SIMULATING NO_3-N TRANSPORT TO SUBSURFACE DRAIN FLOWS AS AFFECTED BY TILLAGE UNDER CONTINUOUS CORN USING MODIFIED RZWQM

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ABSTRACT. *The Root Zone Water Quality Model (RZWQM) was previously modified to simulate subsurface drain flows and evaluate the impact of different tillage systems on subsurface drain flows (Singh and Kanwar, 1994). This article discusses further modifications made in the RZWQM to simulate nitrate-nitrogen (NO_3-N) concentrations and NO_3-N losses with subsurface drain flows. Daily NO_3-N concentrations were simulated in subsurface drain flows under four different tillage systems: chisel plow (CP), moldboard plow (MB), no-tillage (NT), and ridge-tillage (RT) by using the modified RZWQM. Simulations were conducted for the growing seasons of three years (1990 to 1992). Simulated NO_3-N concentrations and losses with subsurface drain flows were compared with the measured data obtained from a water quality research site at Nashua, Iowa. Predicted NO_3-N concentrations generally followed the same pattern as the observed concentrations. Simulated annual average NO_3-N concentrations in subsurface drain flows were within 11% (averaged over all three years) of observed annual average NO_3-N concentrations in subsurface drain flows. The model correctly predicted maximum concentrations under MB treatment and minimum under NT for all three years. Simulated annual NO_3-N losses were within 14% (averaged over all three years) of observed annual NO_3-N losses. Various NO_3-N transformation processes need to be calibrated as a function of tillage system to improve model performance.*
Keywords. *Water quality, Hydrologic modeling, Solute transport.*

It is becoming increasingly evident that intensive use of chemicals in agriculture production systems may create environmental pollution by contaminating subsurface soil and water resources and economic losses due to movement of agricultural chemicals out of crop root-zone. Groundwater contamination by nitrate-nitrogen (NO_3-N) and pesticides has become a serious environmental concern in the nation, especially in the midwestern United States. Agricultural land areas have varying degrees of potential for groundwater pollution depending on the soil type, geology, climate, and more importantly the agricultural management practices. The use of conservation tillage and different crop rotations for agricultural production may help in developing the best management practices to reduce groundwater pollution problems. Conservation tillage (especially a no-tillage system) is an effective practice for conserving energy and soil. However, there is a concern that conservation tillage may increase the risk of groundwater pollution because these tillage systems have been found to increase groundwater recharge (Kanwar et al., 1988; Kay and Baker, 1989). Also, the use of artificial drainage to remove excess water from crop land may increase NO_3-N losses from the system (Baker and Johnson, 1976); however, artificial drainage is an absolute necessity to farm some of the nation's most productive soils. Without artificial drainage, planting and harvesting may not be done in a timely fashion, and on some soils poor growing conditions may result in total crop failure in very wet years and reduced yields in moderately wet years (Kanwar et al., 1983; Ahmad et al., 1992).

Several experimental studies have been conducted to investigate the effects of tillage practices and crop rotation on the movement of surface applied agricultural chemicals to the subsurface drains. Kanwar et al. (1990) established a field hydrology laboratory to study the effects of four tillage systems [moldboard plow (MB), chisel plow (CP), no-tillage (NT), and ridge-tillage (RT)] on the transport of surface applied chemicals (NO_3-N and pesticides) through the soil profile to shallow groundwater. Results from this study showed that NO_3-N concentrations in subsurface drain flows under conventional tillage plots were greater than NO_3-N concentrations in subsurface drain flows under other tillage systems. Leeds-Harrison et al. (1992) observed that drain flow and solute load are affected by tillage treatment.

Although a number of experimental investigations have been conducted to study the transport of NO_3-N to subsurface drains not much work has been done on the simulation of NO_3-N transport to the subsurface drains under different tillage systems. Simulation studies can be used as an inexpensive, time saving, and environmentally safe technique to evaluate the effects of various agricultural management practices on the subsurface movement of NO_3-N. For instance, Kanwar et al. (1983) developed a model to simulate the major water and N transport processes occurring in a typical agricultural watershed during the crop growth period. DRAINMOD (Skaggs, 1978) was extended further as DRAINMOD-N (Breve et al., 1992) for predicting N-transport, uptake, and transformation in artificially drained soils. These models are not capable of incorporating tillage effects. A

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mechanistic soil-crop simulation model that emphasizes soil N dynamics and tillage management decisions is NTRM (Shaffer et al., 1983; Shaffer and Larson, 1987) which has been used to make long-term predictions of yield and environmental impact. Another soil-water-plant-atmosphere system model called Root Zone Water Quality Model (RZWQM) (USDA-ARS, 1992) was recently developed to simulate the effects of various agricultural management practices including tillage on the subsurface movement of nutrients and pesticides.

The purpose of this study was to further extend the capability of the modified RZWQM model (Singh and Kanwar, 1995) to predict NO_3-N concentrations in subsurface drain flows and to evaluate the effect of different tillage systems on NO_3-N losses with subsurface drain flows. The specific objectives of this study were to:

- Extend the modified RZWQM model to simulate NO_3-N concentration in subsurface drainage water.
- Test and evaluate the modified RZWQM by simulating NO_3-N concentrations and NO_3-N losses with subsurface drain flows for 1990, 1991, and 1992 under four different tillage practices and comparing them with observed data from the Nashua Water Quality Site in Iowa.

Model Development and Theory

An Overview of RZWQM

The following paragraphs briefly describe NO_3-N transport processes in RZWQM (USDA-ARS, 1992).

For NO_3-N transport through the soil profile during infiltration, a sequential partial displacement and mixing approach in 1-cm layer increments is used based on the established concept of miscible displacement. Preferential flow in macropore channels is treated separately.

The soil solution is displaced sequentially across 1-cm soil increments in the manner of piston displacement for each infiltration step. Because the volume of flow during an infiltration step is always less than the meso-pore soil water content of a 1-cm increment (usually less than half), displacement of the solution in this increment is only partial. Mixing is allowed to occur within all meso-pores of an increment after each displacement step. Thus, this two-stage process simulates miscible displacement in the meso-pores. During the redistribution process, NO_3-N in the solution move with the water from one depth increment to another, including upward movement due to evaporation.

In RZWQM an Organic Matter/Nitrogen submodel (OMNI), is used for C and N cycling in the soil system. Given initial levels of soil humus, crop residues, other organics, and NO_3-N and ammonium (NH_4-N) concentrations, the model simulates mineralization, nitrification, immobilization, denitrification, and volatilization of appropriate N forms. A multi-pool approach is used for organic matter cycling. Process rate equations are based on chemical kinetic theory and controlled by microbial population size and environmental parameters such as soil temperature, pH, water content, and salinity. Levels of soluble nutrients are used in estimating crop growth, nutrient extraction in surface runoff, and movement through and below the root zone.

Simulation of NO_3-N Concentrations in the Subsurface Drain Effluent

As pointed out by Duffy et al. (1975), NO_3-N concentrations in the subsurface drain effluent are sensitive to the hydrological component of the model; therefore, the various processes of water movement in the soil profile become quite important in predicting the NO_3-N concentration in the subsurface drain effluent. The NO_3-N concentration in the subsurface drain effluent is calculated as total mass of NO_3-N in the drained water divided by the drainage volume per unit area to the subsurface drain. When the subsurface drain flow is zero, the amount of water (and also the NO_3-N) that may actually move is set equal to zero. According to Dutt et al. (1970), the NO_3-N concentrations of the subsurface drain water are functions of the NO_3-N concentrations in the saturated soil profile. On the basis of the flow net studies conducted by Luthin (1966) and Kirkham (1966), it was assumed that the NO_3-N concentrations in the subsurface drain water would be proportional to the NO_3-N concentrations in soil layers below the water table. For this purpose, subsurface drainage per unit thickness (DRN) was calculated for the saturated zone after calculating subsurface drainage by the Hooghoudt equation. Drainage water contribution from each saturated layer (DEL) was calculated by multiplying DRN with the thickness of the layer. The total amount of NO_3-N loss to the subsurface drain flow from a given soil layer within the saturated zone can thus be calculated as follows:

$$\mathrm{CLOSS}_i = \mathrm{CONC}_i\,\mathrm{DEL}_i \tag{1}$$

where

CLOSS_i = amount of NO_3-N lost to subsurface drain flow from layer i ($\mu g/mm^2$)

CONC_i = concentration of NO_3-N in layer i ($\mu g/mm^3$)

DEL_i = amount of water contributed from layer i to subsurface drain flow (mm)

Total NO_3-N loss in the subsurface drain flow for a given time step, DELT, is then calculated in the following way:

$$\mathrm{TLOSS}_j = \sum_{i=1}^{N} \mathrm{CLOSS}_i\,\mathrm{DELT} \tag{2}$$

where

TLOSS_j = total NO_3-N loss in subsurface drain flow for time step j

N = number of soil layers in saturated zone

Average daily NO_3-N concentration (ADC) in subsurface drain flow is calculated by summing the total losses over the day and dividing by daily subsurface drain flow amount:

$$\mathrm{ADC} = \frac{\sum_{j=1}^{M} \mathrm{TLOSS}_j}{\mathrm{DFLUX}} \tag{3}$$

where

ADC = average daily NO_3-N concentration ($\mu g/mm^3$)

DFLUX = daily subsurface drain flow (mm)

M = number of time steps in a day

Model Simulations and Evaluations

Field Operations

Dates of planting, harvesting, fertilizer application, tillage, etc. were input to the model. Table 1 shows the dates of field operations and amount of fertilizer applied for all three years.

Initial NO_3-N Concentrations, Soil Water Content, and Water Table Depth

The subsurface drain flow component of the model was calibrated by using the measured daily subsurface drain flow data for the year 1990. Calibration procedure and parameters for subsurface drain flows are presented and discussed by Singh and Kanwar (1995) in detail. Initial soil water content profile, water table depth, and NO_3-N concentration profile were input to the model. Initial soil water content was adjusted to make sure that simulated subsurface drain flow began approximately at the same time subsurface drain flow actually began in the field. Initial water table depth was set equal to 1.2 m. Depth of the impermeable layer was assumed at 2.72 m which is a reasonable assumption for this site. The NO_3-N concentrations in subsurface drain flow were simulated for years 1990, 1991, and 1992. Initial NO_3-N concentrations in the soil profile were not available for years 1990 and 1991. Therefore, for these years the initial NO_3-N concentrations in the profile were set equal to the NO_3-N concentrations measured in late fall of 1990 (25 October 1990). Initial NO_3-N concentrations in the soil profile were subsequently adjusted to have the simulated NO_3-N concentrations in the subsurface drain flow approximately equal to the observed NO_3-N concentrations at the beginning of the subsurface drain flow. For 1992, pre-fertilization NO_3-N concentration values for the soil profile were available and were used as the initial profile concentrations. Initial NO_3-N concentrations in the soil profile for 1990, 1991, and 1992 are shown in tables 2, 3, and 4.

Table 1. Dates of tillage, planting, NO_3-N application, and harvesting for 1990, 1991, and 1992

Day of Year			
1990	1991	1992	Activity
—	—	92	Spring tillage
105	120	95	Secondary tillage (CP, MB)
107	134	121	Applied 200 Kg-N/ha
122	148	125	Planted corn
140	148	156	Cultivation
186	171	178	Cultivation
280	283	288	Harvested corn
311	—	311	Fall tillage

Table 2. Initial NO_3-N concentrations for simulation runs for all tillage treatments for 1990

	NO_3-N concentration (mg/L)			
Horizon	Chisel Plow	Moldboard Plow	No-till	Ridge-till
1	60	55	55	57
2	35	40	32	30
3	25	38	29	27
4	35	45	24	22
5	35	50	25	22
6	55	55	29	35
7	40	51	41	40
8	40	51	41	40

Measured NO_3-N Concentrations in the Subsurface Drain Effluent

Data on measured NO_3-N concentrations in the subsurface drain effluent were taken from the completion report of the Leopold Center Project (Kanwar et al., 1993a, b) and from the data files of Iowa State University's Water Quality Research Site at Nashua, Iowa. The study site is located on a predominantly Kenyon loam soil with 3 to 4% organic matter. Kenyon soils have a seasonally high water table and benefit from subsurface drainage. Subsurface drains were installed about 1.2 m deep at 28.5 m spacing in 1979. Long-term tillage practices were begun at this site in the fall of 1977 to compare CP, MB, NT, and RT systems. There were three replications of each tillage treatment on 0.4-ha plots. Each plot has one subsurface drain passing through the middle of the plot, and there is a subsurface drain at each of the two borders. The middle subsurface drains of all the plots were intercepted and connected to individual sumps in December 1988 for measuring subsurface drainage and collecting water samples for chemical analyses (Kanwar and Baker, 1991). For NO_3-N sampling, the frequency of sampling averaged three times a week when subsurface drains were flowing.

Simulated NO_3-N Concentrations in the Subsurface Drain Flows

The modified RZWQM was used to predict NO_3-N concentrations in the subsurface drain effluent under four different tillage systems: CP, MB, NT, and RT, for 1990, 1991, and 1992. Figures 1 to 4 compare the predicted and observed daily NO_3-N concentrations in the subsurface

Table 3. Initial NO_3-N concentrations for simulation runs for all tillage treatments for 1991

	NO_3-N concentration (mg/L)			
Horizon	Chisel Plow	Moldboard Plow	No-till	Ridge-till
1	40	35	22	24
2	25	20	15	15
3	15	25	15	15
4	20	25	13	11
5	20	26	13	12
6	28	28	15	20
7	30	36	25	25
8	30	36	25	25

Table 4. Initial NO_3-N concentrations for simulation runs for all tillage treatments for 1992

	NO3-N concentration (mg/L)			
Horizon	Chisel Plow	Moldboard Plow	No-till	Ridge-till
1	11	15	12	12
2	7	5	8	10
3	9	9	9	9
4	9	12	6	8
5	8	13	6	8
6	9	9	7	7
7	8	8	5	6
8	8	8	5	6

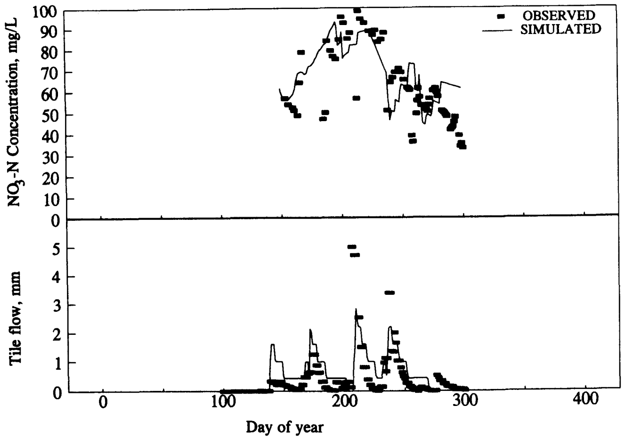

Figure 2–Simulated and observed average NO_3-N concentrations in tile flow for MB, 1990.

drain effluent under CP, MB, NT, and RT tillage systems, respectively, for the year 1990. Similar comparisons for 1991 and 1992 are shown in figures 5 to 8 and figures 9 to 12, respectively. Observed NO_3-N concentrations in the subsurface drain water represent the average of NO_3-N concentrations from three replicate field plots.

A good agreement between the predicted and observed daily NO_3-N concentrations can be seen with few exceptions for all three years. As NO_3-N concentration in the subsurface drain effluent is proportional to the NO_3-N concentration of the saturated profile, a sudden drop in the NO_3-N concentration in the subsurface drain flow represented a heavy rainfall decreasing the NO_3-N concentration in the drainage water with increased subsurface drain flow and vice-versa. Coefficient of determination (R^2) values were calculated for the best fit line for simulated versus observed NO_3-N concentrations in subsurface drain water. The R^2 values ranged from 0.28 to 0.43 for 1990 simulations, 0.39 to 0.57 for 1991 simulations and 0.19 to 0.23 for 1992 simulations.

Discrepancies between the predicted and observed NO_3-N concentrations in the subsurface drain water could be due to: 1) inaccuracies introduced in the hydrologic component of the model causing inaccuracies in the NO_3-N concentration in the soil profile and ultimately in the subsurface drain flow; 2) inaccuracies introduced in the estimation of initial water content and concentrations; 3) unaccounted lateral groundwater flow and NO_3-N losses; and 4) unaccounted deep seepage and NO_3-N losses, etc. Also, the rate of various NO_3-N transformation processes may need to be calibrated for the different tillage practices.

Tables 5 and 6 give the total NO_3-N losses and average concentrations in the subsurface drain effluent for all the three years. Model simulations showed lower NO_3-N concentrations in the subsurface drain water under NT and RT treatments and higher concentrations under MB and CP treatments for all three years. This was in agreement with observed NO_3-N concentration data. Simulated annual NO_3-N losses were within 14% (on average) of the observed annual NO_3-N losses under different tillage systems. For 1990, predicted tillage effects on NO_3-N losses in the subsurface drain effluent were consistent with the observed tillage effects, i.e., maximum NO_3-N loss under NT and minimum loss under MB treatment. But for 1991 and 1992, predicted tillage effects on NO_3-N losses were not always consistent with the observed effects. For 1992, observed NO_3-N losses were not much different under the four tillage systems. Predicted NO_3-N losses with the subsurface drain flows showed a similar trend for 1992. This was expected because 1992 was a relatively dry year with mostly low-intensity rainfall events. Therefore, preferential flow probably was not generated as often as in

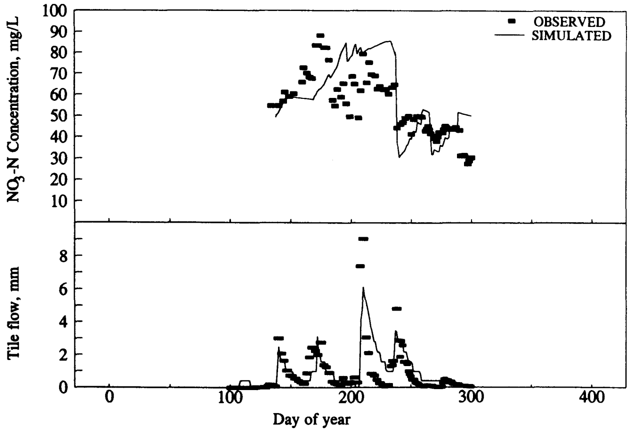

Figure 1–Simulated and observed average NO_3-N concentrations in tile flow for CP, 1990.

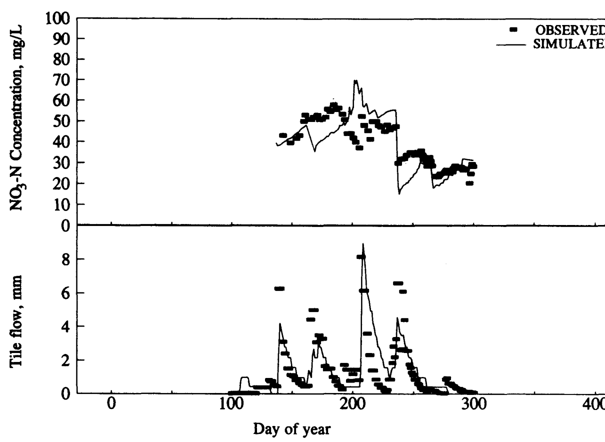

Figure 3–Simulated and observed average NO_3-N concentrations in tile flow for NT, 1990.

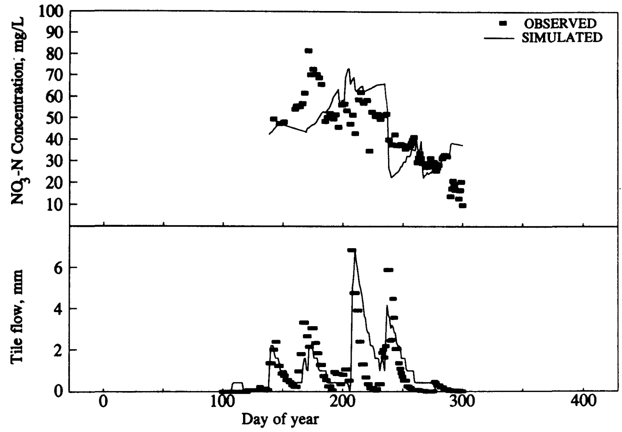

Figure 4–Simulated and observed average NO_3-N concentrations in tile flow for RT, 1990.

1990 and 1991, thus minimizing the tillage effects on subsurface drain flows as well as on NO_3-N losses.

Both observed and simulated average NO_3-N concentrations showed comparable trends (higher concentrations in MB and CP and lower in NT and RT) from year to year. But the trends for the NO_3-N losses were not consistent from year to year indicating again the importance of preferential flow, NO_3-N losses by other pathways (e.g., in deep seepage), and spatial variability effects.

NO_3-N Concentrations in the Soil Profile

NO_3-N concentrations were measured in the soil profile on day of year (DOY) 150, 267, and 297 in 1990 and on DOY 119, 176, and 232 in 1992 as a function of tillage systems. For this purpose three 1.8-m-long soil cores were collected from the middle quarter of each plot. These cores were composited after sectioning them into a set of nine samples representing the following depths: 0 to 0.10, 0.10 to 0.20, 0.20 to 0.30, 0.30 to 0.45, 0.45 to 0.60, 0.60 to 0.90, 0.90 to 1.20, 1.20 to 1.50, and 1.50 to 1.80 m. Composited samples were analyzed for soil water content, NO_3-N, and pesticide concentrations. A detailed methodology of collecting soil samples and analyzing them is described by Weed (1992).

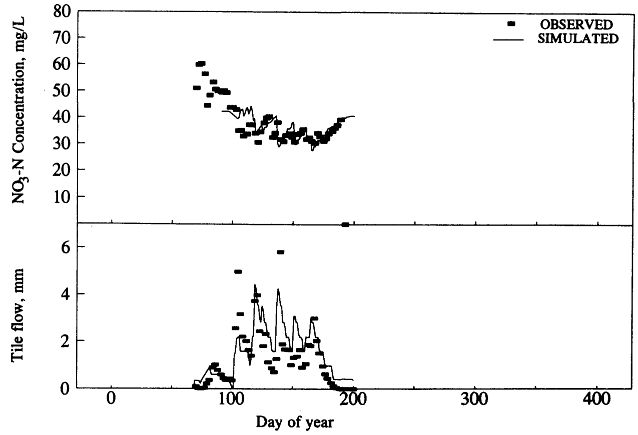

Figure 6–Simulated and observed average NO_3-N concentrations in tile flow for MB, 1991.

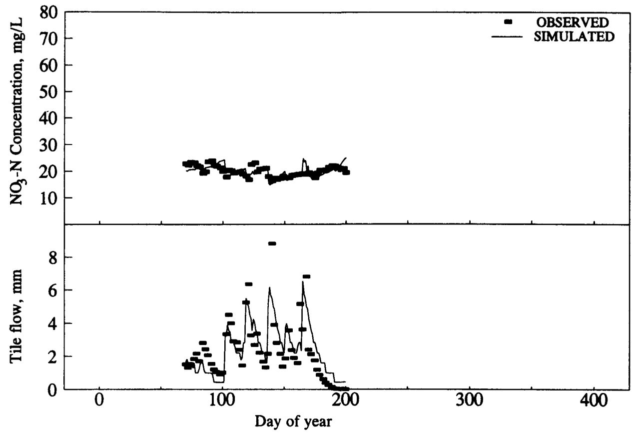

Figure 7–Simulated and observed average NO_3-N concentrations in tile flow for NT, 1991.

Simulated NO_3-N concentration in the soil profile were compared with the measured NO_3-N concentration for 1990 and 1992. Figure 13 gives examples of typical simulated and observed NO_3-N concentrations in the soil profile under different tillage systems for DOY 150, 1990.

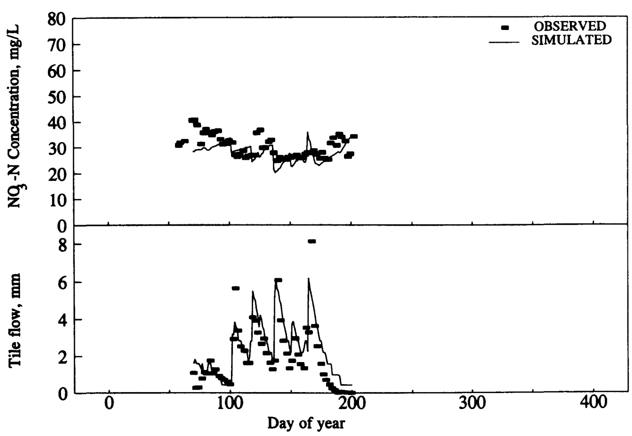

Figure 5–Simulated and observed average NO_3-N concentrations in tile flow for CP, 1991.

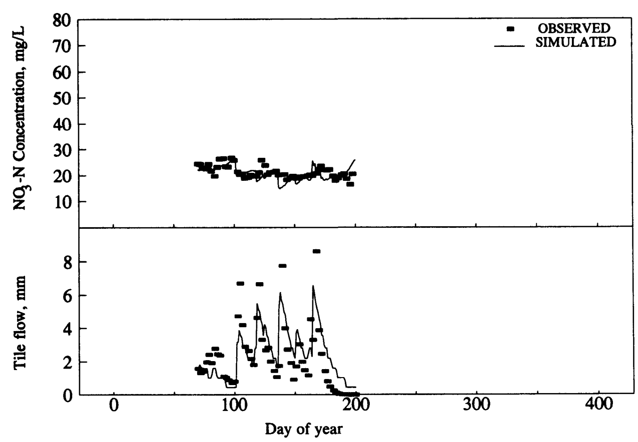

Figure 8–Simulated and observed average NO_3-N concentrations in tile flow for RT, 1991.

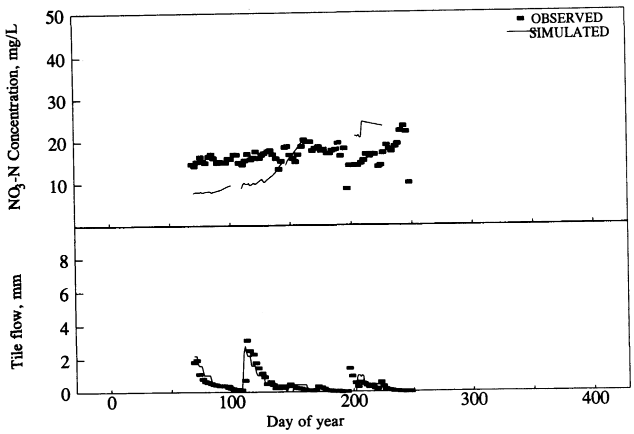

Figure 9–Simulated and observed average NO_3-N concentrations in tile flow for CP, 1992.

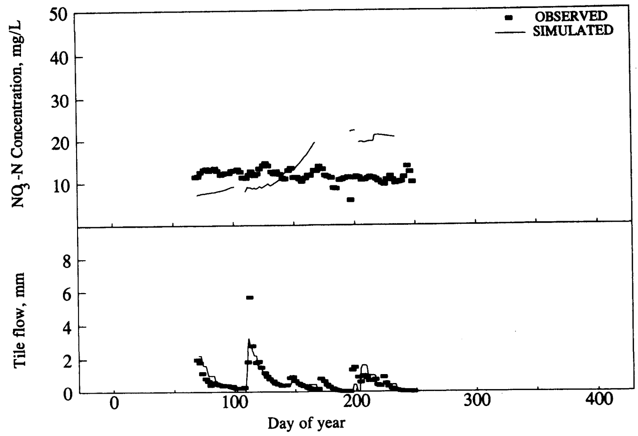

Figure 11–Simulated and observed average NO_3-N concentrations in tile flow for NT, 1992.

Although depth and magnitude of simulated NO_3-N peak concentrations in the soil profile did not match well with the depths and magnitude of observed peak NO_3-N concentrations, predicted concentrations usually showed a range (maximum and minimum NO_3-N concentrations) similar to that of observed NO_3-N concentrations. Both predicted and observed NO_3-N concentrations in the soil profile did not show a clear effect of tillage systems. Simulated soil NO_3-N concentration profiles usually showed that the difference between NO_3-N concentrations under different tillage systems gradually increased with depth. There was no consistent pattern of this type in the observed NO_3-N concentration profiles, indicating the heterogeneity of the system and the effect of various NO_3-N transformation processes. Some other possible reasons for these discrepancies are discussed in earlier sections (NO_3-N concentration in subsurface drain water flow).

Summary and Conclusions

The RZWQM was modified to simulate NO_3-N concentrations in the subsurface drain water effluent and to evaluate the impact of tillage practices (CP, MB, NT, and RT) on NO_3-N losses with subsurface drain water. Daily NO_3-N concentrations and losses in the subsurface drain flow were simulated for each tillage system for 1990, 1991, and 1992. Simulated NO_3-N concentrations and losses were compared with the field measured concentrations and losses to evaluate the model's performance.

The modified RZWQM, in general, showed a good potential for predicting NO_3-N concentrations and losses in the subsurface drain effluent under different tillage systems. Simulated NO_3-N concentrations in subsurface drain flows under different tillage systems usually followed the pattern of observed NO_3-N concentrations. The model correctly predicted higher average NO_3-N concentrations in subsurface drain flows under MB and CP treatments and lower average concentrations under NT and RT treatments for all three years. Simulated annual average NO_3-N concentrations in subsurface drain flows were within 11% of observed annual average NO_3-N concentrations in the subsurface drain flows.

Simulated annual NO_3-N losses were within 14% of observed annual NO_3-N losses with subsurface drain flows. Predicted tillage effects on NO_3-N losses with subsurface drain flows were consistent with observed tillage effects for 1990, i.e., maximum annual NO_3-N losses under NT and minimum losses under MB. But for 1991 and 1992,

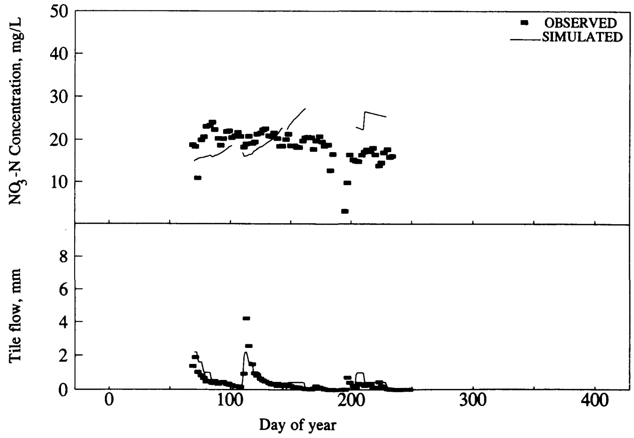

Figure 10–Simulated and observed average NO_3-N concentrations in tile flow for MB, 1992.

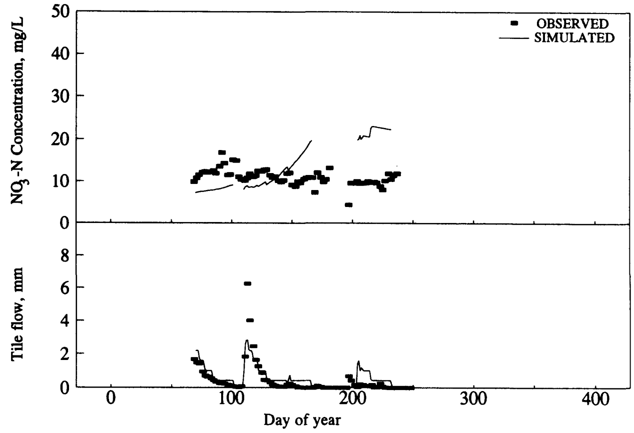

Figure 12–Simulated and observed average NO_3-N concentrations in tile flow for RT, 1992.

Table 5. Total average NO_3-N losses with subsurface drain flow for 1990, 1991, and 1992

Year	Total Rain (mm)	NO_3-N Losses with Subsurface Drain Flow (Kg/ha)* CP	MB	NT	RT
1990	939.0				
	Observed	100.0	58.0	107.2	87.4
		(30.7)	(20.8)	(21.6)	(24.6)
	Predicted	94.5	70.7	95.1	81.3
	Percent difference	5.5	21.8	11.3	7.0
1991	592.0				
	Observed	75.4	61.8	60.4	57.4
		(10.4)	(8.7)	(2.4)	(12.7)
	Predicted	83.0	60.3	60.1	65.1
	Percent difference	10.0	2.4	0.5	13.4
1992	738.0				
	Observed	12.6	12.3	10.9	7.9
		(1.3)	(10.7)	(7.8)	(2.1)
	Predicted	10.3	14.9	12.8	10.5
	Percent difference	18.3	21.1	17.4	32.9

* Numbers in the parentheses show the standard deviation of three replications.

predicted tillage effects on NO_3-N losses were not always consistent with the observed tillage effects.

Simulated NO_3-N concentrations in the soil profile under different tillage systems usually shared the same range (maximum and minimum NO_3-N concentrations), that of observed concentrations, but the depth and magnitude of peak simulated concentrations did not match well with those of observed peaks.

Discrepancies between simulated and observed NO_3-N concentrations and losses indicated a need for better estimates of input data as well as a need for further improvements in the model. Various NO_3-N transformation rates need to be calibrated for the different tillage practices. NO_3-N losses with lateral groundwater flow and deep seepage also need to be accounted for.

Table 6. Average NO_3-N concentrations in subsurface drain flows for 1990, 1991, and 1992

Year	Total Rain (mm)	NO_3-N Concentration in Subsurface Drain Flow (mg/L)* CP	MB	NT	RT
1990	939.0				
	Observed	51.9	61.6	38.2	39.1
		(3.1)	(6.8)	(5.9)	(6.5)
	Predicted	59.3	70.7	39.2	45.2
	Percent difference	14.3	14.7	2.6	15.6
1991	592.0				
	Observed	28.7	36.2	18.7	19.7
		(3.2)	(3.2)	(1.9)	(3.6)
	Predicted	28.0	36.4	20.1	21.7
	Percent difference	2.5	0.6	7.5	10.1
1992	738.0				
	Observed	16.6	18.6	11.7	11.0
		(2.8)	(2.2)	(0.9)	(1.4)
	Predicted	14.0	20.6	13.4	13.4
	Percent difference	15.7	10.8	14.5	21.8

* Numbers in the parentheses show standard deviation of three replications.

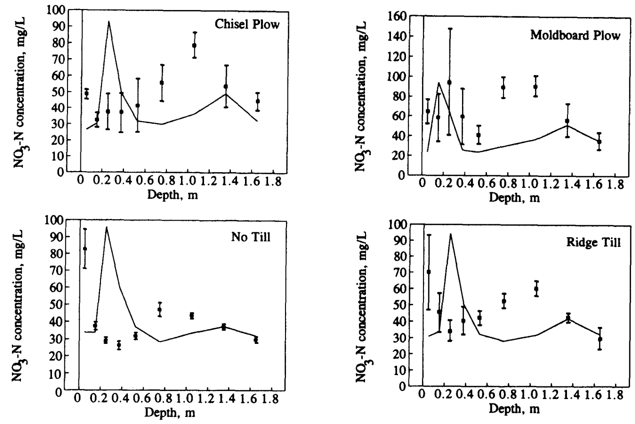

Figure 13–Simulated (lines) and observed (points) NO_3-N concentrations in soil profile for DOY 150, 1990 (error bars show the standard deviation.

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