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SIMULATION OF THE FATE OF NITROGEN FROM THE DISPOSAL OF POULTRY LITTER

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ABSTRACT

SIMULATION OF THE FATE OF NITROGEN FROM THE DISPOSAL OF POULTRY LITTER

A PC/AT computer model was developed to simulate the transport of water, nitrate and ammonia in the soil profile after an application of poultry litter to pasture. The model was written using FORTRAN 77 compiler and can be used on any IBM type compatible computer with a math coprocessor. Poultry litter has been shown to be a potential source of plant nutrients, but mismanagement can result in nitrate pollution of the surface and groundwater. The model is composed of a main program, 11 subroutines and three subprograms. An example was shown of the flexibility and dynamic nature of the computer model. The redistribution and transformation of NH_4 and NO_3 in the soil profile was followed for 84 days. Output of the NH_4 and NO_3 concentration distributions, plant uptake and cumulative soil solution concentrations of these ions in the soil profile on a weekly basis was shown.

H. D. Scott

Completion Report to the U. S. Department of the Interior, Reston, VA, June 1989

Keywords -- Groundwater/Denitrification/Dynamic Programming/Solute Transport/Waste Disposal

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INTRODUCTION

In recent years there has been a marked increased in the number of wells in the Ozark region that contain nitrate-N concentrations above the maximum concentration limit (MCL). This increase in well contamination coincides with the explosive increase in density of poultry houses and operations in the region. Arkansas has the highest production of broilers in the U.S. and a summary of the productivity of the industry for the last 5 years is given in Table 1.

Table 1. The number of chickens, turkeys and broilers produced in Arkansas over the last 5 years.

Year	Chickens	Turkeys	Broilers
	thousands		
1978-1988 avg.	24,626	15,063	737,694
1984	22,560	14,366	724,964
1985	23,766	16,000	759,963
1986	24,382	16,500	786,779
1987	25,343	18,000	878,574
1988	21,435	18,000	896,832

These data were summarized from the 1988 Arkansas Agricultural

Statistics and show that the inventory of poultry in the state has continually increased since 1984 and that the number of broilers is quite large as compared to egg-laying chickens and turkeys.

The economic impact of the poultry industry in Arkansas is shown by the data given in Table 2. These data were also taken from the 1988 Agricultural Statistics and indicate that the poultry industry contributed over $1.3 billion to the state's economy.

Table 2. A summary of the status of the poultry industry in Arkansas during 1988.

Parameter	Chicken	Broiler
Inventory, #	21,435,000	896,832,000
Price per bird, $	3.60	0.34
Gross Income, $	77,166,000	1,250,184,000

If we assume that each broiler produces 2.5 pounds of waste on a dry weight basis annually (Dr. T. L. Barton, personal communication), then the product of the average waste per broiler and their number in the state gives the total amount of waste produced each year. For Arkansas during 1988 this amounted to over 2.22 billion pounds of broiler waste produced.

The chickens and broilers are not, however, evenly distributed throughout the state (Figure 1). During 1988, Cooperative Extension Districts 1, 4 and 7 produced 29.9, 26.5 and 21.2 % of the state's total broiler production, respectively. Thus, the western tier of counties which consists of 23 counties near Oklahoma produced over 77 % of the broilers in Arkansas. The density of broilers in each of these counties and in the three districts, the estimated litter waste produced, and the average application rate on a farmland area basis for 1988 are presented in Table 3.

To further complicate the situation, the poultry waste is not uniformly disposed of during the year. In most cases, the poultry litter is removed from the chicken houses during the spring and land applied to nearby fescue and/or bermudagrass pastures. The poultry litter waste contains a high concentration of organic-N which subsequently undergoes several conversion processes to other forms of nitrogen. Of major concern is the biological conversion of organic-N to nitrate which is soluble in soil water. Land application of the poultry waste can be used to provide a cheap source of fertilizer for the pasture grasses. However, over application closely followed by significant rainfall may result in runoff and/or downward transport of the more mobile elements in the poultry litter to the groundwater, lakes and streams.

Therefore, because of the high production and large amounts of poultry wastes produced in Arkansas, the economic impact of the

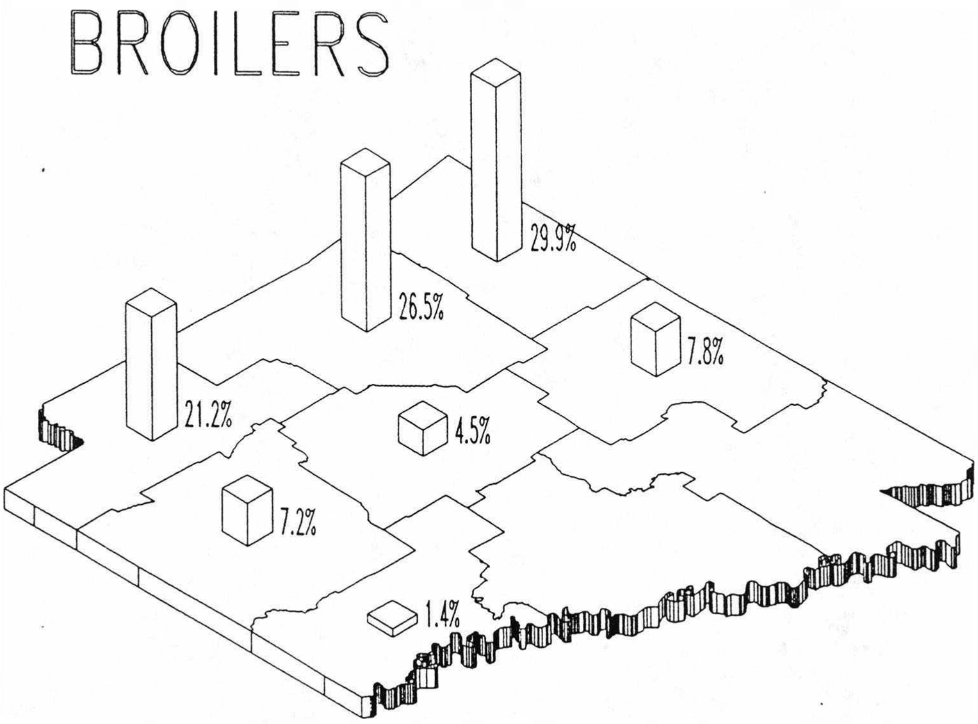


Fig. 1. Percent of total state number of broilers by district.

Table 3. Land area, number and density of broilers and estimated litter waste produced in the three districts.

District and County	Farmland Area	Broilers	Broiler Density	Estimated Waste	
				Produced	Density
	A	(x1000)	(no./A)	(lbx1000)	(lb/A)
District 1					
Benton	302,659	78,090	258.0	195,225	645.0
Boone	242,099	- -	- -	- -	- -
Carroll	240,838	30,100	125.0	75,250	312.5
Madison	260,125	46,065	177.1	115,163	442.7
Newton	98,106	- -	- -	- -	- -
Washington	362,670	113,635	313.3	234,088	783.3
TOTAL	1,506,497	267,890	177.8	669,725	444.6
District 4					
Crawford	131,221	14,268	108.7	35,670	271.8
Franklin	165,498	12,865	77.7	32,163	194.3
Johnson	114,283	21,081	184.5	52,703	461.2
Logan	187,992	24,679	131.3	61,698	328.2
Polk	112,409	49,537	440.7	123,843	1,101.7
Pope	156,212	31,239	200.0	78,098	499.9
Scott	112,523	28,616	254.3	71,540	635.8
Sebastian	118,946	10,564	88.8	26,410	222.0
Yell	196,674	45,181	229.7	112,953	574.3
TOTAL	1,295,758	238,030	183.7	595,075	459.2
District 7					
Hempstead	182,876	35,201	192.5	88,003	481.2
Howard	102,407	43,236	422.2	108,090	1,055.5
Lafayette	110,164	16,581	150.5	41,453	376.3
Little River	146,459	3,248	22.2	8,120	55.4
Miller	174,502	14,799	84.8	36,998	212.0
Montgomery	78,026	17,100	219.2	42,750	547.9
Pike	68,402	22,498	328.9	56,245	822.3
Sevier	126,457	37,459	296.2	93,648	740.5
TOTAL	989,293	190,122	192.2	475,305	480.4

industry on the state and a concern to maintain the water quality standards of our groundwater, lakes and streams, the development of poultry waste management techniques that guide the land disposal activities are of paramount importance. The solution of the problem will involve both temporal and spatial aspects.

A. Purpose and Objectives

The objectives of this research were to develop a PC/AT computer model of the fate and transport of N compounds to the groundwater after the land disposal of poultry litter, and to use the model to predict the fate of these compounds under northwest Arkansas' weather and soil conditions.

B. Related Research and Activities

A summary of Arkansas' water mineral quality data in 1971 and 1972 showed that less than 2.2 % of the samples tested were above the MCL of 10 ppm nitrate-N (Hileman and Sabbe, 1983). A 1986 summary, however, showed that 14 % of the wells tested for drinking water contained nitrates above the nitrate-N MCL (Hileman and Langston, 1986).

Steele and Adamski (1987) reported on a 3-year study around Beaver Lake Reservoir in which ground water samples were collected in the spring of two sites differing in land use. One site consisted of a pasture in which broiler litter had been applied while the other site was mostly forested. Higher concentrations of nitrate and chloride and higher counts of fecal coliform and streptococcus were found during the spring sampling of the pasture site when compared to the forested site. They concluded that agricultural practices such as cattle manure, application of broiler manure and commercial fertilizers and septic tank effluent, individually or in combination, degraded the water quality of the springs.

The data of Hileman and Sabbe and Steele and Adamski indicate that increasing concentrations of groundwater nitrate-N are evident in northwest Arkansas and require an intensified effort to understand the mechanisms responsible for the increased contamination. It appears that the higher concentrations of nitrate-N in these well waters in recent years is correlated with the explosive growth in the poultry industry.

The composition and fertilizer value of poultry litter in Arkansas was determined by Hileman (1967 and 1973). Other studies have characterized the mineralization of N from poultry manure or litter. Castellanos and Pratt (1981) found a linear relationship between the N released during 10-weeks incubation and the CO_2 evolved during four weeks from poultry manure. Hadas et al. (1983) reported N mineralization from poultry litter as a two-phase, first-order kinetics process. Both studies found that a majority of N mineralization occurred during the first day of decomposition. Sims (1986) reported that 40% of poultry litter (sawdust bedding) organic N was mineralized when a litter slurry was incorporated into soil and incubated for 150 days. Gale and Gilmour (1986) found three distinct phases of decomposition of poultry litter. During the rapid phase of decomposition, net N and net C mineralization were linearly related after an initial flush of N mineralization at one day. The rapid phase was followed by a slower phase of net N mineralization which, in turn was followed by an even slower phase of net N mineralization. They also found that decomposition depended on the size fraction of the litter and temperature.

During the decomposition processes of poultry litter, it is apparent that a considerable amount of N is mineralized to NH_4^+. The ammonium formed is either adsorbed onto the exchange complex of soil particles, volatilized as NH_3, or is oxidized to nitrate and leached from the system. Adriano et al. (1974) found that loss rates of N were soil water and temperature dependent. The highest losses were found at the highest temperatures and soil water contents. Their results showed that losses approaching 50 % occurred largely through volatilization of NH_3. They also suggested that leaching of nitrate-N was an important loss pathway. Cooper et al. (1984) showed that less than 10 % of the total N applied in chicken litter over a 4-year period was recovered in corn. The percent of the total N applied that was found in the top 6 m of the soil profile generally decreased with increased manure N application, although N content increased with increased N application. Their results clearly show that NO_3 from poultry litter is highly mobile in the soil profile and that significant nitrate-N concentrations were found at the 6 m depth. Their data showed a significant amount of the total N applied at high rates of poultry litter application had moved below the 6 m depth in the form of nitrate-N and precluded any N mass balance determinations. They concluded that the most feasible means of determining the quantity of manure to apply to crop growth and simultaneously reduce N leaching would be to use a decay series for manure decomposition combined with an estimate of atmospheric loss.

MODEL DEVELOPMENT

The model for prediction of N behavior in the soil environment was originally developed by Selim and Iskandar (1980). The original model was developed in FORTRAN on a IBM System 360 mainframe computer and was used to simulate the movements of NH_4, NO_3 and water simultaneously over depth and time in land treatment systems. The model is based on the solution of the transient soil water flow equation simultaneously with the equations describing the transformation, transport, and plant uptake of N in the soil. Explicit-implicit finite differences was the numerical method used to solve the differential equations. We chose this computer model over other models because of (1) it is relatively simple and flexible, (2) it provides the numerical solution to the water flow equation simultaneously with the ammonium and nitrate transport and transformation equations, (3) it uses transient-state rather than steady-state flow equations, (4) it uses a layered as well as homogeneous soil profiles, and (5) it includes the biochemical pathways necessary to compute a N balance.

A. Description of the Model

The computer model is composed of a main program, 11 subroutines and three function subprograms (Appendix A). A listing and short description of each of these subroutines are presented in Table 4. A general flowchart of the model is shown in Figure 2.

Table 4. Model subroutines and a short description as given by Selim and Iskandar (1980).

Subroutine	Description
IDIST	uses the initial input distribution in the profile
IDIST2	similar to IDIST except that it allows the calculation of the initial distribution regardless of locations at which measurements are provided.
ROOTS	provides the root distribution as a function of time and depth in the soil profile.
INDTDZ	used if the soil water flux is extremely small
WATER	provides the solution for the water flow equation
WPROP	provides the soil-water properties for each soil layer
AMONIA	provides the solution to the ammonium transport and transformation equation under transient flow conditions, and calculates the ammonium uptake by plant roots.
NITRAT	provides the solution to the nitrate transport and transformation equation under transient flow conditions, and calculates the nitrate uptake by plant roots.
ZZ1	provides the rate coefficient for nitrification for each soil horizon as a function of soil water pressure
ZZ2	provides the rate coefficient for denitrification for each soil horizon as a function of soil water content
ZZ3	provides the retardation factor for ammonium exchange
OUTPUT	prints the results at specified times and carries out several integrations in order to calculate the total amount of nitrate and ammonia in the soil solution and total ammonia in the exchangeable phase.
TRIDM	provides the solution of a tridiagonal matrix-vector equation.
QSF	performs the integration of a tabular function Y given at equal distance H using trapezoidal rule

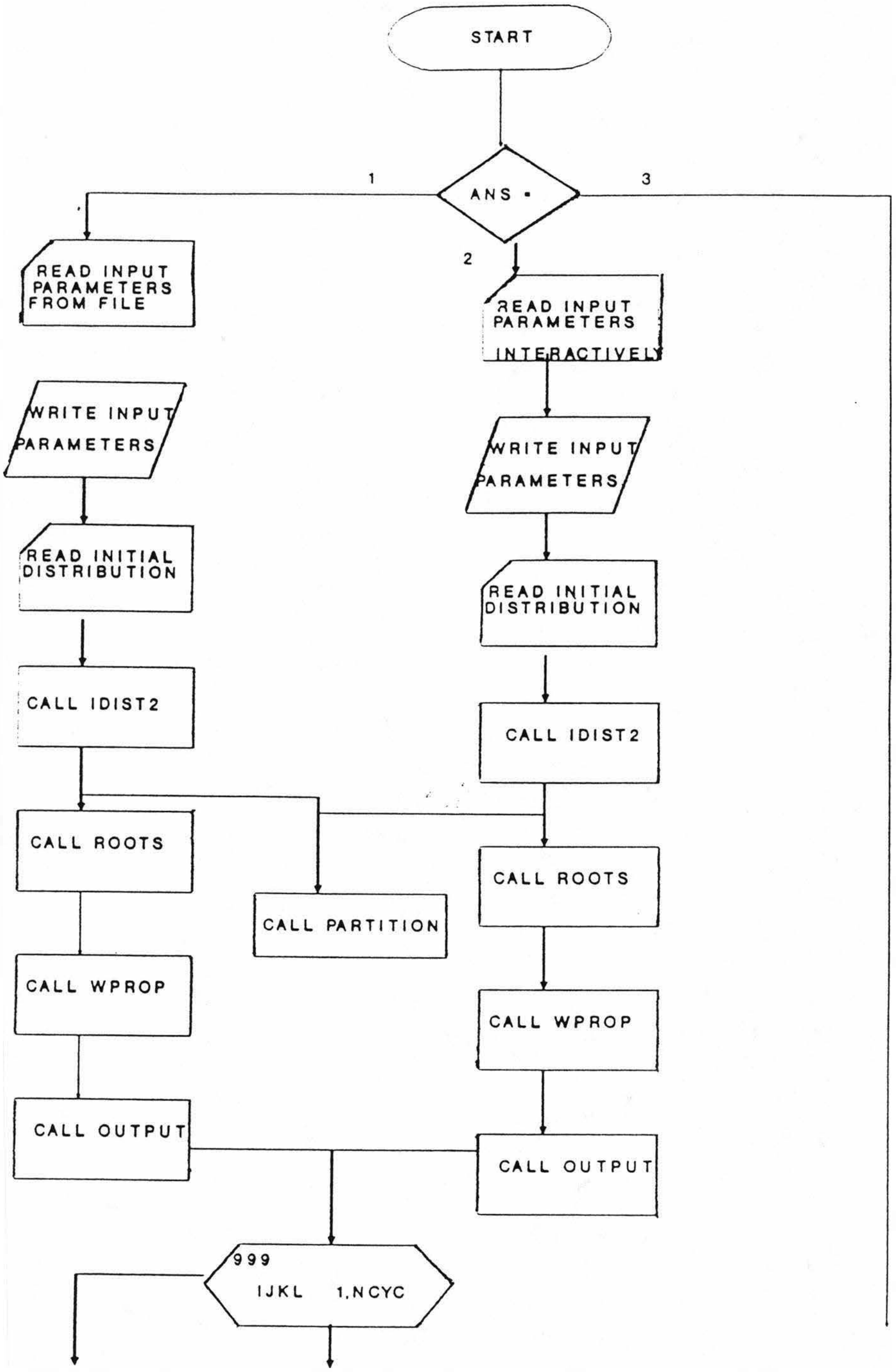
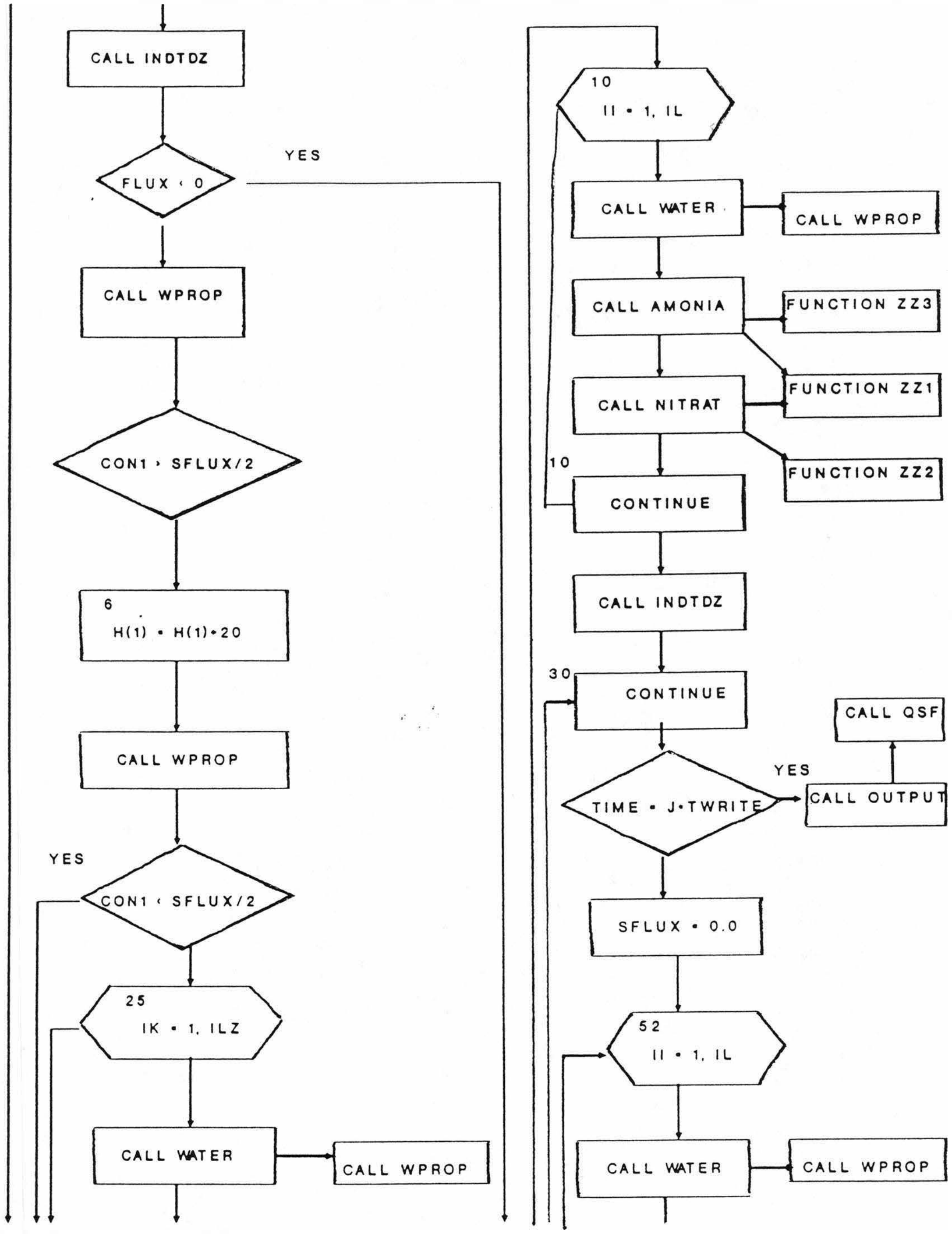
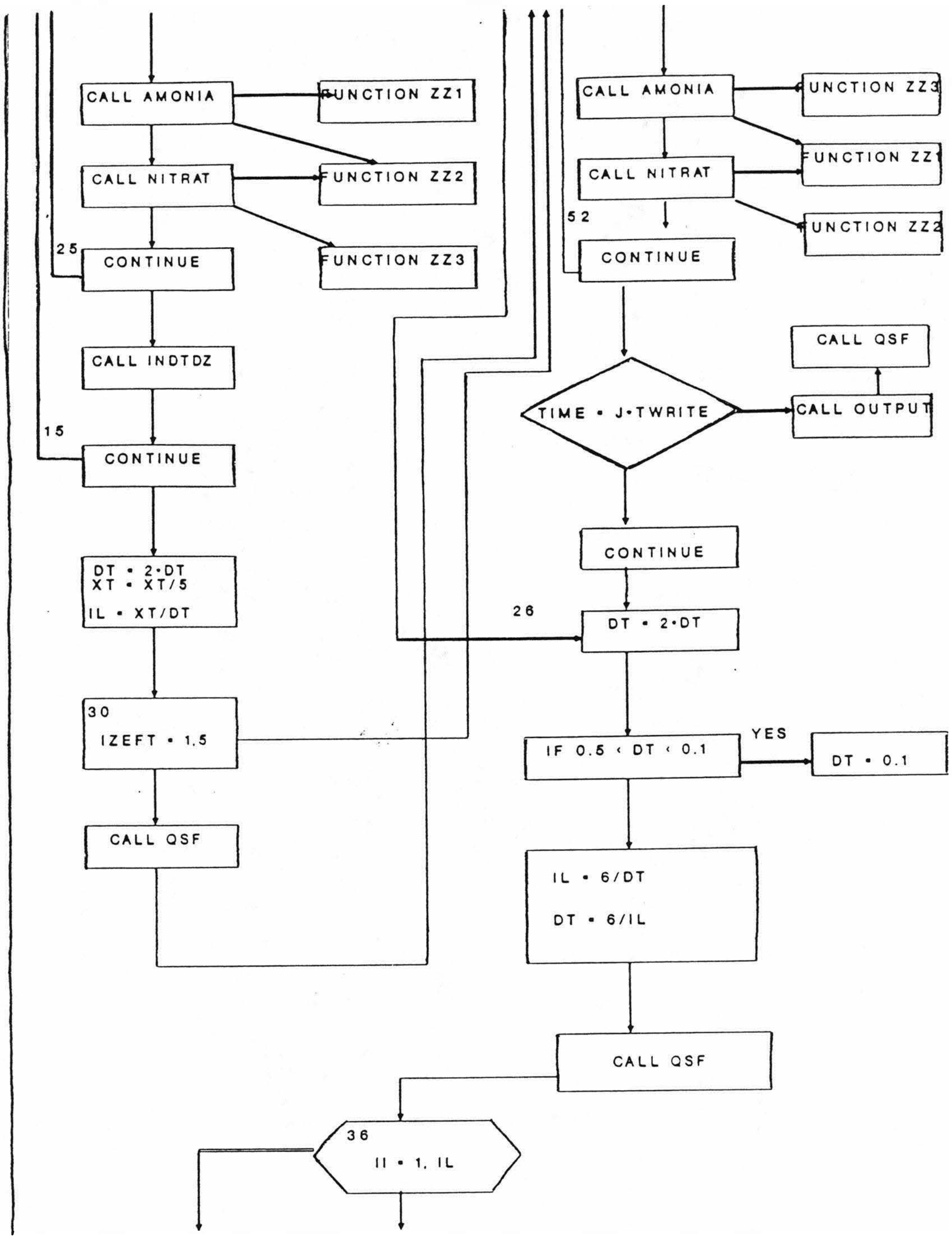


Fig. 2. Model flow chart.

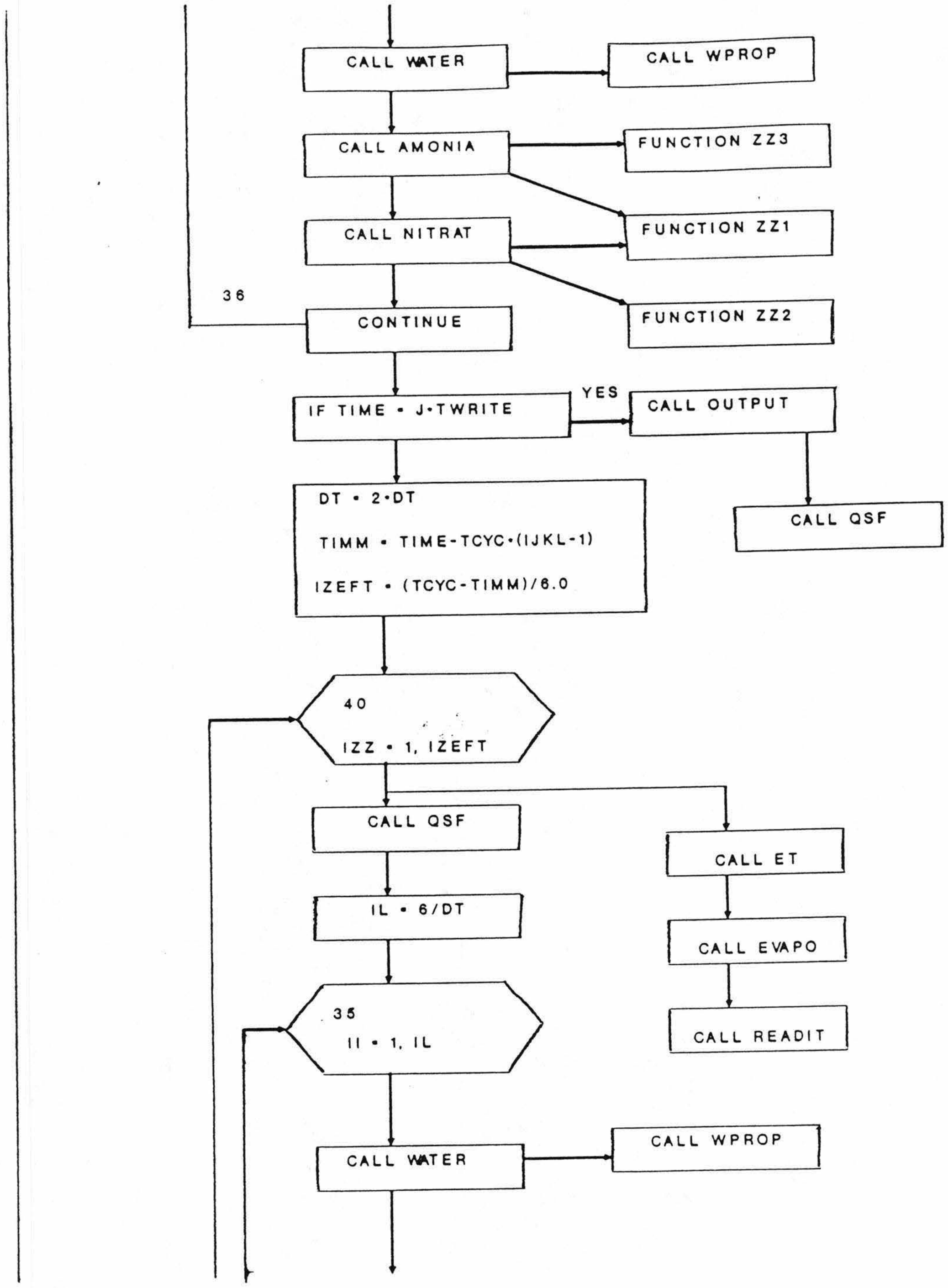
cont.


CALL INDTDZ
FLUX < 0
YES
CALL WPROP
CON1 > SFLUX/2
6
H(1) = H(1)+20
CALL WPROP
YES
CON1 < SFLUX/2
25
IK = 1, ILZ
CALL WATER
CALL WPROP
10
II = 1, IL
CALL WATER
CALL WPROP
CALL AMONIA
FUNCTION ZZ3
FUNCTION ZZ1
CALL NITRAT
FUNCTION ZZ2
10
CONTINUE
CALL INDTDZ
30
CONTINUE
CALL QSF
YES
TIME = J*TWRITE
CALL OUTPUT
SFLUX = 0.0
52
II = 1, IL
CALL WATER
CALL WPROP

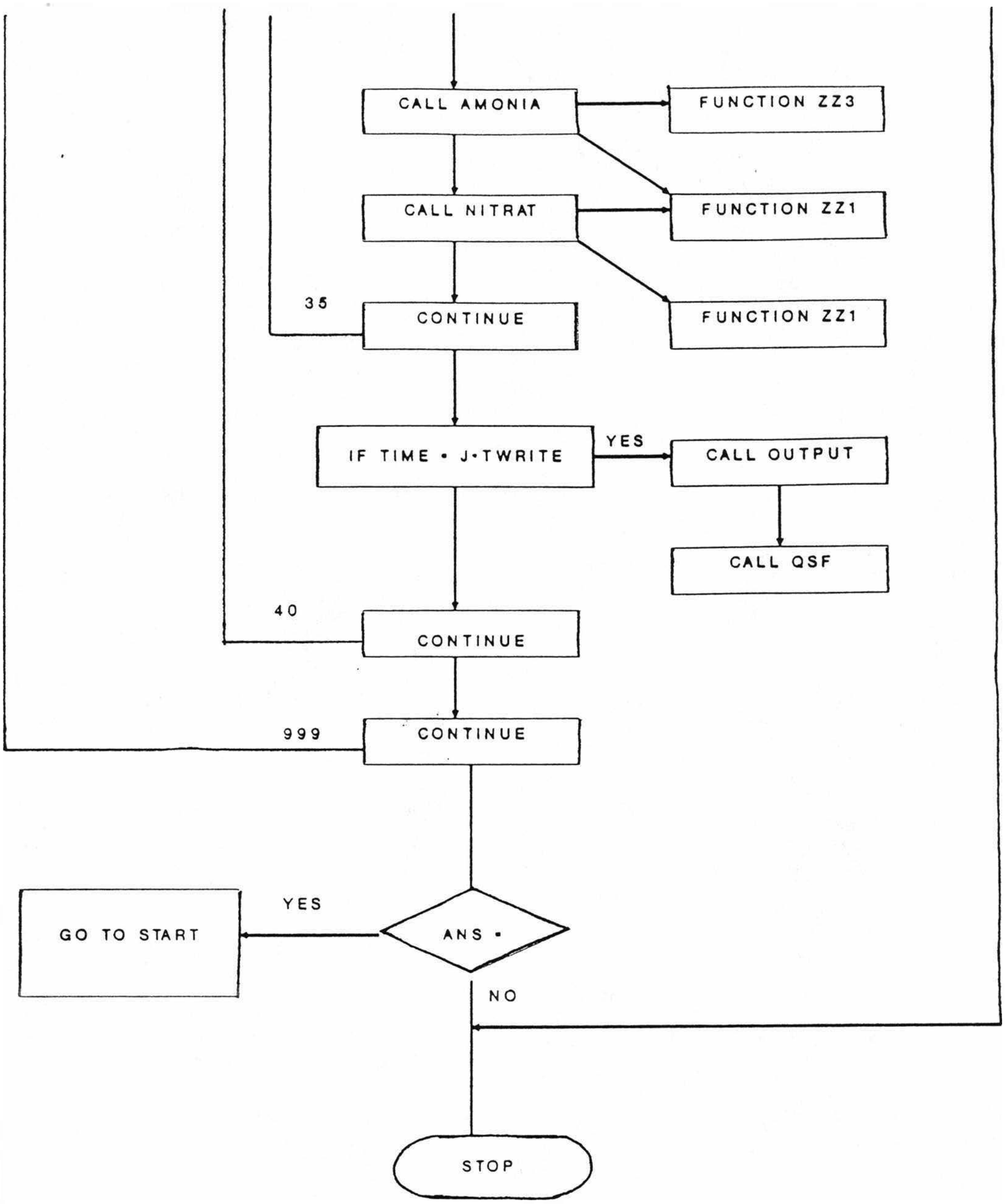
cont.


CALL AMONIA
FUNCTION ZZ1
CALL NITRAT
FUNCTION ZZ2
25
CONTINUE
FUNCTION ZZ3
CALL INDTDZ
15
CONTINUE
DT = 2*DT
XT = XT/5
IL = XT/DT
30
IZEFT = 1.5
CALL QSF
CALL AMONIA
FUNCTION ZZ3
FUNCTION ZZ1
CALL NITRAT
52
FUNCTION ZZ2
CONTINUE
CALL QSF
TIME = J*TWRITE
CALL OUTPUT
CONTINUE
26
DT = 2*DT
IF 0.5 < DT < 0.1
YES
DT = 0.1
IL = 6/DT
DT = 6/IL
CALL QSF
36
II = 1, IL

cont.


CALL WATER
CALL WPROP
CALL AMONIA
FUNCTION ZZ3
CALL NITRAT
FUNCTION ZZ1
36
CONTINUE
FUNCTION ZZ2
YES
IF TIME • J·TWRITE
CALL OUTPUT
DT • 2•DT
TIMM • TIME-TCYC•(IJKL-1)
IZEFT • (TCYC-TIMM)/6.0
CALL QSF
40
IZZ • 1, IZEFT
CALL QSF
CALL ET
IL • 6/DT
CALL EVAPO
35
II • 1, IL
CALL READIT
CALL WATER
CALL WPROP

cont.


CALL AMONIA
FUNCTION ZZ3
CALL NITRAT
FUNCTION ZZ1
35
CONTINUE
FUNCTION ZZ1
IF TIME • J•TWRITE
YES
CALL OUTPUT
CALL QSF
40
CONTINUE
999
CONTINUE
YES
GO TO START
ANS •
NO
STOP

B. Input Parameters to the Model

A menu was written where the user can enter the input data either interactively from the keyboard or from a formatted input file. These input parameters are listed in Table 5.

C. Output Parameters of the Model

The output parameters are provided by the model and can be requested. The output from the computer program can be displayed on the screen, sent to a printer or to a file for later manipulation. A listing of the output parameters is given in Table 6. Most of these output parameters are provided as a function of depth in the profile and time.

Table 5. Input parameters and their units needed for the model.

- initial time step (hr)
- initial soil depth increment (cm)
- initial flux of water application (cm/hr)
- evapotranspiration rate (cm/hr)
- N uptake rate (ug/hr cm of root length)
- Michaelis constant (ug/ml)
- concentration of the applied NH_4-N (ug/L)
- concentration of the applied NO_3-N (ug/L)
- solute dispersion coefficient (cm^2/hr)
- total thickness of the soil profile (cm)
- soil depth to the first soil layer (cm)
- soil depth to the second soil layer (cm)
- soil water parameters for the first 3 horizons which include
  - a. eta value
  - b. alpha value
  - c. a value
  - d. b value
- bulk density (g/cm^3) and saturated water content (cm^3/cm^3) for the first 3 horizons.
- ammonium distribution coefficient for the first 3 horizons (cm^3/g)
- nitrification rate coefficient for the first 3 horizons (hr^{-1})
- denitrification rate coefficient for the first 3 horizons (hr^{-1})
- duration of poultry litter application (hr)
- time before the next application starts (hr)
- simulation time (hr)
- pressure head at specified soil depths for initial distribution (cm)
- soil water content at specified soil depths for initial distribution (cm^3/cm^3)
- NH_4-N concentration at specified soil depths for initial distribution
- NO_3-N concentration at specified soil depths for initial distribution.

Table 6. Output parameters and their units given by the computer model.

- soil water pressure head (cm)
- soil water content (cm^3/cm^3)
- soil water flow velocity (cm/hr)
- ammonium concentration in the soil solution (mg N/ml)
- nitrate concentration in the soil solution (mg N/ml)
- total NO_3-N in the soil solution phase (ug)
- total NH_4-N in the soil solution phase (ug)
- total NH_4 in exchangeable phase (ug)
- total NH_4-N in the soil profile (ug)
- total N denitrified (ug)
- total NO_3 uptake (ug)
- total NH_4-N uptake (ug)
- mass balance for the water, NO_3, and NH_4 in the profile

SIMULATION RESULTS

A specific set of inputs were chosen to illustrate the usefulness of the computer model in simulating the transport and distribution of soil water, NH_4-N and NO_3-N. The input data used in the simulations are presented in Table 7. The example used is for a 300 ug injection of NH_4-N every 7 days followed by a daily application rate of 12 cm of water and evapotranspiration rate of 0.24 cm/day. After 7 days of simulation of the distribution of water, NH_4 and NO_3, the computer model updates the inputs which is then followed by another injection of 300 ug and 7 days of simulation. This process was repeated every 7 days for a total simulation time of 84 days. The depth of the soil profile was assumed to be 140 cm. The initial and final distributions of soil water pressure, water content, flow velocity, and concentrations of NH_4 and NO_3 are given in Table 8.

As shown in Figure 3 the NH_4-N was removed from the top soil very rapidly, while its distribution in the deeper soil layers continued to increase at a relatively slow rate. The removal of the ammonium nitrogen from the top soil can be explained by the fact that it is subjected to biological dissipation processes such as plant uptake and conversion to nitrate by the nitrifying bacteria. It should also be mentioned here that in this simulation, 77.8% of the plant roots were assumed to be in the top 15 cm of the soil profile.

The data in Figure 4 shows that NO_3-N moved rapidly in the soil

Table 7. Input data used for the computer simulations.

Initial time step = 0.01 hr
Initial depth increment = 1.0 cm
Total soil depth = 150.0 cm
Depth to the first layer = 15.0 cm
Depth to the second layer = 45.0 cm
Continuous flux of water application = 0.5 cm/hr
Evapotranspiration rate = 0.01 cm/hr
Nitrogen uptake rate = 0.001 mg/ml
Michaelis constant = 1.0 mg/ml
Concentration of applied NH_4-N = 25.0 mg/ml
Concentration of applied NO_3-N = 0.0 mg/ml
Solute dispersion coefficient = 2.5 cm^2/hr
Duration of litter application = 10.0 hrs
Simulation time for one cycle = 168.0 hrs
Total time of simulation = 84.0 days
Time for output = 24.0 hrs

	First layer	Second layer	Third layer
Eta	0.9600E-05	0.2200E-05	0.2100E-05
Alpha	0.2763E+2	0.3070E+2	0.3887E+02
a	100.0	40.0	30.0
b	1.0	1.0	1.0
Bulk density	1.41	1.59	1.55
Saturated water content	0.44	0.42	0.34
NH4-N distribution coeff.	0.25	0.25	0.25
NH4-N nitrification coeff.	0.10	0.10	0.10
NO3-N distribution coeff.	0.01	0.01	0.01

Table 8. Initial and final distributions of the output parameters.

Depth	Pressure head	Water content	Flow velocity	Concentration NH_4	NO_3
cm	cm	cm^3/cm^3	cm/hr	ug/ml	
Day 1					
0	-30.1	0.34	0.0000	20.40	1.93
10	-20.5	0.37	0.0049	20.52	1.92
20	-13.4	0.32	0.0094	20.76	1.82
30	-11.5	0.33	0.0256	21.05	1.68
40	-14.0	0.31	0.0475	21.35	1.54
50	-85.7	0.09	0.0645	21.55	1.88
60	-77.1	0.10	0.0000	21.70	2.59
70	-68.6	0.10	0.0005	21.80	3.22
80	-60.0	0.11	0.0003	21.83	3.80
90	-51.4	0.13	0.0002	21.84	4.31
100	-42.9	0.14	0.0001	21.87	4.65
110	-34.3	0.16	0.0001	21.99	4.59
120	-25.7	0.18	0.0001	22.14	4.28
130	-17.1	0.22	0.0001	22.31	3.93
140	- 9.7	0.26	0.0001	22.50	3.55
Day 84					
0	-50.3	0.29	0.0000	0.00	0.00
10	-41.0	0.31	0.0082	0.00	0.00
20	-31.1	0.24	0.0001	0.06	0.09
30	-25.6	0.26	0.0009	0.73	0.80
40	-21.2	0.27	0.0034	2.45	2.46
50	-17.8	0.21	0.0055	4.78	4.41
60	-16.8	0.22	0.0077	7.37	6.12
70	-16.0	0.22	0.0094	9.98	7.29
80	-15.4	0.23	0.0110	12.39	7.84
90	-14.8	0.23	0.0127	14.42	7.85
100	-14.3	0.23	0.0143	16.04	7.45
110	-13.8	0.23	0.0159	17.30	6.80
120	-13.3	0.24	0.0175	18.28	6.05
130	-12.4	0.24	0.0191	19.08	5.21
140	- 8.6	0.26	0.0205	19.83	4.21

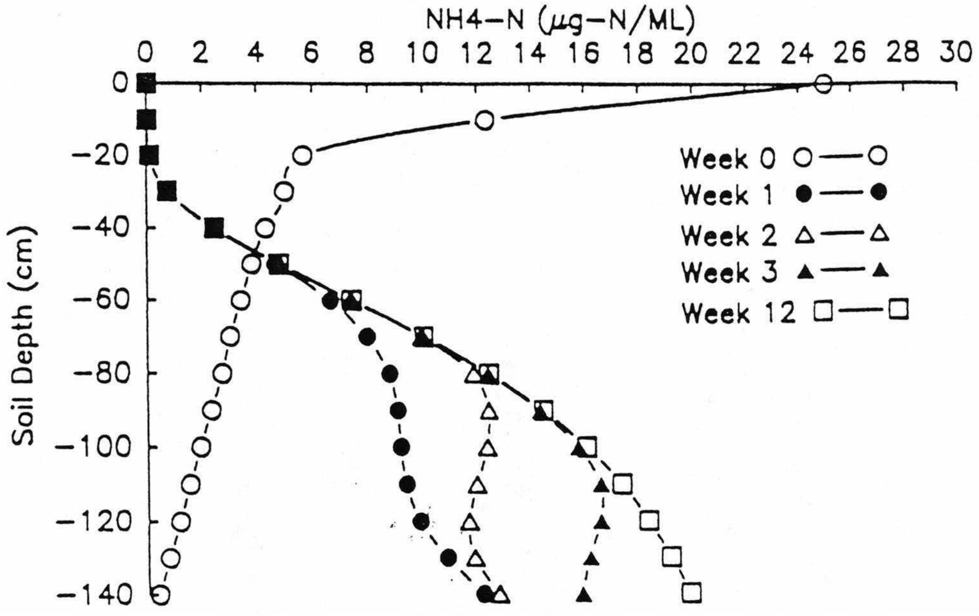


Fig. 3. Predicted ammonium nitrogen distribution with depth and time following weekly application of 300 micrograms of NH_4-N.

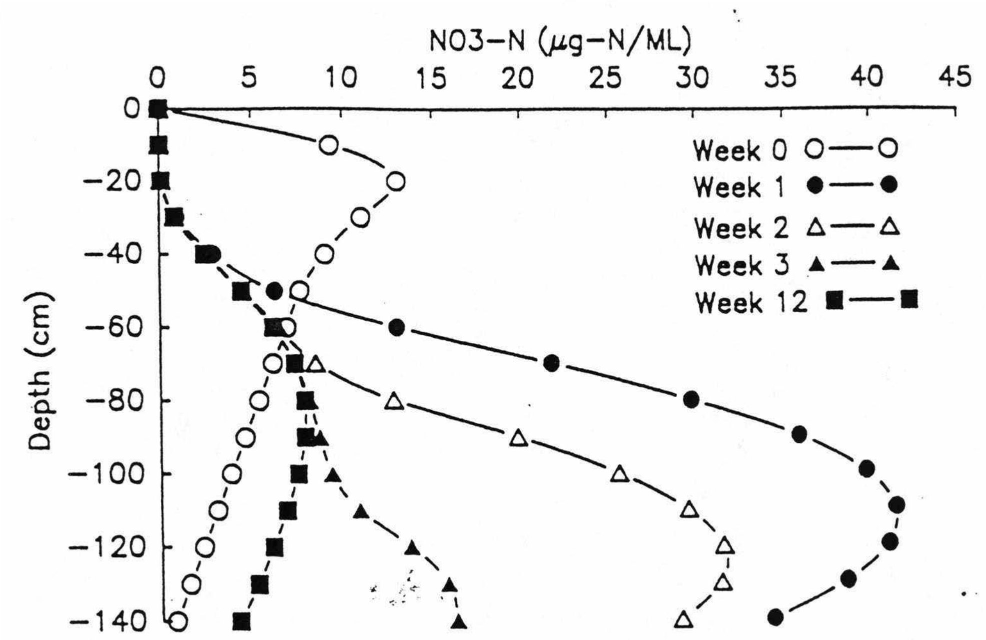


Fig. 4. Predicted nitrate nitrogen distribution with depth and time following weekly application of 300 micrograms of NH_4-N.

profile following the application of the ammonium nitrogen. As time proceeds, the concentration of the NO_3-N decreased at a higher rate. The computer model predicted that the amount of nitrate available for leaching at the bottom of the soil profile decreased with time indicating that there is a potential for groundwater contamination immediately after the application of the poultry litter if the soil conditions are favorable and that as time proceeds this potential for leaching decreases.

The data in Figure 5 shows the simulated results of NH_4- and NO_3- plant uptake over 84 days. The uptake of NH_4-N was higher than NO_3-N at all times, as was indicated clearly in Fig. 3.

The cumulation of the total amount of NH_4- and NO_3-N in the soil solution phase of the entire soil profile is shown in Fig. 6. There was a flush of NO_3-N after the application of the poultry litter, then gradually the NO_3 disappeared as a result of plant uptake and leaching. Much of the NH_4-N was in the solution phase in the soil profile, except at the beginning of the simulation when there was a large plant uptake.

The cumulative amounts of denitrified N over the 84 days of simulation is shown in Figure 7. In general, these results show that denitrification proceeded in two phases. The first phase lasted for 21 days and proceeded at a rate of 3.3 ug/day. This was followed by the second phase which lasted for much longer times and at a rate of 0.6 ug/day.

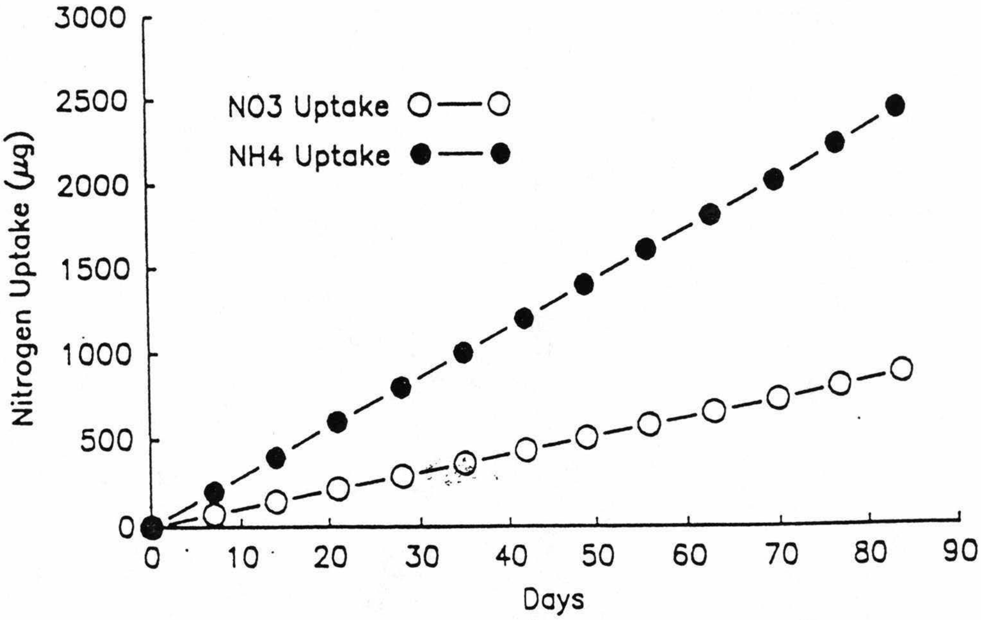


Fig. 5. Predicted ammonium and nitrate nitrogen uptake by plants as a function of time following weekly application of 300 micrograms of NH_4-N.

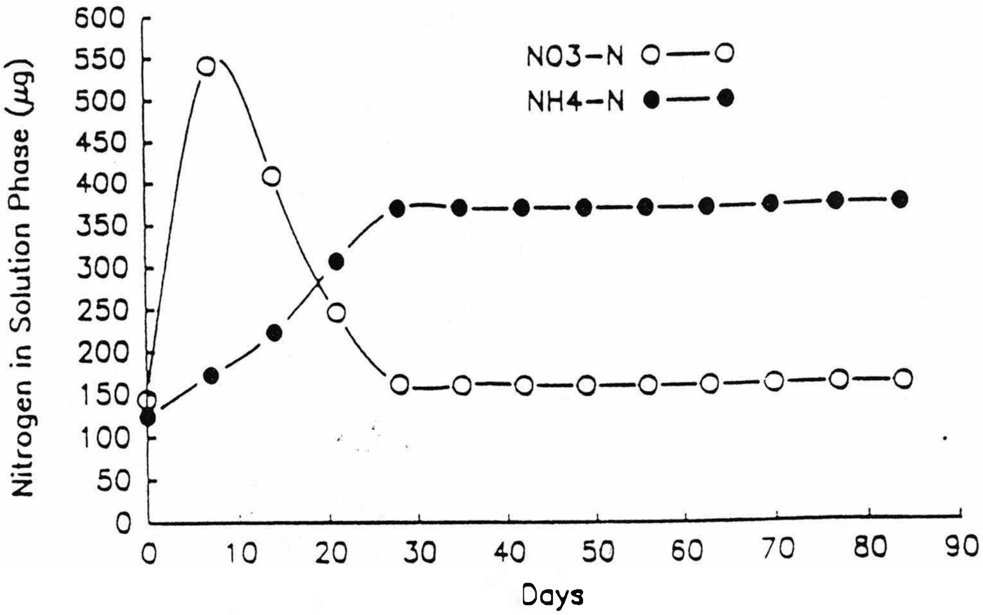


Fig. 6. Predicted total ammonium and nitrate nitrogen in the solution phase as a function of time following weekly application of 300 micrograms of NH_4-N.

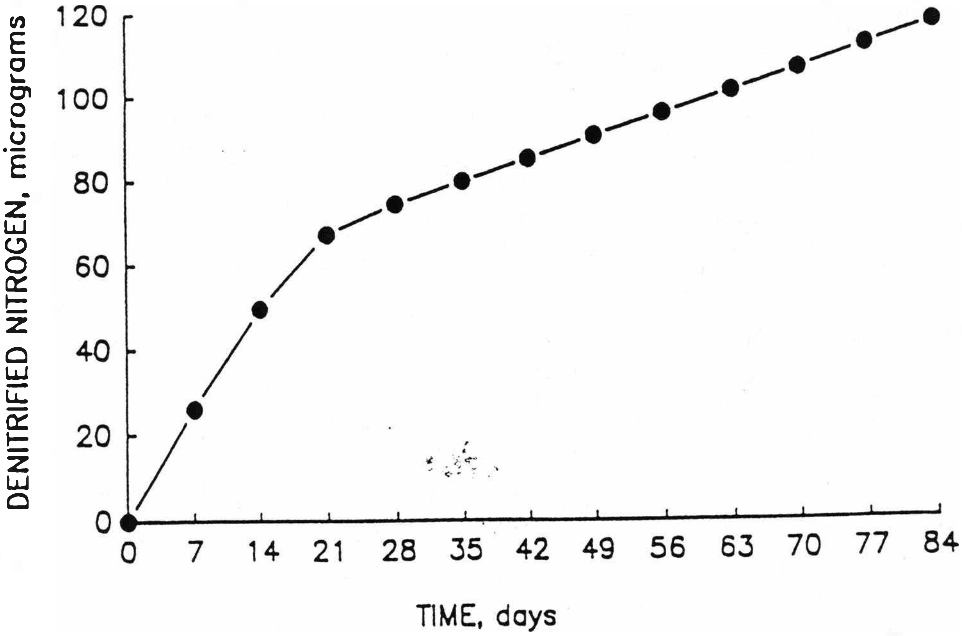


Fig. 7. Predicted amounts of nitrogen denitrified as a function of time after weekly application of 300 micrograms of NH_4-N.

CONCLUSIONS

Simulation of the transport and transformations of NH_4 and NO_3 in the soil profile showed just a few of the capabilities of the computer model. The results showed that the model is flexible and dynamic and can be used as a tool in developing management schemes in the poultry litter disposal on any soil series and weather conditions in Arkansas.

In the future a more detailed weather subroutine should be interfaced with the model to extend its use for the prediction of poultry litter disposal on any soil series that exist in Arkansas. The model capabilities can also be extended by further development of the transformation scheme of the poultry litter and by increasing the time of application from a weekly schedule to an annual schedule. The addition of other factors that may have a significant effect on the transformations and subsequent redistribution of N from a poultry litter application include temperature. All of these additions will help in producing more realistic simulations of the fate of N in the environment from the addition of poultry litter.

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