefficient for $\text{NH}_4\text{-N}$ release are obtained from functions ZZ1, ZZ2, and ZZ3, respectively (see below).

Subroutine NITRAT

This subroutine is labeled the "Nitrate Transport of Transformation Program" in the program listing. The subroutine provides the solution to the nitrate transport and transformation equation under transient flow conditions. It also calculates the nitrate uptake by plant roots. The rate of nitrification and denitrification and the distribution coefficient for $\text{NH}_4\text{-N}$ exchange are obtained from functions ZZ1, ZZ2, and ZZ3, respectively.

Functions ZZ1, ZZ2, ZZ3

Function ZZ1 provides the rate coefficient for nitrification (k_1) for each soil layer. In the example described (see *Sensitivity Analysis*) the rate coefficient was considered dependent on the soil water suction. It was assumed that nitrifying bacteria are present in optimum number and the change in their population during a cycle of wastewater application (most often weekly) is negligible.

Function ZZ2 provides the retardation factor R for ammonium exchange. This is achieved, for each soil layer, from K_D , θ and ρ at incremental soil depths.

All the above functions (ZZ1, ZZ2, and ZZ3) are called by subroutine AMONIA and NITRAT at every time step DT.

Subroutine OUTPUT

The main function of this subroutine is to print the results (output data) at specified times. A second function of this subroutine is to carry out several integration in order to calculate the total amount of $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ in the soil solution and total $\text{NH}_4\text{-N}$ in the exchangeable phase.

Subroutine TRIDM

This subroutine is labeled the "Tridiagonal Matrix Program" in the program listing. The subroutine provides the solution of a tridiagonal matrix-vector equation (see text). This subroutine is utilized by subroutine WATER, AMONIA, and NITRAT at every time step DT.

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APPENDIX A: PROGRAM LISTING

```

C*****C
C*****C
C      C
C      A S I M P L I F I E D   M O D E L   F O R   P R E D I C T I O N   C
C      C
C      O F   N I T R O G E N   B E H A V I O R   I N   L A N D   C
C      C
C      T R E A T M E N T   O F   W A S T E   W A T E R   C
C      C
C*****C
C      C
C      THE PURPOSE OF THIS MODEL IS TO PREDICT THE BEHAVIOR OF THE C
C      AMMONIUM AND NITRATE NITROGEN SPECIES IN THE SOIL IN LAND TREATMENT C
C      SYSTEMS.. THE PROGRAM IS BASED ON THE SOLUTION OF THE TRANSIENT C
C      WATER FLOW EQUATION SIMULTANEOUSLY WITH THE EQUATIONS DESCRIBING C
C      THE TRANSPORT , TRANSFORMATIONS, AND UPTAKE OF NITROGEN BY PLANTS. C
C      C
C      M A I N   F E A T U R E S : C
C      THE MODEL IS VALID FOR UNIFORM AS WELL AS MULTILAYERED SOIL C
C      PROFILES. IN ADDITION, THE PROGRAM IS FLEXIBLE AND IS DESIGNED C
C      TO INCORPORATE THE FOLLOWING (INPUT) CONDITIONS AS DESIRED : C
C      1. RATE OF WASTE WATER APPLICATION C
C      2. DURATION OF WASTE WATER APPLICATION C
C      3. DEPTH OF INDIVIDUAL SOIL LAYERS C
C      4. CONCENTRATION OF AMMONIUM AND NITRATE IN THE C
C      WASTE WATER C
C      5. WASTE WATER APPLICATION CYCLE, I.E. SCHEDULING C
C      6. SOIL WATER PROPERTIES AND NITROGEN TRANSFORMATION C
C      MECHANISMS FOR INDIVIDUAL SOIL LAYERS C
C      7. PLANT ROOT DISTRIBUTION AND GROWTH IN THE SOIL C
C      8. RATE OF NITROGEN UPTAKE BY PLANTS C
C      9. EVAPOTRANSPIRATION RATE C
C      10. INITIAL DISTRIBUTION OF WATER AND NITROGEN C
C      SPECIES IN THE SOIL PROFILE C
C*****C
C
COMMON/L1/ C(310),Y(310)
COMMON/L2/ AA(310),BB(310),CC(310),R(310),RDIST(310)
COMMON/L3/ N,NM1,NM2,NE1,NP2
COMMON/L4/ ALPHA,BETA,DT,DZ
COMMON/L5/ NX,NX1,NRMAX,CON1
COMMON/L6/ FLNH4,FLNO3,DNITRF
COMMON/L7/ SFLUX,ET,QM,QK,CSNH4,CSNO3,DISP,XL
COMMON/L8/ XXX(30),C1(30),C2(30),C3(30),C4(30),NIN
COMMON/L9/ TIME,TIME,TCYC
COMMON/L10/ H(310),CON(310),CAP(310),TH(310)
COMMON/L11/ CL,CL1,CL2,L1,L2
COMMON/L12/ AC1,BC1,AT1,B11
COMMON/L13/ AC2,BC2,AT2,BT2
COMMON/L14/ AC3,BC3,AT3,BT3
COMMON/L15/ ROU1,THS1,ROU2,THS2,ROU3,THS3
COMMON/L16/ REX1,RNI11,RCNIT1
COMMON/L17/ REX2,RNIT2,RNIT2
COMMON/L18/ REX3,RNIT3,RNIT3
100 FORMAT(8F10.3)
101 FORMAT(5X,'INITIAL DT, HR =',F10.5/,5X,'INITIAL DZ , CM=',F10.5//)
200 FORMAT(2F10.5,13)
300 FORMAT(214)

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```

600  FORMAT(10E12.4)
500  FORMAT(E10.4,6F10.5)
105  FORMAT(5X,'FLUX OF WASTE WATER APPLICATION, CM/ HR =' ,F10.5/,
      *5X,'EVAPOTRANSPIRATION RATE, CM/HR =' ,F10.5/,
      *5X,'NITROGEN UPTAKE RATE, MICROGRAM-N/CM OF ROOT LENGTH PER HOUR',
      *5X,'MICHAELIS CONSTANT =' ,F10.5/,
      *5X,'CONCENTRATION OF APPLIED NH4-N , MG/LITRE =' ,F10.5/,
      *5X,'CONCENTRATION OF APPLIED NO3-N , MG/LITRE =' ,F10.5/,
      *5X,'SOLUTE DISPERSION COEFFICIENT, CM**2/HR =' ,F10.5/)
110  FORMAT(5X,'TOTAL LENGTH OF SOIL PROFILE, CM =' ,F10.5/,
      *5X,'SOIL DEPTH TO THE FIRST SOIL LAYER, CM =' ,F10.5/,
      *5X,'SOIL DEPTH TO THE SECOND SOIL LAYER, CM =' ,F10.5/)
115  FORMAT(5X,'SOIL WATER PARAMETERS FOR THE FIRST LAYER :',4E15.4)
120  FORMAT(5X,'SOIL WATER PARAMETERS FOR THE SECOND LAYER :',4E15.4)
125  FORMAT(5X,'SOIL WATER PARAMETERS FOR THE THIRD LAYER :',4E15.4)
130  FORMAT(5X,
      *'FIRST LAYER ; BULK DENSITY =' ,F10.5,10X,'SATURATION =' ,F10.5/,
      *5X,
      *'SECOND LAYER ; BULK DENSITY =' ,F10.5,10X,'SATURATION =' ,F10.5/,
      *5X,
      *'THIRD LAYER ; BULK DENSITY =' ,F10.5,10X,'SATURATION =' ,F10.5/,
      *5X)
135  FORMAT(5X,'FIRST LAYER:',10X,'NH4-N EXCHANGEABLE CCEFFICIENT, CM3/
      *GM =' ,F10.5/,26X,'NITRIFICATION RATE COEF.,HR-1 =' ,F10.5/,26X,
      *'DENITRIFICATION RATE COEF., HR-1 =' ,F10.5)
140  FORMAT(5X,'SECCND LAYER',10X,'NH4-N EXCHANGEABLE CCEFFICIENT, CM3/
      *GM =' ,F10.5/,26X,'NITRIFICATION RATE COEF.,HR-1 =' ,F10.5/,26X,
      *'DENITRIFICATION RATE COEF., HR-1 =' ,F10.5)
145  FORMAT(5X,'THIRD LAYER:',10X,'NH4-N EXCHANGEABLE CCEFFICIENT, CM3/
      *GM =' ,F10.5/,26X,'NITRIFICATION RATE COEF.,HR-1 =' ,F10.5/,26X,
      *'DENITRIFICATION RATE COEF., HR-1 =' ,F10.5)
150  FORMAT(5X,'DURATION OF WASTE WATER APPLICATION , HRS =' ,F10.5/,5X,
      *'SCHEDULE OF WASTE WATER APPLICATION, I.E. CYCLE DURATION =' ,
      *F10.5/,5X,'NUMBER OF CYCLES =' ,I3/)
155  FORMAT(5X,'TIME AT WHICH OUTPUT DATA IS REQUESTED,HR =' ,F10.5/)
160  FORMAT(I25,'I N P U T   D A T A',///)
165  FORMAT('1')
      WRITE(6,160)
      READ(5,100) DTT,DZZ
      WRITE(6,101) DTT,DZZ
      READ(5,100) SFLUX,PT,QM,QK,CSNH4,CSNO3,DISP
      WRITE(6,105) SFLUX,PT,QM,QK,CSNH4,CSNO3,DISP
      READ(5,100) CL,CL1,CL2
      WRITE(6,110) CL,CL1,CL2
      READ(5,500) AC1,BC1,AT1,BT1
      WRITE(6,115) AC1,BC1,AT1,BT1
      READ(5,500) AC2,BC2,AT2,BT2
      WRITE(6,120) AC2,BC2,AT2,BT2
      READ(5,500) AC3,BC3,AT3,BT3
      WRITE(6,125) AC3,BC3,AT3,BT3
      READ(5,100) FOU1,THS1,ROU2,THS2,ROU3,THS3
      WRITE(6,130) FOU1,THS1,ROU2,THS2,ROU3,THS3
      READ(5,100) REX1,RNIT1,RDNIT1
      WRITE(6,135) REX1,RNIT1,RDNIT1
      READ(5,100) REX2,RNIT2,RDNIT2
      WRITE(6,140) REX2,RNIT2,RDNIT2
      READ(5,100) REX3,RNIT3,RDNIT3

```



```

C      READ SOIL DEPTH (LOCATIONS) FOR WATER CONTENT
      READ(5,100) (XXX(I),I=1,NIN)
C      READ WATER CONTENT FOR CORRESPONDING DEPTHS
      READ(5,100) (C1(I),I=1,NIN)
      CALL IDIST2
      DO 12 I=1,NP1
12 TH(I)=R(I)
C      READ NUMBER OF DATA POINTS FOR NH4-N CONCENTRATION
      READ(5,300) NIN
C      READ SOIL DEPTH (LOCATIONS) FOR NH4-N CONCENTRATION
      READ(5,100) (XXX(I),I=1,NIN)
C      READ NH4-N CONCEN. FOR CORRESPONDING DEPTHS
      READ(5,100) (C1(I),I=1,NIN)
      CALL IDIST2
      DO 13 I=1,NP1
13 C(I)=R(I)
C      READ NUMBER OF DATA POINTS FOR NO3-N CONCENTRATION
      READ(5,300) NIN
C      READ SOIL DEPTH (LOCATIONS) FOR NO3-N CONCENTRATION
      READ(5,100) (XXX(I),I=1,NIN)
C      READ NO3-N CONCEN. FOR CORRESPONDING DEPTHS
      READ(5,100) (C1(I),I=1,NIN)
      CALL IDIST2
      DO 14 I=1,NP1
14 Y(I)=R(I)
C
C      CALL RCOTS
      CALL WPROP
      CALL CUTPUT
      WRITE(6,165)
C
      TIME=0.0
      XTINF=TINF
      DO 999 IJKL=1,NCYC
      TINF=TIME+XTINF
      DT=DTT
      DZ=DZZ
      SFLUX=WFLX
C
      N=30
      NX=N
      CALL INDTDZ
      NX1=NX-1
C
      IF(SFLUX.LE.0.0) GO TO 26
      TTT=4.0/(SFLUX*1000.0)
      IF(DT.LE.TTT) GO TO 5
      NT=DT/TTT+0.10
      D1=D1/NT
5  CONTINUE
      ALPHA=DT/(2.0*DZ*DZ)
      BETA=D1/DZ
C
      CALL WPROP
      IF(CON1.GE.(SFLUX/2)) GO TO 15
C
6  H(1)=H(1)+20

```

```

CALL WPROG
IF (CON1.LT.(SFLUX/2)) GO TO 6
IF (H(1).GT.0.0) H(1)=0.0
H(1)=H(1)-60.0
C
XL=1000.0
DELT=2.0
7 CONTINUE
ILZ=30
DO 25 IK=1,ILZ
CALL WATER
CALL AMONIA
CALL NITRAT
H(1)=H(1)+DELT
25 CONTINUE
TIME=TIME+DT*ILZ
CALL INDTDZ
C
15 CONTINUE
C
DT=DT*2.0
ALPHA=DT/(2.0*DZ*DZ)
BETA=DT/DZ
XI=TIME-TIME
XT=XI/5
IL=XT/DT+0.010
DO 30 IZFT=1,5
DO 17 I=1,NX
17 AA(I)=ADIST(I)*CON(I)
CALL CSF(DZ,AA,R,NX)
XL=R(NX)
DO 10 II=1,IL
ADJ=DZ*(1.0-SFLUX/CON1)
H(1)=H(2)-ADJ
CALL WATER
CALL AMONIA
CALL NITRAT
10 CONTINUE
TIME=TIME+IL*DT
CALL INDIDZ
30 CONTINUE
KK=TIME+0.050
J=AA-NKK*(KK/NKK)
IF (J.EQ.0) CALL OUTPUT
SFLUX=0.0
TN=6.0+TCYC*(1JKL-1)
53 IF ((TN-TIME).GT.1.0) GO TO 54
TN=TN+6.0
GO TO 53
54 AL=(TN-TIME)/D1+0.010
DT=(TN-TIME)/11
C
C
DC 31 I=1,NX
31 AA(I)=ADIST(I)*CON(I)
CALL CSF(DZ,AA,R,NX)
XL=R(NX)
DO 52 II=1,IL

```

```

      ADJ=DZ*(1.0-SFLUX/CON1)
      H(1)=H(2)-ADJ
      CALL WATER
      CALL AMONIA
      CALL NITBAT
52  CONTINUE
      TIME=TIME+IL*DT
      CALL INDTDZ
      KK=TIME+0.050
      J=KK-NKK*(KK/NKK)
      IF (J.EQ.0) CALL OUTPUT
C
C
26  CONTINUE
C
      DT=DT*2
      IF (DT.GT.0.050.AND.DT.LT.0.10)  DT=0.10
      ALPHA=DT/(2.0*DZ*DZ)
      BETA=DT/DZ
      IL=6.00/DT+0.010
      DT=6.0/IL
C
      DO 34 I=1,NX
34  AA(I)=RDIST(I)*CON(I)
      CALL QSF(DZ,AA,R,NX)
      XL=R(NX)
      DO 36 II=1,II
      ADJ=DZ*(1.0-SFLUX/CON1)
      H(1)=H(2)-ADJ
      CALL WATER
      CALL AMONIA
      CALL NITBAT
36  CONTINUE
      TIME=TIME+IL*DT
      KK=TIME+0.050
      J=KK-NKK*(KK/NKK)
      IF (J.EQ.0) CALL OUTPUT
C
      DT=2*DT
      IF (DT.GT.0.050.AND.DT.LT.0.10)  DT=0.10
      IF (DT.GT.0.100.AND.DT.LT.0.40)  DT=0.250
C
      ALPHA=DT/(2.0*DZ*DZ)
      BETA=DT/DZ
C
      TIMM=TIME-TCYC*(IJKL-1)
      IZEFT=(TCYC-TIMM)/6.0
      DO 40 IZZ=1,IZEFT
      IL=6.00/DT+0.010
      DT=6.0/IL
      DO 18 I=1,NX
18  AA(I)=RDIST(I)*CON(I)
      CALL QSF(DZ,AA,R,NX)
      XL=R(NX)
      DO 35 II=1,II
      ADJ=DZ*(1.0-SFLUX/CON1)
      H(1)=H(2)-ADJ
      CALL WATER

```

```

CALL AMONIA
CALL NITRAT
35  CONTINUE
    TIME=TIME+IL*DT
    KK=TIME+0.050
    J=KK-NKK*(KK/NKK)
    IF (J.EQ.0) CALL OUTPUT
    DT=2*DT
    IF (DT.GT.2.0) DT=2.0
    ALPHA=DT/(2*CZ*DZ)
    BETA=ET/DZ
40  CONTINUE
C   IF ANY CHANGES IN INPUT DATA ( ESPECIALLY THE BOUNDARY CONDITIONS)
C   ARE REQUIRED IN THE CYCLE, THE INPUTS SHOULD BE ENTERED HERE
C   FOR EXAMPLE NEW FLUX, EVAPOTRANSPIRATION RATE, DURATION OF WASTE
C   WATER APPLICATION, CYCLE DURATION, CONCENTRATION OF NH4-N, AND
C   NO3-N MAY BE ENTERED AS FOLLOWS.
C   READ(5,100) SFLUX, ET,TINF,TCYC,CSNH4,CSNO3
C   P.S.   RAINFALL EVENTS CAN BE TREATED AS A CYCLE BY ENTERING ZERO
C   VALUES FOR APPLIED NH4-N AND NO3-N AS WELL AS PROVIDING THE PROPER
C   INPUTS FOR FLUX (INTENSITY), DURATION OF RAINFALL AS WELL AS THE
C   TOTAL TIME BEFORE THE NEW WASTE WATER APPLICATION BEGINS (TCYC)
C   WARNING:
C           IF THE ABOVE IS DESIRABLE THEN      NEW DATA FOR EACH
C           SUBSEQUENT CYCLE MUST BE PROVIDED
999  CONTINUE
C
    STOP
    END

```

```

C*****C
C
C      I N T I A L      D I S T R I B U T I O N      P R O G R A M
C
C      THIS SUBROUTINE UTILIZES THE INITIAL INPUT DISTRIBUTIONS ,I.E.
C      INITIAL CCNDITIONS, AT ANY NUMBER OF SOIL DEPTHS IN THE SOIL,
C      IN ORDER TO CALCULATE THE PRESSURE HEAD, WATER CONTENT, NH4-N
C      AND NO3-N CONCENTRATION DISTRIBUIONS AT INCREMENTAL DISTANCES DZ
C      (C4) FOR THE ENTIRE SOIL PROFILE. IN THIS PROGRAM
C      THE CALCULATIONS ARE CARRIED OUT USING LINEAR INTEREOLATION
C      USING THE INPUT DATA POINTS.
C      IMPORTANT:
C          IN THIS PROGRAM IT IS NOT NECESSARY TO PROVIDE INITIAL
C          WATER CONTENT DISTRIBUTIONS CORRESPONDING TO THE SOIL
C          SUCTION FOR THE VARIOUS SOIL DEPTH (IN INPUT DATA ).
C          CONVERSION FROM SUCTION OR PRESSURE HEAD TO WATER CONTENT
C          IS CARRIED OUT IN SUBROUTINE WPROP HOWEVER, THE USER
C          MUST PROVIDE SOME VALUE(ZERO IS RECOMMENDED) FOR ALL
C          INPUT DATA POINTS
C
C          W A R N I N G
C      IF INPUT DATA FOR PRESSURE HEADS, NH4-4, ETC. ARE NOT PROVIDED
C      FOR THE SAME SCIL LOCATIONS (DEPTHS) THE USER MUST USE
C      SUBROUTINE IDIST2
C*****C
C
C      SUBROUTINE IDIST
C      COMMON/L1/ C(310),Y(310)
C      COMMON/L3/ N,NH1,NH2,NF1,NF2
C      COMMON/L4/ ALPHA,BETA,DT,DZ
C      COMMON/L8/ XXX(30),C1(30),C2(30),C3(30),C4(30),NIN
C      COMMON/L10/ h(310),CCN(310),CAP(310),TH(310)
C      COMMON/L11/ CL,CL1,CL2,L1,L2
100  FORMAT(8F10.4)
      I=1
      DO 20 K=1,NF1
      A=DZ*(K-1)
5      IF(A-IF.XXX(I+1)) GO TO 10
      I=I+1
      GO TO 5
10      h(K)=C1(I)+(A-XXX(I))*((C1(I+1)-C1(I))/(XXX(I+1)-XXX(I)))
      TH(K)=C2(I)+(A-XXX(I))*((C2(I+1)-C2(I))/(XXX(I+1)-XXX(I)))
      C(K)=C3(I)+(A-XXX(I))*((C3(I+1)-C3(I))/(XXX(I+1)-XXX(I)))
      Y(K)=C4(I)+(A-XXX(I))*((C4(I+1)-C4(I))/(XXX(I+1)-XXX(I)))
20  CONTINUE
      RETURN
      END

```

```

C*****C
C      I N T I A L      D I S T R I B U T I O N      P R O G R A M   N O . 2      C
C*****C
C      THIS SUBROUTINE IS SIMILAR TO SUBROUTINE IDIST EXCEPT THAT      C
C      IT ALLOWS THE CALCULATION OF INITIAL DISTRIBUTION REGARDLESS OF      C
C      LOCATIONS (SOIL DEPTHS) AT WHICH MEASUREMENTS ARE PROVIDED.      C
C      THEREFORE, THIS SUBROUTINE MUST BE USED IF INITIAL DISTRIBUTIONS      C
C      OF ALL VARIABLES ( PRESSURE HEAD, NH4-N, ETC.) ARE NOT AVAILABLE AT      C
C      COMMON SOIL DEPTHS.      C
C      IMPORTANT:      C
C      EACH VARIABLE IS TREATED SEPERATLY. IN ADDITION THE      C
C      NUMBER OF DATA POINTS, LOCATIONS AND VALUES OF EACH      C
C      VARIABLE MUST BE SUPPLIED IN THE MAIN PROGRAM.      C
C*****C

```

```

C      SUBROUTINE IDIST2
COMMON/L2/ AA(310),BB(310),CC(310),R(310),KDIST(310)
COMMON/L3/ N,NM1,NM2,NP1,NP2
COMMON/L4/ ALPHA,BETA,DT,DZ
COMMON/L5/ XXX(30),C1(30),C2(30),C3(30),C4(30),NIN
I=1
DO 20 K=1,NP1
A=DZ*(K-1)
5 IF(A.LE.XXX(I+1)) GO TO 10
I=I+1
GO TO 5
10 R(K)=C1(I)+(A-XXX(I))*((C1(I+1)-C1(I))/(XXX(I+1)-XXX(I)))
20 CONTINUE
RETURN
END

```

```

C*****C
C      R O O T      D I S T R I B U T I O N      P R O G R A M      C
C*****C
C      THIS SUBROUTINE PROVIDES THE ROOT DISTRIBUTION IN THE SOIL PROFILE.
C      THIS ROOT DISTRIBUTION CAN BE EXPRESSED AS A FUNCTION OF TIME AS
C      WELL AS SOIL DEPTH IN THE PROFILE.
C      THIS MAY MAY PROVIDED AS A MATHEMATICAL EXPRESSION.
C      IN THE EXAMPLE BELOW AN EXPONENTIAL DECAY FUNCTION OF ROOT LENGTH
C      WITH SOIL DEPTH IS USED FOR ALL TIMES.
C      IMPORTANT:
C      ROOT DISTRIBUTION IS EXPRESSED IN TERMS OF TOTAL ROOT
C      LENGTH PER UNIT BULK VOLUME OF SOIL.
C*****C

```

```

C      SUBROUTINE ROOTS
COMMON/L2/ AA(310),BB(310),CC(310),R(310),RDIST(310)
COMMON/L3/ N,NP1,NM2,NP1,NP2
COMMON/L4/ ALPHA,BETA,DT,DZ
COMMON/L5/ NX,NX1,NMAX,CON1
COMMON/L6/ TIME,TINF,TCYC
C      MATHEMATICAL EXPRESSION OF ROOT LENGTH AS A FUNCTION
C      OF SOIL DEPTH
DO 5 I=1,N
Z=(I-1)*DZ
5 RDIST(I)=226.0*EXP(-0.160*Z)
C
NX=50
10 CT=RDIST(NX)/RDIST(1)
IF(CT.LT.0.01C) GO TO 15
NX=NX+10
GO TO 10
15 NX1=NX-1
NMAX=NX
RETURN
END

```

```

C*****C
C      PROGRAM FOR ADJUSTING ZONE      C
C      OF INFILTRATION                  C
C*****C
C      THIS SUBROUTINE MAY BE USED ONLY IF THE WATER FLUX IN THE SOIL      C
C      PROFILE IS EXTREMELY SMALL. IN SUCH A CASE IT IS REASONABLE TO      C
C      BE MAINLY CONCERNED WITH THE TOP PORTION OF THE SOIL PROFILE DURING  C
C      THE INITIAL STAGES OF WASTE WATER APPLICATION OR RAINFALL.          C
C      SUCH AN ASSUMPTION IS APPLICABLE IF WATER REDISTRIBUTION CONTINUES  C
C      FOR SEVERAL DAYS WITH NO NEW WASTE WATER APPLICATION OR RAINFALL.   C
C      IN THIS PROGRAM AN INITIAL LENGTH OF 30 CM IS ASSUMED (N = 30).      C
C      THIS LENGTH IS AUTOMATICALLY INCREASED DURING WASTE WATER APPLICATION. C
C      AT THE TERMINATION OF INFILTRATION THE TOTAL LENGTH OF THE PROFILE IS C
C      INCREASED.                                                            C
C      IMPORTANT:                                                            C
C      THE USE OF SUCH A SUBROUTINE IS NOT NECESSARY.                      C
C      HOWEVER IT SAVES A CONSIDERABLE AMOUNT OF COMPUTER TIME             C
C      DURING SIMULATION OF INFILTRATION WHEN DT IS SMALLEST              C
C      IF THIS FEATURE IS NOT DESIRABLE THE USER MAY IGNORE                C
C      IT BY REPLACING N = 30 BY N=CL/DZ+0.01 IN THE MAIN                  C
C      PROGRAM AND DELETING ALL CALL INDIDZ STATEMENTS                      C
C*****C
C
C      SUBROUTINE INDIDZ
C      COMMON/L3/ N,NM1,NM2,NF1,NF2
C      COMMON/L4/ ALPHA,BETA,DT,DZ
C      COMMON/L5/ NX,NX1,NRMAX,CON1
C      COMMON/L6/ TIME,TINF,TCYC
C      COMMON/L11/ CL,CL1,CL2,L1,L2
C      N=N+10
C      IF (TIME.GE.TINF) N=CL/DZ+0.10
C      NM1=N-1
C      NM2=N-2
C      NF1=N+1
C      NF2=N+2
C      NX=NX+10
C      IF (NX.GT.NRMAX) NX=NRMAX
C      NX1=NX-1
C      RETURN
C      END

```



```

C*****C
C                                     C
C           W A T E R   F L C W   P R O G R A M           C
C*****C
C
C   THIS SUBROUTINE PROVIDES THE SOLUTION FOR THE WATER FLOW EQUATION      C
C   FOR A HOMOGENEOUS OR                                                    C
C   FOR A LAYERED SOIL PROFILE                                              C
C   THE METHOD OF SOLUTION IS BASED ON FINITE DIFFERENCE APPROXIMATION      C
C   ( SEE TEXT )                                                            C
C   THE BOTTOM BOUNDARY CONDITION IS INCORPORATED IN THE SOLUTION            C
C   AND IS APPLICABLE FOR A WATER TABLE BOUNDARY OR A SEMI - INFINITE     C
C   (I.E. DEEP) SOIL PROFILE                                                C
C   THE SURFACE BOUNDARY CCNDITION ( FLUX BOUNDARY CONDITION ) IS          C
C   PROVIDED FROM MAIN PROGRAM.                                             C
C*****C
C
C   SUBROUTINE WATER
COMMON/L1/  C(310),Y(310)
COMMON/L2/  AA(310),BB(310),CC(310),R(310),RDIST(310)
COMMON/L3/  N,NM1,NM2,NF1,NF2
COMMON/L4/  ALPHA,BETA,DT,DZ
COMMON/L5/  NX,NX1,NMAX,CON1
COMMON/L6/  ELNH4,ELNO3,DNITR
COMMON/L7/  SFLUX,ET,QM,QK,CSNH4,CSNO3,DISP,XL
COMMON/L8/  XXX(30),C1(30),C2(30),C3(30),C4(30)
COMMON/L9/  TIME,TINF,TCYC
COMMON/L10/ H(310),CON(310),CAP(310),TH(310)
COMMON/L11/ CL,CL1,CL2,L1,L2
COMMON/L12/ AC1,BC1,AT1,ET1
COMMON/L13/ AC2,BC2,AT2,BT2
COMMON/L14/ AC3,BC3,AT3,ET3
COMMON/L15/ ROU1,THS1,ROU2,THS2,ROU3,THS3
COMMON/L16/ REX1,RNIT1,RDNIT1
COMMON/L17/ REX2,RNIT2,RDNIT2
COMMON/L18/ REX3,RNIT3,RDNIT3
CALL WRCOF

C
DC 1 I=1,NM1
AA(I)=CAP(I+1)+ALPHA*(CON(I+1)+CON(I))
BB(I)=-ALPHA*CON(I+1)
CC(I)=-ALPHA*CON(I+1)
1 CONTINUE
DC 2 I=1,NM1
X1=CAP(I+1)*H(I+1)
X2=ALPHA*CON(I)*H(I)-ALPHA*H(I+1)*(CON(I+1)+CON(I))
X3=ALPHA*CON(I+1)*H(I+2)
X4=-BETA*(CON(I+1)-CON(I))
R(I)=X1+X2+X3+X4
2 CONTINUE
R(I)=R(I)+ALPHA*CON(I)*H(I)
I(NM1)=R(NM1)-BE(NM1)*I(NM1)
DC 3 I=1,NX1
X5=-ET*DT*CON(I+1)*RDIST(I+1)/XL
C(I)=C(I)*TH(I)/(TH(I)+X5)
Y(I)=Y(I)*TH(I)/(TH(I)+X5)
R(I)=R(I)+X5
3 CONTINUE
CALL TRIDY(AA,BB,CC,R,NM1)
DC 4 K=2,N
R(K)=R(K-1)
4 CONTINUE
END

```

```

C*****C
C      S C I I - W A T E R   P R O P E R T I E S   P R O G R A M      C
C*****C
C      THIS SUBROUTINE PROVIDES THE SOIL-WATER PROPERTIES FOR EACH SOIL C
C      LAYER IN THE SCII PROFILE NAMELY THE HYDRAULIC CONDUCTIVITY AS C
C      A FUNCTION OF WATER CONTENT OR SUCTION AND THE WATER CONTENT - SUCTION C
C      RELATIONSHIP. FROM THE LATTER, THE WATER CAPACITY TERM IS CALCULATED C
C      IN THIS EXAMPLE MATHEMATICAL EXPRESSIONS ARE USED TO DESCRIBE THESE C
C      SOIL WATER PROPERTIES FOR INDIVIDUAL SOIL LAYERS (SEE TEXT ). C
C*****C
C
C      SUBROUTINE WPROP
C      COMMON/L2/ AA(310),BB(310),CC(310),R(310),RDIST(310)
C      COMMON/L3/ N,NM1,NM2,NF1,NP2
C      COMMON/L5/ NX,NX1,NRMAX,CON1
C      COMMON/L10/ H(310),CCN(310),CAP(310),TH(310)
C      COMMON/L11/ CL,CL1,CL2,L1,L2
C      COMMON/L12/ AC1,EC1,AT1,BT1
C      COMMON/L13/ AC2,BC2,AT2,BT2
C      COMMON/L14/ AC3,BC3,AT3,BT3
C      COMMON/L15/ FOU1,THS1,FOU2,THS2,ROU3,THS3
C      DO 90 I=1,L1
C      R(I)=H(I)
C      IF(R(I).GT.0.0) R(I)=0.0
C      XX=THS1*(1.0+(-R(I)/AT1))**(-2)
C      CAP(I)=XX/AT1
C      TH(I)=THS1/(1.0+(-R(I)/AT1))
C      CON(I)=AC1*EXP(EC1*(TH(I)+TH(I+1))/2)
C 90 CONTINUE
C      I=L1
C      CON(I)=AC1*EXP(EC1*TH(I))
C      LI=L1+2
C      DO 92 I=L1,L2
C      R(I)=H(I)
C      IF(R(I).GT.0.0) R(I)=0.0
C      XX=THS2*(1.0+(-R(I)/AT2))**(-2)
C      CAP(I)=XX/AT2
C      TH(I)=THS2/(1.0+(-R(I)/AT2))
C      CON(I)=AC2*EXP(BC2*(TH(I)+TH(I+1))/2)
C 92 CONTINUE
C      I=L2
C      CON(I)=AC2*EXP(BC2*TH(I))
C
C      I=NF1
C      R(I)=H(I)
C      IF(R(I).GT.0.0) R(I)=0.0
C      XX=THS3*(1.0+(-R(I)/AT3))**(-2)
C      CAP(I)=XX/AT3
C      TH(I)=THS3/(1.0+(-R(I)/AT3))
C      CON(I)=AC3*EXP(BC3*TH(I))
C
C      LI=L2+2
C      DO 93 I=L1I,N
C      R(I)=H(I)

```

```

IF (R(I).GT.0.0) B(I)=0.0
TH(I)=THS3/(1.0+(-R(I)/AT3))
CAP(I)=XX/AT3
XX=THS3*(1.0+(-R(I)/AT3))**(-2)
CON(I)=AC3*EXP(BC3*(TH(I)+TH(I+1))/2)
93 CONTINUE
I=L1+1
TH(I)=(TH(I-1)+TH(I+1))/2
CON(I)=(CON(I-1)+CON(I+1))/2
CAP(I)=(CAP(I-1)+CAP(I+1))/2
I=L2+1
TH(I)=(TH(I-1)+TH(I+1))/2
CON(I)=(CON(I-1)+CON(I+1))/2
CAP(I)=(CAP(I-1)+CAP(I+1))/2
C
CON1=AC1*EXP(BC1*TH(1))
RETURN
END
C*****C
C
C      N I T R I F I C A T I O N   R A T E   P R O G R A M
C
C*****C
C
C      THIS FUNCTION SUBPROGRAM PROVIDES THE RATE COEFFICIENT FOR
C      NITRIFICATION AS A FUNCTION OF SOIL WATER SUCTION FOR
C      INDIVIDUAL SOIL LAYERS (SEE TEXT). THE USER MAY INCORPORATE OTHER
C      VARIABLES, I. E. TIME, SOIL DEPTH, ETC., AS DESIRED.
C      *****
C
FUNCTION ZZ1(M,HH,WC)
COMMON/L4/ ALPHA,BETA,CI,DZ
COMMON/L9/ TIME,TINF,TCYC
COMMON/L11/ CL,CL1,CL2,L1,L2
COMMON/L16/ REX1,RNIT1,RDNIT1
COMMON/L17/ REX2,RNIT2,RDNIT2
COMMON/L18/ REX3,RNIT3,RDNIT3
ZZ1=0.0
WH=-HH
IF(WH.GT.15000) RETURN
Z=M*DZ
IF(Z.GT.CL2) GO TO 10
IF(Z.GT.CL1) GO TO 5
RK1=RAIT1
GO TO 15
5 CONTINUE
RK1=RNIT2
GO TO 15
10 CONTINUE
RK1=RNIT3
15 CONTINUE
IF(WH.GT.10.0) GO TO 1
RETURN
1 IF(WH.GT.50.0) GO TO 2
ZZ1=RK1*(WH-10.0)*0.0050
RETURN
2 IF(WH.GT.100.0) GO TO 3
ZZ1=RK1*(0.200+(WH-50.0)*0.0060)
RETURN
3 IF(WH.GT.433.0) GO TO 4
ZZ1=RK1*(0.500+(WH-100.0)*0.00150)
RETURN
4 ZZ1=RK1*(1.000-(WH-433.0)*0.00020)
IF(WH.GT.1000.0) ZZ1=RK1*(0.950-0.050*WH/1000.0)
RETURN
END

```

```

C*****C
C      D E N I T R I F I C A T I O N      R A T E      P R O G R A M      C
C*****C
C      THIS FUNCTION SUBPROGRAM PROVIDES THE RATE COEFFICIENT FOR      C
C      DENITRIFICATION AS A FUNCTION OF SOIL WATER CONTENT FOR      C
C      INDIVIDUAL SOIL LAYERS (SEE TEXT ). THE USER MAY INCORPORATE OTHER C
C      VARIABLES, I. E. TIME, SOIL DEPTH, ETC., AS DESIRED.      C
C*****C
C
      FUNCTION ZZ2(M,HH,WC)
      COMMON/L4/ ALPHA,BETA,DT,DZ
      COMMON/L9/ TIME,TINF,TCYC
      COMMON/L11/ CL,CL1,CL2,L1,L2
      COMMON/L15/ RCU1,THS1,ROU2,THS2,ROU3,THS3
      COMMON/L16/ REX1,RNIT1,BDNIT1
      COMMON/L17/ REX2,RNIT2,BDNIT2
      COMMON/L18/ REX3,RNIT3,BDNIT3
      ZZ2=0.0
      Z=M*DZ
      IF(Z.GT.CL2) GO TO 10
      IF(Z.GT.CL1) GO TO 5
      RK2=RCIN1
      WSAT=THS1
      GO TO 15
5      RK2=RDIN2
      WSAT=THS2
      GO TO 15
10     RK2=RDIN3
      WSAT=THS3
15     CONTINUE
      IF((WC/WSAT).LT.0.80) RETURN
      ZZ2=RK2*(WC-0.80*WSAT)/(0.10*WSAT)
      IF(WC.GE.(0.90*WSAT)) ZZ2=RK2
      RETURN
      END

```

```

C *****
C
C   A M M O N I U M   E X C H A N G E   P R O G R A M
C
C *****
C   THIS FUNCTION SUBPROGRAM PROVIDES THE RETARDATION FACTOR
C   FOR AMMONIUM EXCHANGE, WHERE R IS A FUNCTION OF SOIL WATER CONTENT AND
C   BULK DENSITY OF INDIVIDUAL SOIL LAYERS.
C *****
C
C   FUNCTION ZZ3(M,HH,WC)
C   COMMON/L4/   ALPHA,BETA,DT,DZ
C   COMMON/L9/   TIME,TINF,TCYC
C   COMMON/L11/  CL,CL1,CL2,I1,L2
C   COMMON/L15/  RCU1,THS1,ROU2,THS2,ROU3,THS3
C   COMMON/L16/  REX1,RNIT1,RDNIT1
C   COMMON/L17/  REX2,RNIT2,RDNIT2
C   COMMON/L18/  REX3,RNIT3,RDNIT3
C   Z=M*CZ
C   IF(Z.GT.CL2) GO TO 10
C   IF(Z.GT.CL1) GO TO 5
C   ZZ3=1.0+REX1*ROU1/WC
C   RETURN
5  ZZ3=1.0+REX2*ROU2/WC
C   RETURN
10 ZZ3=1.0+REX3*ROU3/WC
C   RETURN
C   END

```

```

C*****C
C  A M M O N I U M   T R A N S P O R T   &   T R A N S F O R M A T I O N S   C
C                                     P R O G R A M                               C
C*****C
C  THIS SUBROUTINE PROVIDES THE SOLUTION TO THE AMMONIUM TRANSPORT C
C  AND TRANSFORMATION EQUATION UNDER TRANSIENT FLOW CONDITIONS.      C
C  IT ALSO CALCULATES THE AMMONIUM UPTAKE BY PLANT ROOTS. THE         C
C  METHOD OF SOLUTION IS THE FINITE DIFFERENCE APPROXIMATION METHOD.    C
C  ( SEE TEXT ).                                                       C
C  THE RATE OF NITRIFICATION , DENITRIFICATION AND THE DISTRIBUTION  C
C  COEFFICIENT FOR NH4-N EXCHANGE ARE OBTAINED FROM FUNCTIONS         C
C  ZZ1, ZZ2, AND ZZ3 , RESPECTIVELY.                                   C
C*****C
C
C  SUBROUTINE AMCNIA
C  NH-4 PROGRAM
COMMON/L1/ C(310),Y(310)
COMMON/L2/ AA(310),BB(310),CC(310),R(310),RDIST(310)
COMMON/L3/ N,NM1,NM2,NF1,NF2
COMMON/L4/ ALPHA,BETA,DI,DZ
COMMON/L5/ NX,NX1,NMAX,CON1
COMMON/L6/ ELNH4,PLNC3,CNITRF
COMMON/L7/ SFLUX,EI,QM,QK,CSNH4,CSNO3,DISP,XL
COMMON/L9/ TIME,TINF,TCYC
COMMON/L10/ H(310),CON(310),CAP(310),TH(310)
COMMON/L11/ CL,CL1,CL2,L1,L2
COMMON/L15/ ROU1,THS1,ROU2,THS2,ROU3,THS3
COMMON/L16/ REX1,RNIT1,RDNIT1
COMMON/L17/ REX2,RNIT2,RDNIT2
COMMON/L18/ REX3,RNIT3,RDNIT3
M=1
*FLX=-CON(M)*(H(M+1)-H(M))/DZ+CON(M)
SSINF=WFIX
FF=DZ*2.0
C(1)=(SSINF*FF*CSNH4+DISP*TH(1)*C(3)/2)/(SSINF*FF+DISP*TH(1)/2)
IF(SFLUX.LE.0.0) GO TO 13
M=2
VPP=-CON(M)*(H(M+1)-H(M))/DZ+CON(M)
C
DO 5 I=1,NM1
RKK=723(M,H(M),TH(M))
AA(I)=RKK+2.0*ALPHA*DISP-BETA*VPP/TH(M)
BP(I)=BETA*VPP/TH(M)-ALPHA*DISP
R(I)=RKK*C(M)+ALPHA*DISP*(C(M+1)-2.0*C(M)+C(M-1))
RK1=ZZ1(M,H(M),TH(M))
R(I)=R(I)-DT*RK1*C(M)
M=1+2
VPP=-CON(M)*(H(M+1)-H(M))/DZ+CON(M)
CC(I)=-ALPHA*DISP
5 CONTINUE
M=N
RKK=ZZ3(M,H(M),TH(M))
AA(N+1)=RKK+ALPHA*DISP
R(1)=R(1)+ALPHA*DISP*C(1)

```

```

X1=0.0
DO 6 I=1,NX1
PN=QM*RDIST(I+1)*C(I+1)/(QK+C(I+1)+Y(I+1))
X1=X1+DT*PN
6 R(I)=B(I)-DT*PN/TH(I+1)
PLNH4=PLNH4+X1*DZ
GO TO 14

C
13 CONTINUE
C(1)=C(2)
N=2
VPP=-CON(N)*(H(N+1)-H(N))/DZ+CON(N)
DO 11 I=1,NH1
RKK=Z23(N,H(N),TH(N))
AA(I)=RKK+2.0*ALPHA*DISP-BETA*VPP/TH(N)
BB(I)=BETA*VPP/TH(N)-ALPHA*DISP
R(I)=RKK*C(N)+ALPHA*DISP*(C(N+1)-2.0*C(N)+C(N-1))
RK1=Z21(N,H(N),TH(N))
R(I)=R(I)-DT*RK1*C(N)
N=I+2
VPP=-CON(N)*(H(N+1)-H(N))/DZ+CON(N)
CC(I)=-ALPHA*DISP
11 CONTINUE
N=N
RKK=Z23(N,H(N),TH(N))
AA(NH1)=RKK+ALPHA*DISP
N=2
VPP=-CON(N)*(H(N+1)-H(N))/DZ+CON(N)
RKK=Z23(N,H(N),TH(N))
AA(1)=RKK+ALPHA*DISP-BETA*VPP/TH(N)

C
X1=0.0
DO 7 I=1,NX1
PN=QM*RDIST(I+1)*C(I+1)/(QK+C(I+1)+Y(I+1))
X1=X1+DT*PN
7 R(I)=B(I)-DT*PN/TH(I+1)
PLNH4=PLNH4+X1*DZ
14 CONTINUE
CALL TRIDH(AA,BB,CC,R,NH1)
DO 15 I=2,N
15 C(I)=B(I-1)
C(NH1)=C(N)
RETURN
END

```

```

C
C*****C
C
C      N I T R A T E   T R A N S P O R T   &   T R A N S F O R M O T I O S
C
C      P R O G R A M
C
C*****C
C
C      THIS SUBROUTINE PROVIDES THE SOLUTION TO THE NITRATE TRANSPORT
C      AND TRANSFORMATION EQUATION UNDER TRANSIENT FLOW CONDITIONS.
C      IT ALSO CALCULATES THE NITRATE UPTAKE BY PLANT ROOTS. THE
C      METHOD OF SOLUTION IS THE FINITE DIFFERENCE APPROXIMATION METHOD.
C      ( SEE TEXT ).
C      THE RATE OF NITRIFICATION , DENITRIFICATION AND THE DISTRIBUTION
C      COEFFICIENT FOR NH4-N EXCHANGE ARE OBTAINED FROM FUNCTIONS
C      ZZ1, ZZ2, AND ZZ3 , RESPECTIVELY.
C*****C
C
C      SUBROUTINE NITRAT
C      NO3- PROGRAM
C      COMMON/L1/ C (310),Y (310)
C      COMMON/L2/ AA (310),BB (310),CC (310),R (310),RDIST (310)
C      COMMON/L3/ N,NM1,NM2,NE1,NP2
C      COMMON/L4/ ALPHA,BETA,DT,DZ
C      COMMON/L5/ NX,NX1,NRMAX,CON1
C      COMMON/L6/ FLNH4,FLNO3,DNITRF
C      COMMON/L7/ SFLUX,ET,QM,QK,CSNH4,CSNO3,DISP,XL
C      COMMON/L9/ TIME,TINF,TCYC
C      COMMON/L10/ H (310),CON (310),CAP (310),TH (310)
C      COMMON/L11/ CL,CL1,CL2,L1,L2
C      COMMON/L15/ ROU1,THS1,ROU2,THS2,ROU3,THS3
C      COMMON/L16/ REX1,RNIT1,RDNIT1
C      COMMON/L18/ REX3,RNIT3,RDNIT3
C      M=1
C      WFLX=-CON (M) * (H (M+1)-H (M)) /DZ+CON (M)
C      SSINF=WFLX
C      FF=DZ*2.0
C      Y (1) = (SSINF*FF*CSNO3+DISP*TH (1) *Y (3) /2) / (SSINF*FF+DISP*TH (1) /2)
C      IF (SFLUX.LE.0.0) GO TO 13
C      M=2
C      VPP=-CON (M) * (H (M+1)-H (M)) /DZ+CON (M)
C
C      X2=0.0
C
C      DO 5 I=1,NM1
C      AA (I) =1.0+2.0*ALPHA*DISP-BETA*VPP/TH (M)
C      BB (I) =BETA*VPP/TH (M)-ALPHA*DISP
C      R (I) =Y (M) +ALPHA*DISP* (Y (M+1)-2.0*Y (M) +Y (M-1))
C      RK1=ZZ1 (M,H (M),TH (M))
C      RK2=ZZ2 (M,H (M),TH (M))
C      R (I) =R (I) +DT*BK1*C (M)-DT*RK2*Y (M)
C      X2=X2+DT*BK2*TH (I) *Y (I)
C      M=I+2
C      VPP=-CON (M) * (H (M+1)-H (M)) /DZ+CON (M)
C      CC (I) =-ALPHA*DISP
5  CONTINUE
DNITRF=DNITRF+X2*DZ

```



```

      M=N
      AA(NM1)=1.0+ALPHA*DISP
      R(1)=R(1)+ALPHA*DISP*Y(1)
C
      X1=0.0
      DO 6 I=1,NX1
      PN=QM*RDIST(I+1)*Y(I+1)/(QK+C(I+1)+Y(I+1))
      X1=X1+DT*PN
6      R(I)=R(I)-DT*PN/TH(I+1)
      PLNO3=PLNO3+X1*DZ
      GO TO 14
C
13      CONTINUE
      Y(1)=Y(2)
      M=2
      VPP=-CON(M)*(H(M+1)-H(M))/DZ+CON(M)
C
      X2=0.0
C
      DO 11 I=1,NM1
      AA(I)=1.0+2.0*ALPHA*DISP-BETA*VPP/TH(M)
      BB(I)=BETA*VPP/TH(M)-ALPHA*DISP
      R(I)=Y(M)+ALPHA*DISP*(Y(M+1)-2.0*Y(M)+Y(M-1))
      RK1=ZZ1(M,H(M),TH(M))
      RK2=ZZ2(M,H(M),TH(M))
      R(I)=R(I)+DT*RK1*C(M)-DT*RK2*Y(M)
      X2=X2+DT*RK2*TH(I)*Y(I)
      M=I+2
      VPP=-CON(M)*(H(M+1)-H(M))/DZ+CON(M)
      CC(I)=-ALPHA*DISP
11      CONTINUE
      DNITRF=DNITRF+X2*DZ
      M=N
      AA(NM1)=1.0+ALPHA*DISP
      M=2
      VPP=-CON(M)*(H(M+1)-H(M))/DZ+CON(M)
      AA(1)=1.0+ALPHA*DISP-BETA*VPP/TH(M)
C
      X1=0.0
      DO 7 I=1,NX1
      PN=QM*RDIST(I+1)*Y(I+1)/(QK+C(I+1)+Y(I+1))
      X1=X1+DT*PN
7      R(I)=R(I)-DT*PN/TH(I+1)
      PLNO3=PLNO3+X1*DZ
14      CONTINUE
      CALL TRIDM(AA,BB,CC,R,NM1)
      DO 15 I=2,N
15      Y(I)=R(I-1)
      Y(NP1)=Y(N)
      RETURN
      END

```

```

C*****C
C                                     C
C      P R O G R A M   O U T P U T   C
C*****C
C                                     C
C      THE FUNCTION OF THIS PROGRAM IS TO PRINT THE RESULTS FROM      C
C      MODEL PREDICTION AT SPECIFIED TIMES.  IN ADDITION IT CALCULATES C
C      THE TOTAL AMOUNTS OF NITROGEN IN THE SOIL SYSTEM AND THAT TAKEN C
C      UP BY THE PLANTS                                              C
C*****C
C
C      SUBROUTINE OUTPUT
COMMON/L1/  C (310), Y (310)
COMMON/L2/  AA (310), BB (310), CC (310), R (310), RDIST (310)
COMMON/L3/  N, NH1, NH2, NE1, NE2
COMMON/L4/  ALPHA, BETA, DT, DZ
COMMON/L5/  NX, NX1, NRHAX, CON1
COMMON/L6/  PLNH4, PLNO3, DNITRF
COMMON/L7/  SFLUX, ET, QH, CK, CSNH4, CSNO3, DISP, XL
COMMON/L8/  XXX (30), C1 (30), C2 (30), C3 (30), C4 (30)
COMMON/L9/  TIME, TIMEF, TCYC
COMMON/L10/ H (310), CON (310), CAP (310), TH (310)
COMMON/L11/ CL, CL1, CL2, L1, L2
COMMON/L15/ ROU1, THS1, ROU2, THS2, ROU3, THS3
COMMON/L16/ REX1, RNIT1, RDNIT1
COMMON/L17/ REX2, RNIT2, RDNIT2
COMMON/L18/ REX3, RNIT3, RDNIT3
100  FORMAT ('1')
200  FORMAT ('1', 40X, 'TIME , DAYS =', F10.2/)
299  FORMAT (T10, 'SOIL DEPTH',
      $T25, 'PRESSURE HEAD',
      $T43, 'SOIL-WATER CONTENT',
      $T65, 'WATER FLOW',
      $T80, 'AMMONIUM CONCENTRATION',
      $T107, 'NITRATE CONCENTRATION')
301  FORMAT (T14, 'CM', T31, 'CM', T46, 'CM**3/CM**3', T66, 'VELOCITY', T82,
      $'IN SOIL SOLUTION', T109, 'IN SOIL SOLUTION')
302  FORMAT (T68, 'CM/HR', T82, 'MICROGRAMS-N/ML', T109, 'MICROGRAMS-N /ML'/)
499  FORMAT (T10, F8.2, T24, F10.2, T45, F8.2, T65, F8.4, T86, F8.3, T112, F8.3)
300  FORMAT (25X, ///,
      $25X, 'TOTAL NO-3 NITROGEN IN SOIL SOLUTION PHASE , MICROGRAMS =',
      $F10.3//,
      $25X, 'TOTAL NH-4 NITROGEN IN SOIL SOLUTION PHASE , MICROGRAMS =',
      $F10.3//,
      $25X, 'TOTAL NH-4 NITROGEN IN EXCHANGEABLE PHASE , MICROGRAMS =',
      $F10.3//,
      $25X, 'TOTAL NH-4 NITROGEN IN THE SOIL PROFILE , MICROGRAMS =',
      $F10.3//)
600  FORMAT (25X, 'TOTAL NITROGEN DENITRIFIED , MICROGRAMS =', F10.3//)
500  FORMAT (/,
      $25X, 'TOTAL NITRATE NITROGEN UPTAKE, MICROGRAMS =', F10.3//,
      $25X, 'TOTAL AMMONIUM NITROGEN UPTAKE, MICROGRAMS =', F10.3//)
C
      WRITE (6, 100)
      TIMEH=TIME/24.0
      WRITE (6, 200) TIMEH

```

```

WRITE (6,299)
WRITE (6,301)
WRITE (6,302)
WFLX=SFLUX
DO 20 I=1,NP1,2
ZZ=(I-1)*DZ
WRITE (6,499) ZZ,H(I),TH(I),WFLX,C(I),Y(I)
WFLX=-CON(I)*(H(I+1)-H(I))/DZ+CON(I)
20 CONTINUE
M=NP1
DO 30 I=1,M
AA(I)=TH(I)*C(I)
30 BB(I)=TH(I)*Y(I)
CALL QSF(DZ,AA,R,M)
XNH4=R(M)
CALL QSF(DZ,BE,R,M)
XNO3=R(M)
CALL QSF(DZ,C,R,NP1)
XT=R(NP1)
CALL QSF(DZ,C,R,L1)
X1=R(L1)
CALL QSF(DZ,C,R,L2)
X12=R(L2)
X2=X12-X1
X3=XT-X12
ENH4=X1*ROU1*REX1+X2*ROU2*REX2+X3*ROU3*REX3
XTNH4=XNH4+ENH4
WRITE (6,300) XNO3,XNH4,ENH4,XTNH4
WRITE (6,600) DNITRF
C
WRITE (6,500) FLNO3,PLNH4
RETURN
END

C
C
C*****C
C      T R I D I A G O N A L   M A T R I X   P R O G R A M      C
C
C*****C
C      THIS SUBROUTINE PROVIDES SOLUTION TO THE TRIDIAGONAL MATRIX -
C      VECTOR EQUATIONS FOR SUBROUTINE WATER, AMONIA, AND NITRAT
C
C*****C
C
SUBROUTINE TRIDM(A,B,C,D,N)
DIMENSION A(1),B(1),C(1),D(1)
DO 1 I=2,N
C(I-1)=C(I-1)/A(I-1)
A(I)=A(I)-(C(I-1)*B(I-1))
1 CONTINUE
DO 2 I=2,N
D(I)=D(I)-(C(I-1)*D(I-1))
2 CONTINUE
D(N)=D(N)/A(N)
DO 3 I=2,N
D(N+1-I)=(D(N+1-I)-(B(N+1-I)*D(N+2-I)))/A(N+1-I)
3 CONTINUE
RETURN
END

```

APPENDIX B: EXAMPLE OF INPUT AND OUTPUT

INPUT DATA

INITIAL DT, HR = 0.01000
INITIAL DZ, CM = 1.00000

FLUX OF WASTE WATER APPLICATION, CM/HR = 0.50000
EVAPOTRANSPIRATION RATE, CM/HR = 0.01000
NITROGEN UPTAKE RATE, MICROGRAM-N/CM OF ROOT LENGTH PER HOUR = 0.00100
MICHAELIS CONSTANT = 1.00000
CONCENTRATION OF APPLIED NH₄-N, MG/LITRE = 25.00000
CONCENTRATION OF APPLIED NO₃-N, MG/LITRE = 0.0
SOLUTE DISPERSION COEFFICIENT, CM²/HR = 2.50000

TOTAL LENGTH OF SOIL PROFILE, CM = 150.00000
SOIL DEPTH TO THE FIRST SOIL LAYER, CM = 15.00000
SOIL DEPTH TO THE SECOND SOIL LAYER, CM = 45.00000

SOIL WATER PARAMETERS FOR THE FIRST LAYER :	C.9600E-05	0.2763E+02	0.1000E+03	0.1000E+01
SOIL WATER PARAMETERS FOR THE SECOND LAYER :	0.2200E-05	0.3070E+02	0.4000E+02	0.1000E+01
SOIL WATER PARAMETERS FOR THE THIRD LAYER :	C.2100E-05	0.3887E+02	0.3000E+02	0.1000E+01
FIRST LAYER ; BULK DENSITY =	1.41000	SATURATION =	0.44000	
SECOND LAYER ; BULK DENSITY =	1.59000	SATURATION =	0.42000	
THIRD LAYER ; BULK DENSITY =	1.55000	SATURATION =	0.34000	

FIRST LAYER: NH₄-N EXCHANGEABLE COEFFICIENT, CM³/GM = 0.25000
NITRIFICATION RATE COEFF., HR⁻¹ = 0.10000
DENITRIFICATION RATE COEFF., HR⁻¹ = 0.01000
SECOND LAYER: NH₄-N EXCHANGEABLE COEFFICIENT, CM³/GM = 0.25000
NITRIFICATION RATE COEFF., HR⁻¹ = 0.10000
DENITRIFICATION RATE COEFF., HR⁻¹ = 0.01000
THIRD LAYER: NH₄-N EXCHANGEABLE COEFFICIENT, CM³/GM = 0.25000
NITRIFICATION RATE COEFF., HR⁻¹ = 0.10000
DENITRIFICATION RATE COEFF., HR⁻¹ = 0.01000

DURATION OF WASTE WATER APPLICATION, HRS = 10.00000
SCHEDULE OF WASTE WATER APPLICATION, I.E. CYCLE DURATION = 168.00000
NUMBER OF CYCLES = 1

TIME AT WHICH OUTPUT DATA IS REQUESTED, HR = 24.00000

SOIL DEPTH CM	PRESSURE HEAD CM	TIME - DAYS =	SOIL-WATER CONTENT CM ³ /CM ³	WATER FLOW VELOCITY CM/HR	AMMONIUM CONCENTRATION IN SOIL SOLUTION MICROGRAMS-N/ML	NITRATE CONCENTRATION IN SOIL SOLUTION MICROGRAMS-N /ML
0.0	-50.00	0.0	0.29	0.5000	25.000	0.0
2.00	-48.13	0.30	0.30	0.0000	22.467	1.867
4.00	-46.27	0.30	0.30	0.0000	19.933	3.733
6.00	-44.40	0.30	0.30	0.0000	17.400	5.600
8.00	-42.53	0.31	0.31	0.0000	14.867	7.467
10.00	-40.67	0.31	0.31	0.0000	12.333	9.333
12.00	-38.80	0.32	0.32	0.0000	9.800	11.200
14.00	-36.93	0.32	0.32	0.0000	7.267	13.067
16.00	-35.06	0.22	0.22	0.0046	5.833	14.800
18.00	-33.20	0.21	0.21	0.0002	5.500	13.400
20.00	-31.33	0.20	0.20	0.0001	5.167	13.000
22.00	-29.47	0.19	0.19	0.0001	4.833	12.600
24.00	-27.60	0.18	0.18	0.0001	4.500	12.200
26.00	-25.73	0.16	0.16	0.0001	4.167	11.800
28.00	-23.87	0.17	0.17	0.0001	3.833	11.400
30.00	-22.00	0.16	0.16	0.0001	3.500	11.000
32.00	-20.13	0.15	0.15	0.0001	3.167	10.600
34.00	-18.27	0.14	0.14	0.0001	2.833	10.200
36.00	-16.40	0.13	0.13	0.0001	2.500	9.800
38.00	-14.53	0.13	0.13	0.0001	2.167	9.400
40.00	-12.67	0.09	0.09	0.0000	1.833	9.000
42.00	-10.80	0.09	0.09	0.0000	1.500	8.600
44.00	-9.93	0.09	0.09	0.0000	1.167	8.200
46.00	-8.07	0.09	0.09	0.0000	0.933	7.771
48.00	-6.20	0.09	0.09	0.0000	0.971	7.619
50.00	-4.33	0.09	0.09	0.0000	0.933	7.467
52.00	-2.47	0.09	0.09	0.0000	0.914	7.314
54.00	-0.60	0.10	0.10	0.0000	0.895	7.162
56.00	1.27	0.10	0.10	0.0000	0.876	7.010
58.00	3.13	0.10	0.10	0.0000	0.857	6.857
60.00	5.00	0.10	0.10	0.0000	0.838	6.705
62.00	6.87	0.10	0.10	0.0000	0.819	6.552
64.00	8.73	0.10	0.10	0.0000	0.800	6.400
66.00	10.60	0.10	0.10	0.0000	0.781	6.248
68.00	12.47	0.11	0.11	0.0000	0.762	6.095
70.00	14.33	0.11	0.11	0.0000	0.743	5.943
72.00	16.20	0.11	0.11	0.0000	0.724	5.790
74.00	18.07	0.11	0.11	0.0000	0.705	5.638
76.00	19.93	0.11	0.11	0.0000	0.686	5.486
78.00	21.80	0.12	0.12	0.0000	0.667	5.333
80.00	23.67	0.12	0.12	0.0000	0.648	5.181
82.00	25.53	0.12	0.12	0.0000	0.629	5.029
84.00	27.40	0.12	0.12	0.0000	0.610	4.876
86.00	29.27	0.12	0.12	0.0000	0.590	4.724
88.00	31.13	0.13	0.13	0.0000	0.571	4.571
90.00	33.00	0.13	0.13	0.0000	0.552	4.419
92.00	34.87	0.13	0.13	0.0000	0.533	4.267
94.00	36.73	0.14	0.14	0.0000	0.514	4.114
96.00	38.60	0.14	0.14	0.0000	0.495	3.962
98.00	40.47	0.14	0.14	0.0000	0.476	3.810
100.00	42.33	0.15	0.15	0.0000	0.457	3.657
102.00	44.20	0.15	0.15	0.0000	0.438	3.505
104.00	46.07	0.15	0.15	0.0000	0.419	3.352
106.00	47.93	0.15	0.15	0.0000	0.400	3.200
108.00	49.80	0.15	0.15	0.0000	0.400	3.200

110.00	-34.23	0.16	0.0001	0.365	3.119
112.00	-32.63	0.16	0.0002	0.348	2.956
114.00	-30.93	0.17	0.0002	0.330	2.794
116.00	-29.24	0.17	0.0002	0.312	2.634
118.00	-27.55	0.18	0.0003	0.295	2.475
120.00	-25.88	0.18	0.0004	0.277	2.318
122.00	-24.23	0.19	0.0005	0.259	2.161
124.00	-22.61	0.19	0.0006	0.242	2.006
126.00	-21.02	0.20	0.0008	0.224	1.852
128.00	-19.47	0.21	0.0012	0.206	1.698
130.00	-17.94	0.21	0.0016	0.188	1.546
132.00	-16.40	0.22	0.0021	0.170	1.396
134.00	-14.83	0.23	0.0026	0.151	1.249
136.00	-13.19	0.24	0.0030	0.133	1.106
138.00	-11.48	0.25	0.0034	0.115	0.970
140.00	-9.69	0.26	0.0038	0.097	0.844
142.00	-7.83	0.27	0.0040	0.080	0.732
144.00	-5.92	0.28	0.0041	0.065	0.640
146.00	-3.96	0.30	0.0042	0.054	0.572
148.00	-1.99	0.32	0.0043	0.047	0.533
150.00	-0.00	0.34	0.0043	0.045	0.524

TOTAL NO-3 NITROGEN IN SOIL SOLUTION PHASE , MICROGRAMS = 145.575

TOTAL NH-4 NITROGEN IN SOIL SOLUTION PHASE , MICROGRAMS = 143.187

TOTAL NH-4 NITROGEN IN EXCHANGEABLE PHASE , MICROGRAMS = 168.121

TOTAL NH-4 NITROGEN IN THE SOIL PROFILE , MICROGRAMS = 311.308

TOTAL NITROGEN DENITRIFIED , MICROGRAMS = 0.0

TOTAL NITRATE NITROGEN UPTAKE, MICROGRAMS = 11.072

TOTAL AMMONIUM NITROGEN UPTAKE, MICROGRAMS = 37.800

TIME * DAYS = 1.00						
SOIL DEPTH CM	PRESSURE HEAD CM	SCIL-WATER CONTENT CM ³ /CM ³	WATER FLOW VELOCITY CM/HR	AMMONIUM CONCENTRATION IN SOIL SOLUTION MICROGRAMS-N/ML	NITRATE CONCENTRATION IN SOIL SOLUTION MICROGRAMS-N /ML	
0.0	-30.20	0.34	0.0	18.575	2.351	
2.00	-28.27	0.34	0.0049	18.515	2.378	
4.00	-26.33	0.35	0.0036	18.327	2.448	
6.00	-24.39	0.0049	0.0049	17.874	2.586	
8.00	-22.47	0.36	0.0063	17.121	2.805	
10.00	-20.54	0.37	0.0078	16.081	3.112	
12.00	-18.62	0.37	0.0094	14.805	3.513	
14.00	-16.70	0.38	0.0111	13.361	4.000	
16.00	-14.82	0.31	0.0129	11.849	4.568	
18.00	-14.05	0.31	0.0167	10.355	5.213	
20.00	-13.40	0.31	0.0212	8.950	5.908	
22.00	-12.87	0.32	0.0256	7.682	6.622	
24.00	-12.42	0.32	0.0301	6.577	7.321	
26.00	-12.07	0.32	0.0345	5.635	7.973	
28.00	-11.82	0.32	0.0388	4.843	8.549	
30.00	-11.68	0.33	0.0431	4.174	9.028	
32.00	-11.70	0.33	0.0472	3.600	9.393	
34.00	-11.92	0.32	0.0511	3.094	9.639	
36.00	-12.46	0.32	0.0547	2.635	9.765	
38.00	-13.57	0.31	0.0575	2.213	9.781	
40.00	-15.23	0.30	0.0591	1.825	9.700	
42.00	-21.34	0.27	0.0581	1.477	9.541	
44.00	-54.45	0.18	0.0494	1.188	9.328	
46.00	-88.21	0.09	0.0157	1.003	9.079	
48.00	-87.11	0.09	0.0000	0.901	8.817	
50.00	-85.55	0.09	0.0000	0.839	8.563	
52.00	-83.86	0.09	0.0000	0.802	8.322	
54.00	-82.15	0.09	0.0000	0.779	8.097	
56.00	-80.44	0.09	0.0000	0.763	7.888	
58.00	-78.73	0.09	0.0000	0.750	7.691	
60.00	-77.03	0.10	0.0000	0.739	7.505	
62.00	-75.32	0.10	0.0000	0.726	7.322	
64.00	-73.62	0.10	0.0000	0.714	7.139	
66.00	-71.92	0.10	0.0000	0.701	6.956	
68.00	-70.21	0.10	0.0000	0.688	6.774	
70.00	-68.50	0.10	0.0000	0.675	6.592	
72.00	-66.79	0.11	0.0000	0.661	6.410	
74.00	-65.08	0.11	0.0000	0.647	6.229	
76.00	-63.37	0.11	0.0000	0.633	6.048	
78.00	-61.66	0.11	0.0000	0.619	5.869	
80.00	-59.96	0.11	0.0000	0.605	5.691	
82.00	-58.25	0.12	0.0000	0.591	5.514	
84.00	-56.54	0.12	0.0000	0.576	5.338	
86.00	-54.83	0.12	0.0000	0.561	5.163	
88.00	-53.12	0.12	0.0000	0.546	4.990	
90.00	-51.41	0.13	0.0000	0.531	4.818	
92.00	-49.70	0.13	0.0000	0.516	4.646	
94.00	-47.99	0.13	0.0000	0.500	4.475	
96.00	-46.28	0.13	0.0001	0.484	4.304	
98.00	-44.57	0.14	0.0001	0.468	4.134	
100.00	-42.86	0.14	0.0001	0.452	3.963	
102.00	-41.15	0.14	0.0001	0.435	3.792	
104.00	-39.45	0.15	0.0001	0.418	3.622	
106.00	-37.74	0.15	0.0001	0.400	3.453	
108.00	-36.03	0.15	0.0001	0.383	3.285	

110.00	-34.33	0.16	0.0001	0.365	3.119
112.00	-32.63	0.16	0.0002	0.348	2.956
114.00	-30.93	0.17	0.0002	0.330	2.794
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140.00	-9.69	0.26	0.0038	0.097	0.844
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144.00	-5.92	0.28	0.0041	0.065	0.640
146.00	-3.96	0.30	0.0042	0.054	0.572
148.00	-1.99	0.32	0.0043	0.047	0.533
150.00	-0.00	0.34	0.0043	0.045	0.524

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TOTAL AMMONIUM NITROGEN UPTAKE, MICROGRAMS = 37.800

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Selim, H.M.

Simplified model for prediction of nitrogen behavior in land treatment of wastewater / by H.M. Selim and I.K. Iskandar. Hanover, N.H.: U.S. Cold Regions Research and Engineering Laboratory; Springfield, Va.: available from National Technical Information Service, 1980.

iv, 53 p., illus.; 28 cm. (CRREL Report 80-12.)

Prepared for Directorate of Civil Works - Office, Chief of Engineers by Corps of Engineers, U.S. Army Cold Regions Research and Engineering Laboratory.

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1. Land treatment. 2. Models. 3. Nitrogen cycle. 4. Wastewater treatment. I. I.K. Iskandar, co-author. II. United States. Army. Corps of Engineers. III. Army Cold Regions Research and Engineering Laboratory, Hanover, N.H. IV. Series: CRREL Report 80-12.