Modification of Root Zone Water Quality Model (RZWQM) to simulate the tillage effects on subsurface drain flows and NO3-N movement

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Modification of root zone water quality model (RZWQM) to simulate the tillage effects on subsurface drain flows and NO₃-N movement

Singh, Piyush, Ph.D.
Iowa State University, 1994
Modification of Root Zone Water Quality Model (RZWQM) to simulate the tillage effects on subsurface drain flows and NO$_3$-N movement

by

Piyush Singh

A Dissertation Submitted to the Graduate Faculty in Partial Fulfillment of the Requirements for the Degree of

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Ames, Iowa
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GENERAL INTRODUCTION

Groundwater contamination from agricultural chemicals is becoming an increasing concern. Agricultural land areas have varying potentials for groundwater pollution depending on the soil type, geology, climate, and more importantly the agricultural management practices used. Tillage management is an important agricultural management practice needed to minimize subsurface soil and water contamination. Tillage modifies soil physical and hydraulic properties affecting the movement of both water and solutes. However, it is extremely difficult to detect unambiguous changes in soil hydraulic properties or solute transport characteristics. This difficulty is due to spatial variability (Biggar and Nielsen, 1976) and also temporal variations in both soil and climatic conditions. Nevertheless it is necessary to investigate the tillage influences on subsurface solute and water movement to groundwater to develop management practices for enhancing soil and water quality.

A number of experimental studies have been conducted to investigate tillage influences on soil properties as well as on subsurface soil and water quality. Some of the studies involved collecting undisturbed soil cores from different tillage plots and measuring soil physical properties such as bulk density, porosity, soil strength, and moisture release curve parameters (e.g., Kanwar, 1989; Powers et al., 1992; Hill, 1990; Tollner et al., 1984). Some studies involved infiltration measurements under different tillage treatments (e.g., Freese et al., 1993; Bruce et al., 1990, Logsdon, 1993, Mukhtar et al., 1985). Some of the investigations were based on solute transport experiments on undisturbed soil columns (e.g., Singh and Kanwar, 1991; Serem and Madramootoo, 1993; Andreini and Steenhuis, 1990), while some others involved monitoring subsurface drain flows both for quantity and quality under different tillage practices (Kanwar, 1991; Madramootoo and Mousavizadeh, 1993).
As pointed out by Hallberg et al. (1986), subsurface drainage studies can be a useful tool for assessing the impact of agricultural management practices on groundwater quality. Monitoring of subsurface drain flows to investigate tillage effects should provide more conclusive results because field drainage systems incorporate the complexity of the real soil-crop-water system as well as integrating the effects of spatial variability. These aspects are not represented in laboratory experiments or in the measurements involving small soil cores or suction cups. Tile drained areas are also readily available for water-quality research at many research stations as well as production fields, providing a methodology to study field-scale transport of solutes at relatively modest cost.

There is a growing evidence that preferential flow contributes to field-scale transport (Thomas and Philips, 1979; Bowman and Rice, 1986) of solutes and is not adequately described by convective dispersive models. Several subsurface drainage studies have shown rapid appearance of tracers in the subsurface drain outflow immediately after tracer application at the soil surface (Richard and Steenhuis, 1988; Everts and Kanwar, 1990).

Besides experimental investigations, mathematical modeling could be another way to study tillage influences on subsurface movement of water and chemicals. Mathematical models are used as cost-effective, time-saving, and environmentally safe tools to analyze the behavior of the soil-water-crop system. In general, models are used to analyze system behavior under both current (or past) conditions and anticipated (or future) conditions. Modeling requires some basic knowledge of the system being analyzed. However, it also promotes an improved understanding of the system through sensitivity analysis of system characteristics and observations of the resulting system response, as predicted by the model and characterized by the field data. This research function is especially important for soil leaching models to help expand our current knowledge of the complex soil-water-crop system within the vadose zone. A number of subsurface chemical transport models have been developed to simulate water and chemical movement in the vadose
zone. Some examples of these models are Pesticide Root Zone Model (PRZM; Carcel et al., 1985), Groundwater Loading Effects of Agricultural Management Systems Model (GLEAMS; Leonard et al., 1990), Nitrogen, Tillage and Residue Management model (NTRM; Shaffer and Larson, 1987), and the Root Zone Water Quality Model (RZWQM; USDA-ARS, 1992a). Fewer models have been developed which simulate nitrate nitrogen (NO$_3$-N) transport in subsurface drain effluent (Kanwar et al., 1983) and pesticide transport in subsurface drain effluent (Utermann et al., 1990). Most of these models fall in the category of one-dimensional, process-based, lumped-parameter models.

The goal of this research was to simulate tillage influences on subsurface drain flows and NO$_3$-N losses in drain effluent by incorporating the concepts of preferential flow. For this purpose the Root Zone Water Quality Model (RZWQM, USDA-ARS, 1992a) was selected and modified to simulate subsurface drain flows and NO$_3$-N losses in the drain flows. RZWQM is a process-based integrated model of the soil-water-plant-atmosphere system that incorporates preferential flow concepts and can be used for analyzing the effects of various management practices on the subsurface environment. It simulates the movement of both nutrients and pesticides in the root zone.

The specific objectives of this study were to:

1. Characterize different tillage systems (moldboard plow, chisel plow, ridge till, and no-till) by measuring soil physical properties. Use this information for simulating water and NO$_3$-N movement through the vadose zone under different tillage systems.

2. Add a subsurface drainage component in RZWQM and simulate subsurface drain flows under different tillage systems for 1990, 1991, and 1992. Evaluate the model's performance by comparing the predicted results with the observed subsurface drain flows.
3. Further modify the model to simulate NO$_3$-N losses in the subsurface drain effluents for 1990, 1991, and 1992. Evaluate the model's performance by comparing simulated NO$_3$-N losses with observed NO$_3$-N losses in subsurface drain flows.

Dissertation Organization

This dissertation is organized in paper format and is comprised of three papers. Each paper focuses on a major objective in the same order as given above. The first paper describes the characterization of tillage systems on the basis of soil physical properties. Results from a simulation run of RZWQM (before modifying it to add subsurface drain flow component) based on field-measured properties are also included and discussed in this paper.

The second paper mainly focuses on the development of a subsurface drain flow component, its incorporation into RZWQM and calibration of the modified RZWQM for Iowa State University's Northeast Research Center water quality site. Results of the subsurface drain flow simulations for three growing seasons (1990 to 1992) are also presented in this paper and compared with the observed subsurface drain flow data.

The third paper describes the further modifications made in RZWQM to simulate NO$_3$-N concentrations and losses with the subsurface drain flows. Results on simulated NO$_3$-N concentrations and losses in subsurface drain flows are presented for the years 1990, 1991, and 1992. The model's performance was evaluated by comparing the simulated results with the observed results. At the end of the dissertation, there is an overall summary giving the major conclusions of this study and a complete bibliography including the references cited in the general introduction.
CHARACTERIZING TILLAGE AND SIMULATING THE MOVEMENT OF WATER AND NO₃-N IN THE VADOSE ZONE BY USING ROOT ZONE WATER QUALITY MODEL (RZWQM)

A paper to be submitted to Soil and Tillage Research

Piyush Singh and Rameshwar S. Kanwar

Abstract

Tillage modifies physical and hydraulic properties of soil affecting the movement of water and solutes in both the surface and subsurface environments. This study compares four tillage systems -- chisel plow (CP), moldboard plow (MB), no-tillage (NT), and ridge-tillage (RT) on the basis of soil physical properties. Three soil properties -- saturated hydraulic conductivity (Ksat), bulk density (BD), and macroporosity (MP) were measured for the surface horizon as a function of tillage for three different soils (Kenyon, Floyd, and Readlyn). Analyses of Ksat, BD, and MP data showed no significant difference among the tillage systems for any soil except for Readlyn. Significant effect of tillage was observed on Ksat values for Readlyn soil at the 7.5-15 cm depth increment.

A simulation study was performed to mathematically model tillage effects on the movement of water and nitrate-nitrogen (NO₃-N) in the root zone under continuous corn production utilizing field measured soil properties. The Root Zone Water Quality Model (RZWQM; USDA-ARS, 1992a) was used to conduct these simulations. The model usually predicted lower moisture contents then observed ones in the soil profile. The model predicted higher NO₃-N concentrations in the soil profile for MB and RT treatments in comparison to CP
and NT treatments, but the depth and magnitude of simulated NO$_3$-N peak concentrations were substantially different than those of observed peaks. Discrepancies in simulated and observed moisture content and NO$_3$-N concentrations in the soil profile indicated a need for improvement in hydrology and nutrient component of the model.

**Introduction**

Numerous studies in the last decade have confirmed the presence of agricultural chemicals in groundwater in Iowa and other North Central region states (Hallberg et al., 1985; Gish et al., 1991; Spalding et al., 1989; Parson and Witt, 1988). NO$_3$-N is the most common agricultural chemical found in the groundwater. Also, Parson and Witt (1988) have reported the presence of 73 pesticides in the groundwater of 34 states.

Nitrogen fertilizers and pesticides applied to the surface prior to and immediately following the planting operation are particularly susceptible to loss through surface runoff or leaching to groundwater through the soil profile. Tillage practices modify the physical and hydraulic properties of the soil and, therefore, the amounts of water and chemicals moving both and over and through the soil water (Blevins et al., 1990). For example, tillage disrupts macropores (structural cracks, worm or root holes), whereas no-tillage systems allow macropore networks to develop and persist. These macropores may act as preferential pathways for rapid movement of water and/or chemicals in the solution phase. Conservation tillage systems often reduce surface water contamination because soil erosion and water runoff are reduced. At the same time, concern is raised that conservation tillage may increase groundwater contamination because of increased infiltration. This shows a clear need for evaluating the impacts of different tillage systems on the subsurface movement of water and chemicals.
Evaluation and assessment of impacts of different tillage systems on subsurface soil and water quality can be accomplished in two possible ways: a) by conducting field experiments over a considerably long period or b) by developing and utilizing computer simulation models based on existing concepts of soil and water movement through vadose zone soil. The latter approach can be considered more economical, faster, and environmentally safe in comparison with field experiments. Nevertheless, simulation models also need extensive input data sets to make accurate predictions. Characterizing different tillage systems, in terms of soil physical properties, for example, will be an essential feature of a computer simulation model developed to simulate tillage effects on subsurface water and chemical movement. A number of studies have been conducted to characterize different tillage systems in terms of infiltration rate, macroporosity, soil water characteristics, and bulk density (Freese et al., 1993; Singh et al., 1991; Logsdon et al., 1990; Bruce et al., 1990; Powers et al., 1992). Some other studies focus on experimentally determining tillage effects on subsurface soil and water quality (Kanwar et al., 1992; Brinsfield, et al., 1987; Weed, 1992). On the other hand, little work has been done on simulating tillage effects on the subsurface water and chemical movement and comparing these predictions with observed data.

This study was designed with a purpose of characterizing four different tillage systems by measuring soil physical properties and using this information later in simulating water and NO$_3$-N movement through the vadose zone under these different tillage systems. Four tillage systems, namely conventional tillage (MB), ridge-tillage (RT), chisel plow (CP), and no-tillage (NT), were considered for this study. Soil physical properties selected to characterize tillage were bulk density (BD), saturated hydraulic conductivity (Ksat), and macroporosity (MP) at different depth increments. The Root Zone Water Quality Model (RZWQM; USDA-ARS, 1992a) was selected to simulate the subsurface movement of water, and NO$_3$-N under these four different tillage systems.
Part A. Characterization of Tillage Systems

Undisturbed soil cores were collected from a water-quality experimental site at Iowa State University's Northeast Research Center near Nashua, IA in summer 1992. The study site has 36 0.4-ha plots under four different tillage systems (MB, RT, CP, and NT) to study the long-term effect of tillage on surface and subsurface water quality. These plots are located on three different soils, Kenyon (fine-loamy, mixed, mesic Typic Hapludoll), Floyd (fine-loamy, mixed, mesic Aquic Hapludoll), and Readlyn (fine-loamy, mixed, mesic Aquic Hapludoll); Kenyon being the prominent soil type at the site. Figure 1A shows a soil map for this experimental site. This map was adopted from Logsdon et al. (1993). Figure 1B gives an schematic of the parent soil materials for the major soils at this site. In 1992, moldboard plowing was done on April 2, and chisel plowing was done on April 2 and 3. Further cultivation was done on MB and CP plots on May 5. NT and RT plots were cultivated on June 26 and 27.

Undisturbed soil cores (120 cm long, 5.4 cm in diameter) were collected from the Nashua experimental site in the middle of July 1992. Figure 1A shows the sites for soil core sampling. Each site represents a combination of one tillage and soil type under continuous corn production. At each sampling site, three soil cores were collected 2-3 meter apart from an inter-row area between the 11th and 12th rows (Figure 2A). The following paragraphs describe the methodology of collecting soil cores and determining Ksat, BD, and MP.

Macroporosity was also determined for each tillage system by utilizing tension infiltration measurements (conducted in the beginning of June 1992) at the Nashua Water Quality Site. The tension infiltration tests were conducted in collaboration with Dr. Sally Logsdon of the National Soil Tilth Laboratory. Figure 1A shows the tension infiltration measurement sites.
Methodology

A Giddings soil probe (Giddings Machine Company, Ft. Collins, CO) was used to take 120-cm long soil cores. For this, a 5.4 cm inner diameter acetate liner was inserted in a steel tube with a cutting bit attached at the end. This tube was pushed into the soil with hydraulically driven attachment mounted on a tractor. After taking out the liner with a soil core in it, plastic caps were placed at both ends of the liner.

These cores were brought to ISU’s Agricultural and Biosystems Engineering Department and were stored in a cooler until further analysis. At a later time these cores were taken out of the cooler and sectioned with a power saw to get two 7.5-cm long subsamples at every 20-cm interval. Figure 3 describes this sectioning scheme as well as position of these samples with respect to soil horizons of each series’ typifying pedons in the county. One set of these samples (0-7.5, 35-42.5, 70-77.5, and 105-112.5 cm) was used for bulk density (BD) determinations, while the other set (7.5-15, 42.5-50, 77.5-85, and 112.5-120 cm) was used for saturated hydraulic conductivity (Ksat) determinations. After BD determinations, soil samples were sent to National Soil Tilth Laboratory, Ames, IA for particle-size analysis as a function of soil type and depth. Table 1 shows soil texture data as a function of depth for the three soils.

Ksat determinations

To determine Ksat, soil cores were taken out of the acetate liner by cutting the liner from sides. Then a metal ring of 7.5-cm inner diameter was placed around the soil core. The gap between the soil core and metal ring was filled with molten wax to avoid any flow along the walls (Figure 2B). These cores were then saturated for more than 24 hours by placing them in a container and raising the water slowly in the container. Then these cores were placed on the Ksat measuring set-up (constant head permeameter) and Ksat was determined for each core under a
constant head after steady state flow was established.

**Bulk density (BD) determinations**

For BD determinations the entire volume of soil was taken out of the liner, weighed, and then placed in the oven to determine its moisture content. BD was calculated as the dry weight of soil in the core divided by its volume.

**Macroporosity (MP) estimation**

MP (pores >1.0 mm diameter, corresponding to a tension of 3 cm) was estimated from tension infiltration data by using Poiseuille's equation. Watson and Luxmoore (1986) made use of Poiseuille's equation and assumed a unit hydraulic gradient to determine the maximum number of pores for a given pore size per unit area:

\[
N = \frac{8 \mu K_m}{\pi \rho g x^4}
\]

where

- \( N \) = number of pores of radius \( r \) per unit area, \( /L^2 \)
- \( \mu \) = viscosity of water, \( M/L/T \)
- \( K_m \) = difference in infiltration rate at two tensions, \( L/T \)
- \( g \) = gravitational constant \( L/T^2 \)
- \( \rho \) = density of water, \( M/L^3 \)
- \( r \) = equivalent pore radius of lower tension at which the difference \( K_m \) is determined, \( L \)
MP is calculated as the total area of pores of radius \( r \) (i.e., \( N \pi r^2 \)). These calculations were made for infiltration rates attributed to pores greater than 1.0 mm equivalent pore diameter (\( K_m \) being the difference between ponded infiltration and infiltration at 3 cm tension). The results are given in Tables 2 and 3 for the surface and 15-cm depths, respectively.

Results and Discussion

Saturated hydraulic conductivity (Ksat)

Figure 4 shows average Ksat (average of three replications) values at different depth increments for each tillage and soil types. Tables 1 to 3 in appendix A show Ksat values for individual replications and standard deviations for Floyd, Kenyon, and Readlyn soil types, respectively. These data showed a large variability in Ksat values (coefficient of variation, CV, ranging from 50 to 155%; see Table 1 in Appendix B). Only Ksat data for the upper two depth increments (7.5-15 cm, and 42.5-50 cm) were included in the statistical analysis to determine possible tillage effects on Ksat. Ksat data for these increments should be sufficient to show tillage effects for tillage induced modifications in the physical soil properties that are expected to occur in the tilled horizon (about 20-25 cm thick). Moreover, some compaction due to sampling technique was also observed at lower depths (overall compaction ranging from 0 to 15 cm in a 120 cm long soil core), thus affecting the quality of samples from lower depths.

For the first depth increment (7.5-15 cm), the highest Ksat values were observed under MB treatments for Floyd and Kenyon soils and under RT for Readlyn soil. Minimum Ksat values were observed under CP treatment for Readlyn and Kenyon soils and under NT for Floyd soil. A statistical analysis for the effect of tillage (f-test at 95% confidence interval) showed no effect of tillage for the Kenyon and Floyd soils, but showed a significant effect of tillage on Ksat values for the Readlyn soil. An example of the Analysis of Variance (ANOVA) test is presented in Appendix
B. Results of statistical analyses for Ksat data are summarized in Table 1 of Appendix B.

For the second depth increment (42.5-50 cm) the minimum Ksat value was observed under MB treatment for all three soil types. However, maximum Ksat values were observed under CP for Kenyon and Readlyn soils and under NT for Floyd soil. Unusually high values of Ksat (e.g., Ksat of 0.036 cm/s under CP treatment at 77.5-85 cm for Kenyon soil) were the result of the presence of macropores. All the cores were visually checked for macropores, and a direct correlation was found between the number and/or size of macropores and flow rates from the sample. Ksat data for the upper two depth increments (7.5-15 and 42.5-50 cm) also show that Ksat under MB treatment generally decreased with depth, while Ksat under CP treatment showed the opposite trend. The Ksat trend under MB treatment was expected due to the greater porosity at the surface and the presence of a plow pan. This might cause higher Ksat for the top depth increment and the lower Ksat for the second increment. A similar trend might be expected for CP, but it was not evident from the Ksat data.

Ksat values under NT and RT treatments did not change substantially with depth. This trend is also expected since both NT and RT treatment received minimum tillage (field cultivation and row planter with fluted coulter, respectively) causing less disturbance and modification in soil properties of the tilled layer.

Logsdon et al. (1990) also found a large variability in Ksat values obtained for undisturbed soil cores for various Minnesota and Wisconsin soils. They attributed variability in the tilled horizon to the sparse number of large biopores and cracks resulting in some cores having none.

**Bulk density (BD)**

Figure 5 shows average BD values at four different depths (4, 39, 74, and 109 cm) as a function of tillage and soil type. BD values for individual replications and standard deviations are
given in Tables 4 to 6 of Appendix A for all three soil types. As in the case of Ksat data, BD values for upper two depths (0-7.5 cm and 35-42.5 cm) were included in the analysis to determine possible tillage effects on BD. Under all tillage treatments and soil types there was a definite trend of increasing BD with the depth. However, an f-test (95% confidence interval) conducted for each soil type separately, showed that tillage did not have any statistically significant effect on BD values for either depth for all three soil types. Results of statistical tests for BD data are summarized in Table 2 of Appendix B.

In Kenyon and Readlyn soils, CP and NT treatments had higher bulk densities for the first depth increment in comparison with MB and RT treatments, but this trend was just opposite for Floyd soil. At the second depth increment, MB treatment showed highest bulk densities for all three soils while NT treatment the lowest except for the Floyd soil for which the lowest BD occurred under RT treatment. The bulk density values were quite similar to the values obtained by Logsdon et al. (1993) at the same site. Bruce et al. (1990) also studied the effect of summer crop tillage on BD for a sandy loam soil. They reported highest BD under NT treatment (1.43 Mg/M$^3$) and lowest under MB (1.36 Mg/M$^3$), CP being in the middle (1.41 Mg/M$^3$).

**Macroporosity (MP)**

Tables 2 and 3 show average MP data at the surface and the 15 cm depth for the three soil types as a function of tillage. Figure 6 presents this information in graphical form for better visualization. Again, there was a large variability in the MP data (CV ranging from 23 to 133%; see Table 3 in Appendix B). Figure 6 shows that at there was no definite trend in macroporosity for different tillage systems. For example, at the surface, maximum MP was observed under MB treatment in Floyd and Kenyon but under NT treatment in Readlyn soil. Similarly, at the 15 cm depth maximum MP was observed under RT treatment in Floyd and Kenyon soils and under CP
treatment in Readlyn soil. A statistical analysis done for each soil type separately (f-test, at 95% confidence interval) showed no significant effect of tillage on MP. Results of these statistical tests are summarized in Table 3 of Appendix B.

Freese et al. (1993) also measured MP for a sandy clay loam soil by a water desorption method using soil cores of 7.5 cm diameter and 7.5 cm length. They reported highest MP (pores > 0.03 cm diameter) under MB treatment (0.2 M^3/M^3) and lowest under NT (0.12 M^3/M^3).

Thus, analysis of Ksat, BD, and MP data reveals no significant difference among tillage systems even in the tilled horizon for all soils except Readlyn. Logsdon et al. (1993) found in a similar study that differences in the surface infiltration due to management varied with time due to cultivation, surface seal formation after heavy spring rains, and soil cracking under drying conditions. They concluded in their study that the temporal variation of infiltration rate was much greater than management-induced variation.

**Part B. Simulating Tillage Effects on the Subsurface**

**Movement of Water and NO₃-N**

A simulation study was conducted to mathematically model tillage effects on the movement of water and NO₃-N through the root zone for crop growth season of year 1990. The Root Zone Water Quality Model (RZWQM) was selected to simulate the effect of four different tillage practices (CP, MB, NT, and RT) on the transport of nitrate under continuous corn production. Soil properties data collected to characterize tillage (Part A of this paper) were utilized as part of the input to this model. The following paragraphs provide a brief outline of the model, simulation procedure, and the results from model simulations.
A Brief Overview of RZWQM

RZWQM (USDA-ARS, 1992a) V-1.0 was developed to simulate the movement of the water, nutrients, and pesticides over and through the root zone of a unit area. It is primarily a one-dimensional model designed to simulate conditions at a representative point (unit area) in a field. The model can be used as a tool for assessing the impacts of alternative agricultural management strategies on the subsurface environment. These alternatives include evaluation of: management plans on a field-by-field basis, different levels of conservation tillage, surface sealing effects, and water quality impacts of irrigation and methods of fertilizer and pesticide application. RZWQM consists of six subsystems or processes that define the simulation program. These processes, namely physical, plant growth, soil chemical, nutrient, pesticide, and management processes, are described one by one in the following paragraphs.

Physical processes

Physical processes include a large number of interrelated hydrological processes. These processes include infiltration; chemical transport during infiltration; transfer of chemicals to runoff during rainfall; water and chemical flow through macropore channels and their absorption by the soil matrix; soil hydraulic properties estimation from BD and 33 kPa or 1500 kPa water content; heat flow; evapotranspiration, root water uptake and soil water redistribution; and chemical transport during redistribution. Soil surface evaporation and plant transpiration are calculated using a form of the Penman-Monteith equation that enables each to be separately identified but linked through energy transfer. These daily evaporation and transpiration rates are impacted by continuously changing soil and cover conditions brought about by tillage, residue accumulation, plant growth, and soil water movement.
Plant growth processes

The plant growth model predicts the relative response of plants to changes in environment. Environmental change can be manifested either as normal variations in climatic variables or by differences in management practices. The model simulates carbon dioxide assimilation, carbon allocation, dark respiration, periodic tissue loss, plant mortality, root growth through the soil profile, transpiration, and nitrogen (N) uptake.

Soil chemical processes

Soil chemical processes include soil inorganic chemical processes, nutrient processes, chemical transport, and pesticide processes. The inorganic processes include bicarbonate buffering, dissolution and precipitation of calcium carbonate, gypsum, and aluminum hydroxide; ion exchange involving bases and aluminum; and solution chemistry of ion-pair complexes. The chemical state of the soil is characterized by soil pH, solution concentration of the major ions, and adsorbed cations on the exchange complex. The model is capable of handling soil solution chemistry across a wide range of soil pH.

Nutrient processes

The nutrient processes define carbon (C) and N transformations within the soil profile. 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. A multi-pool approach is used for organic matter cycling. Transformation rate equations are based on chemical kinetic theory, and are controlled by microbial population density and other environmental variables such as soil temperatures, pH, water content, and salinity. Level of soluble nutrients are used in estimating crop growth, nutrient
extraction in surface runoff, and movement through and below root zone.

Management processes

The management submodel consists of a description of management activities influencing the state of the root zone. It includes typical tillage practices for most crop rotations and the impact these tillage practices have on surface roughness, BD, and micro- and macroporosity. The timing of typical management practices such as fertilizer and pesticide applications, irrigation, planting densities and timing, primary tillage, cultivation, and harvest operations are functions of soil moisture conditions. Algorithms to describe BD reconsolidation as a function of time, rainfall, and tillage have been adopted and modified from the WEPP projects (Alberts et al., 1989).

Methodology

The study site was located on a predominantly Kenyon loam (fine-loamy, mixed, mesic, Typic Hapludoll) soil with 3 to 4% organic matter at Iowa State University's Northeast Research Center, Nashua, IA. These soils have seasonally high water tables and benefit from subsurface drainage. A 15-ha field experiment with 36 0.4-ha plots was established on this site in 1977, later being used to investigate tillage effects on surface and subsurface water quality. Tillage treatments included CP, MB, NT, and RT systems.

Collecting soil samples for moisture content and NO₃-N analyses

Three 180-cm-long soil cores were collected from each plot in the year 1990. The first set of cores was collected on May 30, the second set on September 25, and the third set on October 25 covering the whole growing season. To collect samples, a zero contamination hand sampler was used to remove 180 cm long 2.5 cm diameter cores. As the sampler was pushed into the soil, each
core slid into a clean liner made of PETG (polyethylene, terephthalate, glycol modified) plastic to protect the sample from contamination. These samples were frozen promptly after collection. Three cores were collected for each plot. Soil cores for the same plot were composited after sectioning them into a set of nine samples representing following depths: 0-10, 10-20, 20-30, 30-45, 45-60, 60-90, 90-120, 120-150, and 150-180 cm. Composited samples were analyzed for soil moisture and NO$_3$-N concentrations. Soil moisture was measured by weighing a sample of soil, drying it at 105°C for 24 h, reweighing the cooled sample, and calculating the soil moisture as the percentage water on dry soil basis. For NO$_3$-N analysis, a weighed sample of wet soil was mixed with 2 N potassium chloride (KCl). This mixture was shaken for one hour, then filtered. The resulting filtrate was analyzed with a Lachat Model AE ion analyzer. A detailed methodology of collecting soil samples and analyzing them is given by Weed (1992).

**Modeling Simulations**

All of the measured input parameter values used in the model simulation were either measured in the field or were taken from previously conducted research at this site. Input parameter values for which no data were available, were estimated using the databases provided in the RZWQM's user manual (USDA-ARS, 1992b). Thus, only on-site input data or estimates derived by the model were used in the simulations. Movement of water and NO$_3$-N was simulated under CP, MB, NT, and RT treatments. A unit gradient was assumed for the lower boundary condition for all the simulation runs.

For model simulations, a variable-depth-increment scheme (layer thickness ranging from 1 cm at the top to 15 cm at the bottom) was used as described in the technical documentation of RZWQM (USDA-ARS, 1992a). The profile depth simulated was 1.67 m. Seven soil horizons for Kenyon loam soil (Figure 3) were delineated for model input. Soil profile information was
collected from soil survey report of Butler County, IA (USDA-SCS, 1982). The respective soil properties were used as inputs for each of these horizons as described in following section.

**Soil properties data**

BD and MP for the surface horizon (0-20 cm) were determined experimentally as a function of tillage for Kenyon soil as described in Part A of this paper. For subsequent horizons BD values were taken from the soils database of Sharpley and William (1990) and a MP of 0.01% was assumed for these horizons. Total porosity for each horizon was calculated from BD and an assumed value of 2.65 g/cm³ for particle density. Other soil properties such as 33 kPa moisture content ($\Theta_{33kPa}$), 1500 kPa moisture content ($\Theta_{1500kPa}$), and pH for the Kenyon soil were also taken from Sharply and William (1990). All other hydraulic properties such as Ksat, effective porosity, bubbling pressure, were estimated by the model based on soil texture, BD, and $\Theta_{33kPa}$ values.

Experimentally measured values of soil texture were used as input to the model. Soil heat properties (dry volumetric heat capacity and heat conductivity) were estimated by using soil texture data as described by Jury et al. (1991) and used as input to the model. Actual tillage, planting, fertilizer application, and harvest dates were used as inputs to the model and are shown in Table 4.

**Weather data**

Daily meteorological data including minimum and maximum temperature, wind speed, radiation, relative humidity, and pan evaporation is required by the model as input. All the daily meteorological data except wind speed and pan evaporation were available for the Nashua weather station. These data were obtained from Dr. Elwynn Taylor, Professor, Agronomy Dept., Iowa State University. Daily evaporation was estimated by the model by using short-wave radiation as the
energy input to the evaporation algorithm. When wind speed is missing, the model assumes a wind speed of 10 km/day.

RZWQM accepts rainfall in the form of breakpoint rainfall data to incorporate the effects of rainfall intensity on the subsurface movement of water and chemicals. Breakpoints represent breaks or change in slope in the cumulative rainfall versus time plot. For this study, hourly rainfall data for Nashua weather station were obtained from Dr. Elwynn Taylor, Professor, Agronomy, Iowa State University. For each rainfall event, cumulative rainfall was plotted as a function of time. Breakpoints were recorded at every point where there was a significant change in the slope. For the periods when hourly rainfall data were not available, daily rainfall was recorded and breakpoints were noted from a rainfall event of similar magnitude for which hourly rainfall data were available.

The model also requires values of surface albedos for dry and wet soil, mature crop and residue, and sunshine fraction, as input. Surface albedos were taken from Jury et al. (1991). Sunshine factor is estimated based on latitude information provided as input to the model.

Plant growth variables and parameters

RZWQM uses a generic plant growth model to simulate corn growth. Default values of plant growth parameters were used for generic growth model, as recommended in the RZWQM user manual. Planting and harvesting days, number of plantings, planting depth, planting density, harvesting efficiency, etc., are input to the model and were based on the actual field information collected at the research site.
Initial conditions

Initial conditions specified for the simulations mainly consisted of pH, initial moisture content and temperature, soil inorganic chemistry variables (CEC, fractions of exchangeable ions, etc.), organic matter pools, microorganisms pools, solution chemistry, gas pools, and initial NO$_3$-N concentrations in the soil profile.

Except for pH, organic matter pools, initial moisture content, and NO$_3$-N concentration profiles default values provided in the model were used. Soil pH values for different tillage practices were taken from soil test results (Karlen et al., 1991). Organic matter values were obtained from Nashua soil report (Table 1) and were divided into slow (60%), medium (35%), and fast (5%) pools as described in RZWQM user’s manual (USDA-ARS, 1992b). Initial moisture contents were specified as $\Theta_{22kpa}$; $\Theta_{22kpa}$ values were taken from soil series data (Sharpley and William, 1990) and were the same for all the tillage systems. Initial NO$_3$-N concentrations were specified as the observed concentrations in the soil samples at the end of October 1990. A careful review of the soil sample data revealed that NO$_3$-N concentration profiles at the end of October 1990 were quite similar to that of the pre-fertilizer application concentrations in the spring of 1991, indicating little change in concentration profiles through the 90-91 winter period. Initial NO$_3$-N concentrations for simulation runs are provided in Table 5.

Results and Discussion

The model was run from Julian day (JD) 100 to JD 300 covering the 1990 crop growing season. Simulated results and their comparison with observed data are discussed in the following paragraphs.
Soil moisture content

Figures 7, 8, and 9 show both observed and simulated volumetric moisture content (m.c.) in the soil profile on JD 150 (May 30), 268 (September 25) and 298 (October 25) for the year 1990. These figures show that simulated m.c. was usually less than observed m.c.. Also, the difference between observed and simulated values decreased with depth for all three dates. Simulated m.c. profiles on JD 150 show that MB treatment had a higher m.c. at all depths in comparison with other tillage treatments. On the other hand, the observed m.c. profiles on JD 150 showed no consistent pattern. Simulated m.c. profiles on JD 268 and 298 do not show any substantial difference between tillage treatments as opposed to observed m.c. values. Observed m.c. data show more distinction between tillages in surface layers (maximum m. c. being in NT treatment). This difference gradually decreases with depth. One of the possible causes of difference between simulated and observed m.c. in the soil profile is the assumption of unit hydraulic gradient at the bottom. A unit hydraulic gradient assumption at the bottom does not represent the actual field condition of a fluctuating water table. The unit gradient assumption results in deep seepage from the profile which, at times, is much higher than the observed tile drainage values in the field. To give an example of this process, simulated deep seepage was plotted as a function of time for CP treatment (Figure 10). Total simulated deep seepage that occurred under CP treatment was about 32 cm in comparison to observed average tile drainage of about 18 cm under CP treatment (Kanwar et al., 1993). Observed m.c. values for deeper layers are close to saturated m.c. showing the presence of a water table. A unit hydraulic gradient boundary assumption, therefore, is not consistent with the actual field situation of a fluctuating water table. Water table depths for the Nashua experimental site (in plot piezometer data for continuous corn plots; Kanwar et al., 1993) were plotted in Figure 11 as a function of time for the year 1993 to show typical water table fluctuations during a growing season. Thus, there is clearly a need to incorporate fluctuating
water table and tile drainage components in RZWQM to accurately simulate hydrologic processes in actual field conditions.

Some other factors affecting the moisture movement through the soil profile could be inconsistencies between estimated and actual rainfall intensities, discrepancies between estimated and actual values of some of the soil properties, and finally, unaccounted spatial variability in soil properties which plays a major role in the subsurface water and solute transport.

**Soil NO$_3$-N transport**

Figures 12, 13, and 14 show simulated and observed NO$_3$-N concentrations (mg/L) in the soil profile. Observed NO$_3$-N concentrations in the soil profile showed no clear pattern regarding tillage effects on NO$_3$-N concentrations. However, MB and CP treatments generally showed higher NO$_3$-N concentrations in comparison with NT and RT treatments. For JD 150 and 268, MB treatment had the highest NO$_3$-N concentration in the soil profile. Minimum NO$_3$-N concentrations in the soil profile usually occurred under NT treatment. For JD 298, CP treatment had the highest NO$_3$-N concentrations and again NT the lowest. A detailed discussion on these observations is provided by Weed (1992).

Simulated NO$_3$-N concentrations were more or less in the same range as those of observed concentrations. But the model predicted substantially higher NO$_3$-N concentration under MB and RT treatments in comparison to NT and CP treatments, usually at all depths, for JD 150. On the other hand, for JD 268, and 298, simulated NO$_3$-N concentration profiles for different tillage treatments were more or less similar to a depth of 60 cm. For deeper soil horizons MB and RT treatments showed substantially higher NO$_3$-N concentrations in comparison to NT and CP treatments for both JD 268 and 298. Usually the simulated peak concentrations occurred within the same depth increments for all tillages (except on JD 268), but depths of simulated peaks were
many depth increments off from the depth of observed peaks. A comparison of observed peak and simulated peak NO$_3$-N concentrations in the soil reveals that the model generally overpredicted maximum NO$_3$-N concentrations for all the treatments. Discrepancies between simulated and observed NO$_3$-N concentrations indicate a need for evaluation and validation of various N transformation processes in the light of different tillage systems besides improving the hydrologic and plant growth components of the model.

Figures 13 and 14 also show that observed NO$_3$-N concentrations at depths from 20 to 80 cm were higher on JD 298 (October 25) than those on JD 268 (September 25). This could have been a result of continued mineralization but minimal plant uptake or leaching losses. Simulated NO$_3$-N concentrations also showed a similar trend. Simulated mineralization and plant uptake rates were plotted as a function of time (Figure 15) for CP treatment to check if the model also exhibits the phenomena of reduced plant uptake and continued mineralization. Figure 15 shows that variations in plant uptake and mineralization rates were in agreement with expected trends.

**Summary and Conclusions**

Four tillage systems (CP, MB, NT, and RT) were characterized by measuring soil physical properties (Ksat, BD, and MP) for three different soil types (Kenyon, Floyd, and Readlyn). Ksat, BD, and MP data for 50-cm deep soil profile showed no significant effect of tillage systems for all soil types except for Readlyn. For Readlyn, Ksat data at 7.5-15 cm depth increment showed a significant effect of tillage. Root Zone Water Quality Model (RZWQM) was used to simulate water and NO$_3$-N movement through vadose zone utilizing field-measured soil properties. RZWQM usually predicted lower m.c. than observed in the field conditions. A unit hydraulic gradient boundary caused deep seepage from the bottom of the soil profile which was considerably higher than observed tile drainage, resulting in lower predicted m.c. in the soil profile. Although
predicted NO$_3$-N concentrations were usually within the range (maximum and minimum NO$_3$-N concentrations) of observed NO$_3$-N concentrations, the depth and magnitude of predicted peak NO$_3$-N concentrations were substantially different than observed ones. The model predictions did not compare well with the observed data regarding the tillage effects on water and NO$_3$-N transport, indicating a need for improvement in the hydrologic and nutrient components of the model as well as their evaluation and validation in the light of different tillage practices.

References


Table 1. Particle size distribution and organic carbon content for three soils as a function of depth

<table>
<thead>
<tr>
<th>Soil</th>
<th>Depth (cm)</th>
<th>%Clay</th>
<th>%Sand</th>
<th>%Silt</th>
<th>% Organic Carbon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floyd</td>
<td>0-7.5</td>
<td>26.6</td>
<td>28.4</td>
<td>45.0</td>
<td>2.9</td>
</tr>
<tr>
<td></td>
<td>35-42.5</td>
<td>26.0</td>
<td>32.6</td>
<td>41.4</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>70-77.5</td>
<td>24.1</td>
<td>53.8</td>
<td>22.1</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>105-112.5</td>
<td>23.6</td>
<td>47.6</td>
<td>28.8</td>
<td>0.2</td>
</tr>
<tr>
<td>Kenyon</td>
<td>0-7.5</td>
<td>21.5</td>
<td>36.5</td>
<td>42.0</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>35-42.5</td>
<td>25.6</td>
<td>40.9</td>
<td>33.5</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>70-77.5</td>
<td>29.0</td>
<td>43.5</td>
<td>27.5</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>105-112.5</td>
<td>25.0</td>
<td>44.4</td>
<td>30.6</td>
<td>0.2</td>
</tr>
<tr>
<td>Readlyn</td>
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<td>30.5</td>
<td>43.5</td>
<td>2.4</td>
</tr>
<tr>
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<td>24.9</td>
<td>37.6</td>
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</tr>
<tr>
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<td>20.6</td>
<td>55.7</td>
<td>23.7</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>105-112.5</td>
<td>25.9</td>
<td>46.4</td>
<td>27.7</td>
<td>0.3</td>
</tr>
</tbody>
</table>
Table 2. Macroporosity at the surface as a function of soil type and tillage practice.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>I=Ponded infiltration (μm/s)</th>
<th>Io=Infiltration at 3 cm tension (μm/s)</th>
<th>Km (I-Io) (μm/s)</th>
<th>Number* of macropores</th>
<th>Macroporosity (m³/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NT-K</td>
<td>98.08</td>
<td>4.58</td>
<td>93.51</td>
<td>0.039</td>
<td>0.00031</td>
</tr>
<tr>
<td>NT-R</td>
<td>402.04</td>
<td>6.98</td>
<td>395.06</td>
<td>0.164</td>
<td>0.00129</td>
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<tr>
<td>NT-F</td>
<td>39.08</td>
<td>2.74</td>
<td>36.34</td>
<td>0.015</td>
<td>0.00012</td>
</tr>
<tr>
<td>CP-K</td>
<td>56.01</td>
<td>3.44</td>
<td>52.58</td>
<td>0.022</td>
<td>0.00017</td>
</tr>
<tr>
<td>CP-R</td>
<td>120.50</td>
<td>4.76</td>
<td>115.74</td>
<td>0.048</td>
<td>0.00038</td>
</tr>
<tr>
<td>CP-F</td>
<td>132.79</td>
<td>2.63</td>
<td>130.16</td>
<td>0.054</td>
<td>0.00043</td>
</tr>
<tr>
<td>MB-K</td>
<td>127.40</td>
<td>3.29</td>
<td>124.11</td>
<td>0.052</td>
<td>0.00041</td>
</tr>
<tr>
<td>MB-R</td>
<td>191.38</td>
<td>5.17</td>
<td>186.21</td>
<td>0.077</td>
<td>0.00061</td>
</tr>
<tr>
<td>MB-F</td>
<td>601.63</td>
<td>5.16</td>
<td>596.47</td>
<td>0.248</td>
<td>0.00195</td>
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<tr>
<td>RT-K</td>
<td>38.88</td>
<td>3.65</td>
<td>35.24</td>
<td>0.015</td>
<td>0.00012</td>
</tr>
<tr>
<td>RT-R</td>
<td>125.46</td>
<td>4.01</td>
<td>121.45</td>
<td>0.051</td>
<td>0.00040</td>
</tr>
<tr>
<td>RT-F</td>
<td>86.84</td>
<td>4.75</td>
<td>82.10</td>
<td>0.034</td>
<td>0.00027</td>
</tr>
</tbody>
</table>

F=Floyd, K=Kenyon, R=Readlyn
CP=Chisel Plow, MB=Moldboard Plow, NT=No Till, RT=Ridge Till
*per cm²
Table 3. Macroporosity at 15-cm depth as a function of soil type and tillage practice.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>I=Ponded infiltration (µm/s)</th>
<th>Io=Infiltration at 3 cm tension (µm/s)</th>
<th>Km (I-Io) (µm/s)</th>
<th>Number* of macropores</th>
<th>Macroporosity (m²/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NT-K</td>
<td>52.96</td>
<td>2.25</td>
<td>50.71</td>
<td>0.021</td>
<td>0.00017</td>
</tr>
<tr>
<td>NT-R</td>
<td>101.75</td>
<td>1.24</td>
<td>100.51</td>
<td>0.042</td>
<td>0.00033</td>
</tr>
<tr>
<td>NT-F</td>
<td>108.32</td>
<td>1.78</td>
<td>106.54</td>
<td>0.044</td>
<td>0.00035</td>
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<tr>
<td>CP-K</td>
<td>17.35</td>
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<td>16.52</td>
<td>0.007</td>
<td>0.00005</td>
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<tr>
<td>CP-R</td>
<td>137.06</td>
<td>2.13</td>
<td>134.93</td>
<td>0.056</td>
<td>0.00044</td>
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<tr>
<td>CP-F</td>
<td>81.36</td>
<td>2.15</td>
<td>79.21</td>
<td>0.033</td>
<td>0.00026</td>
</tr>
<tr>
<td>MB-K</td>
<td>129.96</td>
<td>1.28</td>
<td>128.69</td>
<td>0.054</td>
<td>0.00042</td>
</tr>
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<td>MB-R</td>
<td>84.99</td>
<td>1.43</td>
<td>83.56</td>
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<td>0.00027</td>
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<td>MB-F</td>
<td>43.27</td>
<td>1.98</td>
<td>41.29</td>
<td>0.017</td>
<td>0.00013</td>
</tr>
<tr>
<td>RT-K</td>
<td>138.39</td>
<td>6.60</td>
<td>131.79</td>
<td>0.055</td>
<td>0.00043</td>
</tr>
<tr>
<td>RT-R</td>
<td>79.60</td>
<td>2.21</td>
<td>77.39</td>
<td>0.032</td>
<td>0.00025</td>
</tr>
<tr>
<td>RT-F</td>
<td>240.46</td>
<td>0.84</td>
<td>239.62</td>
<td>0.100</td>
<td>0.00078</td>
</tr>
</tbody>
</table>

F=Floyd, K=Kenyon, R=Readlyn
CP=Chisel Plow, MB=Moldboard Plow, NT=No Till, RT=Ridge Till
*per cm²
Table 4. Dates of tillage, planting, chemical application, and harvesting for simulation runs.

<table>
<thead>
<tr>
<th>Date</th>
<th>Julian date</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>5/1/90</td>
<td>121</td>
<td>Spring tillage</td>
</tr>
<tr>
<td>5/4/90</td>
<td>124</td>
<td>Surface broadcast 2.2 Kg/ha alachlor and 2.8 Kg/ha atrazine</td>
</tr>
<tr>
<td>5/5/90</td>
<td>125</td>
<td>Applied 200 Kg-N/ha</td>
</tr>
<tr>
<td>5/12/90</td>
<td>132</td>
<td>Planted corn</td>
</tr>
<tr>
<td>5/26/90</td>
<td>147</td>
<td>Cultivation</td>
</tr>
<tr>
<td>5/30/90</td>
<td>150</td>
<td>Late spring soil sampling</td>
</tr>
<tr>
<td>7/5/90</td>
<td>186</td>
<td>Cultivation</td>
</tr>
<tr>
<td>9/25/90</td>
<td>268</td>
<td>Late season soil sampling</td>
</tr>
<tr>
<td>10/07/90</td>
<td>280</td>
<td>Harvested corn</td>
</tr>
<tr>
<td>10/25/90</td>
<td>298</td>
<td>Post-harvest soil sampling; Fall tillage</td>
</tr>
</tbody>
</table>

Table 5. Initial NO₃-N concentrations for simulation runs for all tillage treatments

<table>
<thead>
<tr>
<th>Horizon</th>
<th>NO₃-N concentration (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Chisel Plow</td>
</tr>
<tr>
<td>1</td>
<td>55</td>
</tr>
<tr>
<td>2</td>
<td>25</td>
</tr>
<tr>
<td>3</td>
<td>20</td>
</tr>
<tr>
<td>4</td>
<td>31</td>
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<td>5</td>
<td>31</td>
</tr>
<tr>
<td>6</td>
<td>51</td>
</tr>
<tr>
<td>7</td>
<td>42</td>
</tr>
</tbody>
</table>
Figure 1A. Nashua field plots diagram showing tillage plots, soil map units, and locations of soil core sampling (+) and infiltration measurements (adopted from Logsdon et al., 1993)

- CC: continuous corn
- SC: soybean corn
- CS: corn soybean
- NT: no-till
- CP: chisel plow
- MB: moldboard plow
- RT: ridge-till
Figure 1B. Typical pattern of soils and parent material in Kenyon-Clyde-Floyd association (USDA-SCS, 1982)
Figure 2A. A schematic showing the position of soil sample in the field and wheel tracks of sprayer (S), planter (P), and combine (C)

Figure 2B. A schematic showing soil core sealed with wax for Ksat determination
Figure 3. Typical soil horizons for all three types of soils (USDA-SCS, 1982) and a vertical cross-section of soil core showing Ksat and BD subsamples.
Figure 4. Saturated hydraulic conductivities (cm/s) for three soils as a function of tillage and depth.
Figure 5. Bulk density for three soils as a function of tillage and depth
Figure 6. Macroporosity for three soils as a function of tillage and depth
Figure 7. Simulated (lines) and observed (points) moisture content (cm$^3$/cm$^3$) in the soil profile for JD 150 (error bars show the standard deviation)
Figure 8. Simulated (lines) and observed (points) moisture content (cm$^3$/cm$^3$) in the soil profile for JD 268 (error bars show the standard deviation)
Figure 9. Simulated (lines) and observed (points) moisture content (cm$^3$/cm$^3$) in the soil profile for JD 298 (error bars show the standard deviation).
Total simulated deep seepage = 32.2 cm

Figure 10. Simulated deep seepage from soil profile under CP treatment
Figure 11. Water table depths for continuous corn plots at Nashua field site
Figure 12. Simulated (lines) and observed (points) NO3-N concentrations in soil profile for JD 150 (error bars show the standard deviation)
Figure 13. Simulated (lines) and observed (points) NO3-N concentration in soil profile for JD 268 (error bars show the standard deviation)
Figure 14. Simulated (lines) and observed (points) NO3-N concentrations in soil profile for JD 298 (error bars show the standard deviation)
Figure 15. Simulated plant uptake and mineralization rates for CP treatment
MODIFICATION OF RZWQM FOR SIMULATING SUBSURFACE DRAINAGE
BY ADDING A TILE FLOW COMPONENT

A paper to be submitted to TRANSACTIONS of the ASAE

Piyush Singh and Rameshwar S. Kanwar

Abstract

Fluctuating water table and subsurface drain flow components were incorporated in the Root Zone Water Quality Model (RZWQM) to simulate subsurface drain flows under four different tillage systems - chisel plow (CP), moldboard plow (MB), no-tillage (NT), and ridge-tillage (RT). Simulations were conducted for the growing seasons of three years (1990, 1991, and 1992). The modified model was calibrated by using observed subsurface drain flows for 1990. Model performance was further evaluated by predicting subsurface drain flows for 1991 and 1992 using the calibrated parameters. The modified model, in general, showed a good response to rainfall in terms of time of peak flows and total subsurface drain flow for a given year. Also, predicted tillage effects on subsurface drain flows were consistent with the observed effects (i.e., maximum tile flow for NT and minimum for MB). However, the modified model overpredicted total tile flows by 13% on average, and the magnitude of peaks was generally underpredicted. Model performance could be improved by using more accurate input data, incorporating deep seepage and lateral groundwater flow components, and incorporating spatial variability of soil characteristics in the model.
Introduction

Agricultural drainage is defined as a timely removal and disposal of excess water from agricultural land by means of open surface and/or subsurface drainage methods. Artificial drainage systems are needed to supplement natural drainage and enhance crop growth conditions. Artificial drainage has made agricultural development possible on much of the most productive land in the United States. Subsurface drainage of wet areas alters the time and route by which excess precipitation reaches surface waters. Decreases in the amount of overland flow, increases in percolation, lower water table, and alteration in the flow path of some of the infiltrated water result from subsurface drainage (Baker and Johnson, 1976).

On the other hand, tillage practices directly affect the soil water properties of surface soil and therefore the leaching characteristics (Kanwar et al., 1988). Tillage also disturbs the macropores, whereas no-tillage allows macropore systems to develop and persist. Macropores can act as preferential pathways for rapid movement of water and chemicals to the groundwater. Because of concerns for non-point source pollution, the fate of agricultural chemicals under different tillage systems is of considerable interest and importance. Therefore it is necessary to understand all the factors that affect it. Investigating the quantity and quality of subsurface drainage water under different tillage systems can be helpful in understanding the leaching characteristics of soil under different tillage systems and determining the suitable tillage practices for water quality enhancement. For example, Kanwar (1991) studied the effects of four tillage systems (CP, MP, NT, RT) on the quantity and quality of subsurface drain flows. He reported that greater drain flows from no-tillage plots under continuous corn resulted in larger NO\textsubscript{3}-N losses in comparison with NO\textsubscript{3}-N losses from other tillage systems. Several other studies have been conducted to measure the loss of NO\textsubscript{3}-N through subsurface drainage (Burwell et al., 1976; Taylor and Thomas, 1977; Gast et al., 1978; Baker and Johnson, 1981; Gold and Loudan, 1982; Kanwar
et al., 1985, 1988, 1993a,b; Randall and Nelson, 1985).

Besides experimental investigations, a number of modeling studies have been conducted involving the development and utilization of mathematical models to simulate subsurface drainage. Kirkham (1958) developed an analytical solution for steady state flow to parallel tile drains in a homogenous soil underlain by impermeable layers. Dutt et al. (1972) and Duffy et al. (1975) developed mathematical models which could be applied to a tile-drained agricultural area. Skaggs (1978) developed a computer simulation model DRAINMOD that simulates the movement of soil water as affected by various subsurface water-management systems. DRAINMOD has been extended further as DRAINMOD-N for predicting nitrogen (N) transport, uptake, and transformation in artificially drained soils. Kanwar et al. (1983) developed a computer simulation model to simulate N losses with tile drainage water. Scotter et al. (1990) developed a simple numerical solution for transient soil water flow to a mole drain for assumed or measured values for rainfall, evaporation, deep percolation, drain spacing, and depth. Workman and Skaggs (1990) developed a water-management model capable of simulating preferential flow. However, none of these models incorporates the tillage effects on subsurface drainage flows and quality.

The main purpose of this paper was to develop a comprehensive subsurface drainage flow model by incorporating a fluctuating water table and tile drainage components into the Root Zone Water Quality Model, RZWQM (USDA-ARS, 1992a). RZWQM is a process-based, integrated model of soil-water-plant-atmosphere system that can be used for analyzing the effects of various agricultural management practices, including tillage, both on the subsurface environment and crop production. Adding a tile drainage component makes this model capable of simulating subsurface drain flows and evaluate the impact of different agricultural management systems on subsurface drain flows. Following were the specific objectives of this paper:
1. Develop a fluctuating water table and subsurface drain flow component and incorporate it into the RZWQM.

2. Evaluate the performance of the modified RZWQM model by simulating subsurface drain flows under different tillage systems and comparing these flows with observed tile flow data for 1990, 1991, and 1992 from the Nashua Water Quality Site in Iowa (Kanwar et al., 1993b).

**Model Development and Theory**

Fluctuating water table and subsurface drainage components were developed and incorporated into RZWQM to simulate subsurface drainage flows under different tillage systems. For this, a separate subroutine was developed to simulate moisture movement under variably saturated conditions and calculate daily subsurface drain flows as a function of water table depth. The following paragraphs describe the procedure in detail.

**A Brief Overview of RZWQM**

This section describes RZWQM components dealing with water movement in the soil matrix and macropores. Water flow in RZWQM is based on a simple two-domain or bi-continuum approach. The two domains of flow are the soil matrix and macropore channels. These domains interact through walls of the macropore channels which act as a common boundary for a source/sink term. The only source of water and chemicals transported through the macropores is overland flow (rainfall excess) generated at the soil surface and the chemicals it picks up from the surface soil by mixing and raindrop impact. The solution flow in macropore channels is assumed to be very rapid and unaffected by pore tortuosity. The solution is, however, subject to lateral absorption into the drier soil matrix. The reactive chemicals in solution are also subject to adsorption to or desorption from the macropore walls. For purposes of chemical transport, the soil
matrix is further subdivided into micropore (immobile) and mesopore (mobile) zones.  

The Green-Ampt equation is used to calculate infiltration rates into the profile:

\[ V = \frac{K_s \left( H_e + H_o + Z_{wf} \right)}{Z_{wf}} \]  \[ \text{[1]} \]

where \( V \) is the infiltration rate at any given time, \( K_s \) is the effective saturated hydraulic conductivity of the wetting zone, \( H_e \) is the capillary drive or suction at the wetting front, \( H_o \) is the depth of subsurface ponding, if any, and \( Z_{wf} \) is the depth of wetting front. In early stages of rainfall, the infiltration rate calculated by the Green-Ampt equation may be greater than the rainfall rate.

For a homogenous soil or the surface of a layered soil, the saturated hydraulic conductivity, \( K_s \), in the Green-Ampt equation is set equal to the field saturated hydraulic conductivity of the soil or horizon. For a layered soil profile with hydraulic conductivity decreasing with depth, the hydraulic conductivity is set equal to the harmonic mean \( K_{sat} \) conductivity of the wetted zone. Thus for such a layered soil the \( K_{sat} \) changes as the wetted depth increases with time. If hydraulic conductivity of a subsoil layer in a layered soil is greater than that of the harmonic mean of the layers above, the latter continues to govern the flow in the subsoil layer.

The capillary drive, \( H_e \), in the Green-Ampt equation, varies from horizon to horizon, corresponding to the location of the wetting front. It is calculated from the unsaturated hydraulic conductivity-suction function \( K(h) \) of the wetting horizon. For the purpose of calculations, the soil profile is divided into 1-cm depth increments down to the bottom of the profile. A simple and efficient scheme is used to integrate Eq.[1] for obtaining cumulative infiltration and time under these conditions.
Redistribution of Water and Chemicals After Infiltration

After infiltration, the soil water is redistributed by using the Richards Equation:

\[
\frac{\partial \Theta}{\partial t} = -\frac{\partial}{\partial z} \left[ K(h, z) \frac{\partial h}{\partial z} - K(h, z) \right] - S(z, t)
\]  \hspace{1cm} [2]

where

\( \Theta \) = volumetric soil water content

\( t \) = time

\( z \) = soil depth

\( h \) = soil water pressure depth

\( K \) = unsaturated hydraulic conductivity, a function of \( h \), and \( z \), and

\( S(z, t) \) = root water uptake rate

The upper boundary condition for Equation [2] is defined as moisture flux equal to evaporation rate at the surface while the lower boundary condition can be specified as constant head or unit gradient boundary. A detailed desorption of moisture redistribution is given in RZWQM technical documentation (USDA-ARS, 1992a).

The Transport of Overland Water and Chemical Solution through Macropores

Average volume fraction of macroporosity and average size of voids (radius of cylindrical macropores and width of cracks) are assumed to be known. From this information, the number of pores or total length of cracks per unit area of soil is calculated. The maximum flow rate capacity (\( K_{\text{mac}} \)) of these macropores is then calculated using Poiseuille's law, assuming gravity flow (unit hydraulic head gradient). After ponding, the water and solutes available at the soil surface are allowed to flow into macropores to the limit of macropore flow capacity. In each depth increment
macropore flow is also allowed to flow into deadend macropores; macropore flow is absorbed by the soil matrix by radial or lateral infiltration from macropores. This routing continues until the available solution within a given time step is exhausted or the lowest depth of interest is reached. Below the lowest depth, solution is allowed to drain away freely.

Management Practices

In addition to planting and harvesting, RZWQM accommodates the following management practices: tillage events, fertilizer application, pesticide application, and irrigation. By incorporating all these practices into the model, RZWQM is able to simulate many of the processes that occur in a soil during a normal growing season.

Tillage effects are incorporated in RZWQM by changing the BD, and macroporosity, and by incorporating plant residues into the soil. The extent of these changes depends upon whether it is primary or secondary tillage and upon the type of implement used.

Development of a Tile-Drainage Component

To enable RZWQM to accurately simulate the hydrologic processes in soils having subsurface drainage, a tile flow or subsurface drain flow component was added to RZWQM (Ver. 1.0). For this purpose a new moisture redistribution submodel (MOIST) was developed. This new submodel was capable of simulating fluctuating water table and subsurface drain flows as a function of water table depth. Submodel MOIST was incorporated in RZWQM to replace the original moisture redistribution submodel. The following paragraphs describe the moisture redistribution (MOIST) and tile flow subroutine (TDRAIN) in detail.
Moisture Movement Submodel (MOIST)

The moisture redistribution component calculates the unsaturated and saturated flow rates of water within the soil profile after infiltration. It also calculates the daily water table depths and drainage into tiles. This component is based mainly on the moisture movement component of Kanwar (1981).

The water content in the soil is expressed as the water content on a volume basis. In the model, the soil water for a given layer varies between wilting point and field saturated moisture content (specified as 90% of the saturated moisture content). Wilting point is defined as the 1500 kpa moisture content below which it is assumed that no evapotranspiration and no flow occurs through the soil. Field saturated moisture content is defined as the maximum amount of water held by the soil. Above the water table, water content is assumed to vary from 1500 kpa to 33 kpa (moisture content at field capacity). Since the properties of the actual soil profile are heterogenous the values of wilting point and field capacity are functions of depth in the model. A variable-depth scheme (layer thickness ranging from 1 cm at top to 15 cm at bottom) is used to divide the 167 cm deep soil profile into 22 layers. The procedure for dividing the soil profile in different layers is discussed in detail in RZWQM technical documentation (USDS-ARS, 1992a).

MOIST subroutine is called after the infiltration has occurred, thus a moisture profile, right after infiltration, potential evapotranspiration rate, soil physical and hydraulic properties, and depth of water table are input to subroutine. Figure 1 describes a general communication procedure between RZWQM and MOIST. Subroutine MOIST first checks the water table depth and divides the profile into saturated and unsaturated zones. Next it calculates evapotranspiration values from unsaturated layers and determines average inter-layer hydraulic conductivity (K) and diffusion coefficient (D). When the moisture content of a given layer is greater than 33 kpa moisture content (θ_{33kpa}) excess moisture (θ - θ_{33kpa}) is drained to the next layer. If moisture content for a given
layer is below 1500 kPa ($\Theta_{1500\text{ kPa}}$) drainage and ET from this layer are stopped. If moisture content is between $\Theta_{33\text{ kPa}}$ and $\Theta_{1500\text{ kPa}}$, flow rate to the next layer, is calculated by the following equation (Beek and Frissel, 1973)

$$V_i = -D_i(\theta) \frac{d\theta}{dx} + K_i(\theta)$$  \[3\]

where

$V_i$ = flow rate of water (cm/day) in layer $i$

$D_i(\theta)$ = average diffusivity of soil (cm$^2$/day)

$\theta_i$ = water content of soil (cm$^3$/cm$^3$)

$x$ = thickness of soil (cm)

$K_i$ = average saturated hydraulic conductivity of soil (cm/day)

This differential equation can be written as a set of finite difference equations when water flows down from one layer into another layer. The flow rate between layers is calculated according to the following equation:

$$V_i = D_{i-1/2} \left[ \frac{\theta_{i-1} - \theta_{i}}{l} \right] + K_{i-1/2} \quad i=1 \ldots L$$  \[4\]

where

$l$ = thickness of layer (cm)

$D_{i-1/2} = \frac{[D(\theta_{i-1}) + D(\theta_i)]}{2}$ average diffusivity (cm$^2$/hr)

$K_{i-1/2} = \frac{[D(\theta_{i-1}) + K(\theta_i)]}{2}$ average conductivity (cm/hr)

$L$ = index of the layer just above the layer containing water table
Hydraulic conductivity $K(\Theta)$ was passed to MOIST from the main model, and diffusivity $D(\Theta)$ was calculated by using a function adopted from Staple (1969) for loam soil.

Finally, the thickness of unsaturated zone and the water table depth are updated after redistribution of moisture and tile drainage is calculated as a function of the updated water table depth. Figure 2 shows a flow chart of main processes taking place in submodel MOIST. A Fortran listing of the submodel is given in Appendix C.

Changes were also made in the macropore flow component of the model. In the present version of RZWQM the excess water left in the macropores after lateral infiltration to soil matrix was directly drained out of the soil profile to satisfy free flow boundary condition at the bottom. This component was modified to add this excess water from the macropores directly to the subsurface drain flows.

Subsurface Drain Flow Component (TDRAIN)

This component (submodel TDRAIN) calculates subsurface drain flow as a function of water table depth and was based on the tile flow component of DRAINMOD (Skaggs, 1978), and Kanwar et al. (1983). TDRAIN first calculates the thickness of the saturated zone and the effective lateral conductivity. Lateral saturated hydraulic conductivities vary with depth and are input to this component. Drainage flux is calculated by the steady-state Hooghoudt equation:

$$DFLUX = 4.0 \times 10^{2} \times K \times \frac{2.0 \times H_d + E_s}{S^2}$$  \[5\]
where

\[ S = \text{drain spacing, cm} \]
\[ H_d = \text{equivalent depth of the impermeable layer from the center of the drain, cm} \]
\[ \text{DFLUX} = \text{drainage flux (cm/hr)} \]
\[ K = \text{effective lateral hydraulic conductivity, cm/hr} \]
\[ E_w = \text{elevation of water table above the tile drains, cm} \]

The basic assumption of this equation is that the lateral water movement occurs mainly in saturated regions. Although drainage is not a steady-state process, a good approximation has been obtained by using the above equation. Various parameters used in Equation 5 are shown in Figure 3. The values of lateral hydraulic conductivities and other parameters related to drainage flux are given in the next section. Figure 4 shows a flow chart for main processes taking place in subroutine TDRAIN.

After calculating total tile drainage by the Hooghoudt equation, tile drainage per unit thickness (UDRN) is calculated for the saturated zone. The moisture contribution (DEL) from each layer is then calculated by multiplying UDRN by the thickness of the layer. Since thickness of the layers increased with depth, more moisture is contributed from the layers below the tile lines, which is in accordance with the flow net studies of Kirkham (1966). Moisture content of each saturated layer is reduced by the amount DEL and the depth of water table is updated based on the new moisture profile. At the end of the day, hourly drainage flux is added together to determine daily subsurface drainage flux.
Subsurface Drainage Simulations

The modified RZWQM was first calibrated using observed subsurface drain flows for the year 1990, and then its performance was evaluated by comparing simulated subsurface drain flows with the observed flows for years 1991 and 1992. Observed subsurface drain flow data was collected from a water quality site at Iowa State University’s Northeast Research Center (NERC) near Nashua, IA (Kanwar et al., 1993a). The following paragraphs describe the simulation procedure in detail.

Description of the Experimental Site and Observed Tile Flow Data

The study site is located on a predominantly Kenyon loam soil with 3 to 4% organic matter at Iowa State University’s Northeast Research Center (NERC), Nashua, Iowa. These soils have high water tables and benefit from subsurface drainage. Pre-Illinoian till units of 60 m overlie a carbonate aquifer used for water supply. However, in some areas bedrock is near the surface. The site has 36, 0.4-ha experimental plots with fully documented tillage and cropping records for the past fourteen years. Tile lines were installed about 1.2 m deep at 28.5-m spacings in 1979. Each 0.4-ha plot has one tile line passing through the middle of the plot and there is a tile line at each of the borders. The middle tile lines of all the plots were intercepted and connected to individual sumps in December 1988 for measuring daily subsurface drainage and collecting water samples for chemical analysis. A detailed description of the automated subsurface drain monitoring system is given by Kanwar (1991).

Long-term tillage studies were initiated at this site in the fall of 1977 to evaluate the effects of CP, MB, NT, and RT systems. Crop rotations and tillage subplots were replicated three times.
Model Input Data

Weather data

The model requires daily input values of air temperature (minimum and maximum), wind speed (km/day), short wave radiation (MJ/m²/day), pan evaporation (cm H₂O/day), and relative humidity (%). All the daily weather data were available for the Nashua weather station except wind speed and pan evaporation. When the data on wind speed are missing, the model assumes a wind speed of 10 km/day. When the pan evaporation value is not supplied, the model uses short-wave radiation as the energy input into the evaporation algorithm and estimates pan evaporation.

The model requires values of surface albedos for dry and wet soil, mature crop and residue, sunshine fraction, as input. These albedos provide the base values of energy reflectance from these surfaces. The albedos are modified as environmental conditions change. Surface albedos were taken from Jury et al. (1991). Sunshine factor is estimated based on latitude information provided as input to the model. The model uses the Shuttleworth and Wallace (1985) approach to calculate ET.

Rainfall data

The model requires input of rainfall data as breakpoint rainfall data. If a given rainfall event is plotted as cumulative rainfall as a function of time, each point where there is a significant change in slope (representing a change in rainfall intensity) will represent a breakpoint. For the simulations for 1990, 1991, and 1992, hourly rainfall data from Nashua weather station were acquired. To convert hourly rainfall data into breakpoint rainfall data, cumulative rainfall was plotted as a function of time for each rainfall event and breakpoints were recorded wherever there was a significant change in the slope of cumulative rainfall versus time curve. For the period when hourly rainfall data were not available (rain gage damaged or datalogger not working), daily
rainfall values were noted from NERC rain gage (which recorded only daily rainfall). A similar rain event (approximately equal in magnitude) was selected from hourly rainfall data for the Nashua weather station. The pattern of this hourly rainfall was used to estimate breakpoints for the missing rainfall events.

**Soil properties data**

A 167-cm deep soil profile was considered for simulation. This profile was divided into seven soil horizons depending on the information gathered from soil survey reports for Kenyon loam (USDA-SCS, 1982). For each horizon physical soil properties e.g., soil bulk density, porosity (estimated by BD and a particle density of 2.65 g/cm³), macroporosity, particle size distribution were used as input to the model. Soil bulk density, macroporosity for the surface horizon, and particle size distribution at various depths of the profile were experimentally measured. Singh (1994) describes the detailed methodology of these measurements. For subsequent horizons soil BD data were adopted from Sharpley and William (1990) and macroporosity of 0.01% was assumed. Among soil hydraulic properties only 33 kpa moisture content (θ33kpa; field capacity) for respective soil horizons were taken from Sharpley and William (1990) and specified as input. All other hydraulic properties such as saturated hydraulic conductivity, effective porosity, and bubbling pressure were estimated by the model based on BD, θ33kpa, and texture data. Table 1 shows some major soil properties for different soil horizons.

Input data on soil heat properties consisted of dry volumetric heat capacity, heat conductivity, and shape factors. Soil heat properties were estimated from soil texture data for each horizon as described by Jury et al. (1991).
Plant growth variables and parameters

RZWQM uses a generic plant growth model to simulate corn growth. Default values of plant growth parameters were used for generic growth model, as recommended in the RZWQM user manual. Planting and harvesting days, number of plantings, planting depth, planting density, harvesting efficiency, etc., are input to the model and were based on the actual field information collected at the research site.

Tillage management variables

RZWQM needs tillage related information to simulate tillage effects on soil properties (bulk density, macroporosity, and residue incorporation). This information mainly consists of date of tillage, tillage implement used, depth of tillage, tillage intensity, etc. However, tillage effects for this simulation study were incorporated by using field-measured values of BD, MP, residue cover, and incorporated residue amount for surface horizon as a function of tillage. There were two reasons for this. First, field-measured valued were considered to more accurately represent actual field conditions rather than depending on empirical functions used in RZWQM to estimate bulk density and macroporosity as a function of tillage. Secondly, tillage effects are not incorporated in simulations until the end of growing season since a fall tillage was the common practice at the field site.

Model Simulations and Evaluations

Boundary and Initial Conditions

To simulate fluctuating water table conditions, an impermeable layer was assumed at the bottom of the soil profile. Deep seepage through this impermeable layer was set equal to zero. The upper boundary was characterized by infiltration and evaporation rate at the surface layer.
Initial soil moisture profile, temperature profile, water table depth, and organic matter and chemical concentration profiles were input to the model. Initial soil moisture content was subjected to calibration. In the first simulation run, it was set equal to $\Theta_{\text{fc}}$ (field capacity), but adjusted in the subsequent simulations to get tile flow predictions nearly equal to observed tile flows (see model calibration section for detailed discussion). Initial water table depth was set equal to 120 cm (equal to depth of tile drains). Organic carbon contents were determined for Kenyon loam as a function of depth (Singh, 1994) and were used as initial values in the model. Organic carbon values ranged from 2% at surface to 0.1% at 150 cm depth. Initial temperature profile was adopted from Hillel (1982) for spring season. Table 2 shows initial moisture and temperature profiles, used for final simulation runs.

Model Calibration

Subsurface drain flow data from 1990 were used to calibrate the model. Tile flows were simulated for the growing season of 1990 under different tillage systems (CP, NT, MB, and RT) and compared with the observed tile flows recorded at the NERC water quality research site at Nashua. Tillage systems were characterized by BD, macroporosity (field-measured, Singh, 1994), surface residue cover (estimated from crop yield and percent cover data; Wischmeier and Smith, 1978), and incorporated residue amount for the surface horizon. Incorporated residue amount (Mg/ha) was calculated as the difference between residue amounts before and after tillage, based on residue amount estimation technique of Wischmeier and Smith (1978), assuming no residue losses during tillage operation. Incorporated residue amounts were further converted into slow (structural) and fast (metabolic) pools based on C:N ratio (40 for corn) as described in RZWQM user's manual (USDA-ARS, 1992b), Table 3 shows input values of these variables for each tillage system. Measured tile flow data were collected from the Nashua water-quality site. Tile flows were
being continuously monitored for 1990, 1991, and 1992 to investigate tillage effects on subsurface drain flows quantity and quality (Kanwar, 1991). Cumulative tile flows were recorded three times a week and a linear interpolation was used to calculate daily tile flows.

A surface crust (conductivity = 0.2 cm/h) was specified in the case of the MB treatment, and all macropores were assumed to be disrupted by tillage (macroporosity equal to zero). Freese et al. (1993) reported, based on their experiments, that surface sealing was more important than bulk density or porosity in reducing infiltration rates in MB plots. Macropores are not effective when a surface crust is present, which is the case in MB plots. Roth et al. (1988) also confirmed that porosity has little influence on infiltration when a surface seal is present. For the rest of the tillage treatments, field-measured macroporosity was used first but adjusted in subsequent trial runs to minimize the error between total observed and predicted tile flows for 1990. Final macroporosity values for 1990 are given in Table 3.

The hydrology component of the model was calibrated by using the tile flow data from the year 1990, a normal year when there were sustained tile flows. The criterion used for calibrating the model was to minimize the difference between the measured and predicted cumulative tile flow for the growing season of 1990 (JD 100 to 300; April 10 to October 27). A trial and error procedure was used to determine the best value of any parameter that could not be physically measured and some that were measured such as macroporosity. Each parameter was varied within a reasonable range while all other parameters were kept constant. The procedure was continued until an acceptable value for the parameter was obtained. A list of various calibrated parameters is given in Table 4.

It was found during the calibration procedure that initial moisture content of the soil profile had a significant effect on subsurface drain flows. When initial moisture content was set equal to $\Theta_{25 \text{ kpa}}$ for 1990, it resulted in much higher tile flow than observed flows in the earlier part
of the simulations. Therefore, initial moisture content of the soil profile for 1990 was reduced to achieve better tile flow predictions. Table 1 shows initial moisture contents for the profile.

Figures 5, 6, 7, and 8 show daily measured and predicted tile flows under CP, MB, NT, and RT tillage systems, respectively, for the growing season of 1990. There is generally good agreement between measured and predicted values, although discrepancies exist for some days. Observed versus Predicted daily subsurface drain flows were compared to calculate coefficient of determination (R^2) for simulation run under each tillage treatment. Figure 1 in Appendix D shows an example of such comparison. The R^2 values for these simulation runs (Table 1, Appendix D) ranged from 0.49 (for MB) to 0.62 (for NT).

The model predicted peak tile flows on the same days they were actually observed and also predicted zero flow within a few days of when tiles actually stopped flowing. Given the fact that a certain degree of spatial variability exists under actual field conditions, the model predictions were encouraging. Table 5 shows the total predicted and measured flows for 1990.

Even though the model slightly overpredicted total flows for all the tillage systems it did show maximum tile flow for no-till and minimum for MB system, consistent with the observed trends. Although predicted peak flows were usually underpredicted the model did show relatively higher peak flows under NT treatment in comparison with the rest of the treatments. A similar trend was observed in the measured tile flow data suggesting that water moved preferentially under the NT system causing higher peaks in tile flows.

In the case of the NT treatment, simulated tile flow peaks were underpredicted except on JD 209. It was noted that runoff was generated on JD 208 and 209, part of which was contributed by the model to tile flow due to macropore flow. On other days (where predicted peaks were much lower than observed peaks) runoff was not generated at all by the model. Therefore, there was no macropore flow, contributing to simulated tile flow for these days. That is why even when
the macropores are present under NT system, no macropore flow is generated by the model because rainfall intensity was not enough to generate any rainfall excess. Rainfall intensity, therefore, can be critical in predicting accurate tile flows. As mentioned earlier, daily rainfall data recorded for the Nashua weather station did not match well with the daily rainfall values recorded by the field rain gauge. It seems that macropore flow was actually an important contribution to tile flow for all the storm events where peak flow occurred in NT plots. Tile flow peaks under other tillage treatments were not as high as under NT treatment for the same rainfall events, indicating less or no soil macroporosity under other tillage systems than that under NT system. Other factors which could also contribute to difference in tile flow amounts for different tillage systems, but which were not taken into account, were deep seepage and lateral groundwater flow component.

Consideration should also be given to the dynamic nature of the soil and spatial variability in soil properties. Although the model is capable of showing a good response to rainfall pattern, it does not take into account the spatial variability in soil properties or weather induced changes in some of the soil properties such as macroporosity during the simulation period. These temporal changes sometimes could be significant. For example, macroporosity of soil is not only a function of tillage, but also changes with crop type, weather patterns, worm activity (which is again related to weather pattern ultimately), soil moisture status, cultivation, etc. Incapability of the model to mimic spatial variability and weather-induced changes in the soil properties also contributes to the discrepancies in observed and predicted tile flows.

### Model Testing and Evaluations

To test the ability of the model to predict system response, the model was tested with tile flow data for 1991 and 1992. Initial moisture content in the soil profile was adjusted for these simulations to make sure that simulated tile flow begins the same day tile flow actually begins in
the field. The rest of the input data were the same as that for 1990 simulations. Initial moisture content, macroporosity, and residue cover amount are given in Table 2 and 3. Simulations were conducted from JD 70 to 200 for 1991 and from JD 70 to JD 250 for 1992. These dates represent the beginning and ending of the observed tile flows. The daily observed and predicted tile flows for 1991 and 1992 are shown in Figures 9 to 12 and 13 to 16, respectively.

Predicted tile flows for 1991 compare reasonably well with observed tile flows, except for the RT treatment where predicted peaks were significantly lower than observed peaks. Total predicted tile flows for the season were also in close agreement with the observed ones (Table 5) except under the CP treatment where the model overpredicted total tile flow by about 14 percent. Coefficient of determination ($R^2$) was calculated for the best fit lines for observed versus predicted daily tile flow data. The $R^2$ values are summarized in Table 1 of Appendix D. The $R^2$ values for 1991 tile flow simulations ranged from 0.69 (for CP treatment) to 0.54 (for RT treatment). Again the reasons explained in the earlier section may be responsible for these discrepancies. Best fit lines for observed versus predicted daily tile flow plots were statistically compared with 1:1 line (see appendix D for procedure). Best fit lines for all three years under all four treatments were significantly different from 1:1 line (Table 1, Appendix D). Although total rainfall for 1991 (during the simulation period) was less in comparison with the rainfall in 1990, total tile flows were greater suggesting a higher initial moisture content in the profile and probably a higher degree of preferential flow, suggesting more macroporosity in year 1991.

Simulated tile flows for 1992 (Figures 13 to 16) again followed the observed trend reasonably well. Although simulated tile flows for 1992 were overpredicted (about 20 percent on average; Table 5) again maximum tile flows occurred under NT and minimum under MB treatment similar to observed trends for this year. The $R^2$ values (Table 1, Appendix D) for observed versus simulated daily subsurface drain flow data ranged from 0.62 (for NT) to 0.69 (for
RT). However, tillage effects were not prominent in observed as well as simulated tile flows for this year in comparison to those in 1990 and 1991. This year was a relatively dry year, with mostly low-intensity rainfall events. Therefore, in 1992, probably preferential flow was not generated as much as in years 1990 and 1991, thus minimizing the tillage effects on subsurface drain flows.

Sensitivity Analysis

The objective of sensitivity analysis was to introduce small perturbations in various hydrologic parameters or variables of the model and study their relative effects on the output variables of interest. Output variable selected for this sensitivity analysis was total drain flow volume for the year 1991. Effect of following hydrologic variables/parameters on total drain flow was considered: initial moisture content of the soil profile, macroporosity, BD, Θ_{33kPa} lateral saturated hydraulic conductivity (Ksat), drain depth, and drain spacing. Since tillage effects are expected to be confined within the surface horizon, sensitivity analysis for following variables was conducted by changing their values for surface horizon (0-25 cm) only: macroporosity, BD, and Θ_{33kPa}. Lateral Ksat, drain depth, and drain spacing were selected as these are important parameters in Equation 5 that affect drain flow volume. The numerical values of the parameters under study were increased by 10 and 20 percent of their calibrated values. The effects of these changes are presented in Figures 17 and 18.

From Figure 17, it is clear that total drain flow volume predicted by the model is most sensitive to Θ_{33kPa} and BD of surface horizon. For the 10 percent increase in Θ_{33kPa}, about 27 percent decrease in drain flow and for a 20 percent increase in Θ_{33kPa}, about 60 percent decrease in drain flow was obtained. When BD for surface horizon was increased by 10 and 20 percent reduction of about 23 and 61 percent in total drain flow were obtained, respectively. Since model
estimated saturated hydraulic conductivity from $\Theta_{33kpa}$ and BD values, these parameters are critical in infiltration and moisture movement calculations. The next most important variable affecting drain flow was initial moisture content of the soil profile. When initial moisture content was increased by 10 percent of its designated value, about 22 percent increase in drain flow was obtained. Similarly, for a 20 percent increase in initial moisture content, about 44 percent increase in drain flow was obtained. Thus, it is important to have accurate measurements of BD, $\Theta_{33kpa}$, and initial moisture content of the soil profile to obtain good predictions of total drainage flow volume.

Changes in macroporosity values did not produce any substantial effects on total drain flows. Twenty percent increase in macroporosity of the surface horizon resulted in only 2 percent increase in drain flow. This was expected as 20 percent increase in a macroporosity value of 0.003 m$^3$/m$^3$ represented a macropore volume of 0.0006 m$^3$/m$^3$ which was not enough to cause any substantial effects on total drain flow.

Lateral Ksat, drain depth, and drain spacing also affected total drain flow (Figure 18) but not as much as $\Theta_{33kpa}$, BD, and initial moisture content. A 20 percent increase in lateral Ksat and drain depth resulted in about 16 percent and 4 percent increase, respectively, in total tile flow. On the other hand a 20 percent increase in drain spacing resulted in 3 percent decrease in tile flow.

**Summary and Conclusions**

A fluctuating water table and tile flow component was developed and added to RZWQM to simulate subsurface drain flows under different tillage practices. Tillage systems were characterized by experimentally measured soil properties for the surface horizon. For deeper soil horizons, soil properties were taken from published data for the Nashua Water Quality Site. Weather and rainfall data were collected from on-site weather station records. The model was first calibrated to minimize the difference between cumulative predicted and observed tile flow data for
1990. Model performance was further evaluated by predicting tile flows for 1991 and 1992 using the calibrated parameters. Although the model overpredicted total tile flows (13 percent on average), predicted tillage effects on tile flows were consistent with the observed effects (i.e., maximum tile flow in NT and minimum under MB). Although magnitudes of the peak flows were usually underpredicted, the model showed a good response to rainfall in terms of time of peak flows and total flows.

A sensitivity analysis involving various hydrologic parameters showed that bulk density, $\Theta_{33\text{pa}}$, and initial moisture content have more effect on total subsurface drain flows than lateral $K_{\text{sat}}$, drain depth, and drain spacing.

To further improve the predictions of the tile flows as a function of tillage systems, soil spatial variability should be considered in the model. An accurate breakpoint rainfall data-set is also necessary to get an accurate measure of rainfall intensity and to investigate the effect of macropore flow on subsurface drain flows. The results of this study show that modified RZWQM has a good potential to be used as a tool to predict subsurface drain flows as a function of various tillage practices.

References


Singh, P. 1994. Characterizing tillage and simulating the movement of water and NO₃-N in the vadose zone by using Root Zone Water Quality Model. Paper 1 In Modification of Root Zone Water Quality Model (RZWQM) to simulate the tillage effects on subsurface drain flows and NO₃-N movement. Ph.D. Dissertation. Iowa State University, Ames, IA.


Table 1. Soil properties for different soil horizons used as input for subsurface drainage simulations

<table>
<thead>
<tr>
<th>Horizon Number</th>
<th>Depth (cm)</th>
<th>$\Theta_{33\text{cp}}$ (cm$^3$/cm$^2$)</th>
<th>Bulk Density$^1$ (g/cm$^3$)</th>
<th>Porosity (cm$^3$/cm$^3$)</th>
<th>Organic Carbon$^2$ (%)</th>
<th>Particle size dist.(%)$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0-20</td>
<td>0.30</td>
<td>*3</td>
<td>*3</td>
<td>2.0</td>
<td>38 42 20</td>
</tr>
<tr>
<td>2</td>
<td>20-41</td>
<td>0.27</td>
<td>1.52</td>
<td>0.43</td>
<td>0.8</td>
<td>41 34 25</td>
</tr>
<tr>
<td>3</td>
<td>41-50</td>
<td>0.26</td>
<td>1.55</td>
<td>0.42</td>
<td>0.6</td>
<td>42 32 26</td>
</tr>
<tr>
<td>4</td>
<td>50-69</td>
<td>0.28</td>
<td>1.60</td>
<td>0.40</td>
<td>0.4</td>
<td>43 30 27</td>
</tr>
<tr>
<td>5</td>
<td>69-89</td>
<td>0.28</td>
<td>1.65</td>
<td>0.38</td>
<td>0.3</td>
<td>44 28 28</td>
</tr>
<tr>
<td>6</td>
<td>89-123</td>
<td>0.26</td>
<td>1.70</td>
<td>0.36</td>
<td>0.2</td>
<td>44 31 25</td>
</tr>
<tr>
<td>7</td>
<td>123-167</td>
<td>0.28</td>
<td>1.75</td>
<td>0.34</td>
<td>0.1</td>
<td>44 31 25</td>
</tr>
</tbody>
</table>

$^1$Taken from Sharpley and William (1990)

$^2$Experimentally measured (Singh, 1994)

$^3$Experimentally measured as a function of tillage (see Table 3)
Table 2. Initial moisture and temperature profiles for simulations for all three years

<table>
<thead>
<tr>
<th>Horizon Number</th>
<th>Moisture content(^1) (cm(^2/cm^3))</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.20 0.27 0.27</td>
<td>23</td>
</tr>
<tr>
<td>2</td>
<td>0.22 0.27 0.32</td>
<td>21</td>
</tr>
<tr>
<td>3</td>
<td>0.23 0.26 0.30</td>
<td>19</td>
</tr>
<tr>
<td>4</td>
<td>0.23 0.26 0.28</td>
<td>18</td>
</tr>
<tr>
<td>5</td>
<td>0.23 0.26 0.28</td>
<td>18</td>
</tr>
<tr>
<td>6</td>
<td>0.24 0.26 0.29</td>
<td>19</td>
</tr>
<tr>
<td>7</td>
<td>0.31 0.31 0.31</td>
<td>20</td>
</tr>
</tbody>
</table>

\(^1\)Calibrated

Table 3. A list of input soil properties for the surface horizon (0-20 cm) and their values for different tillage systems

<table>
<thead>
<tr>
<th>Soil Property</th>
<th>CP</th>
<th>MB</th>
<th>NT</th>
<th>RT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk Density (g/cm(^3))</td>
<td>1.41</td>
<td>1.38</td>
<td>1.50</td>
<td>1.38</td>
</tr>
<tr>
<td>Porosity (cm(^3/cm^3))</td>
<td>0.47</td>
<td>0.48</td>
<td>0.43</td>
<td>0.48</td>
</tr>
<tr>
<td>Macroporosity (cm(^3/cm^3))</td>
<td>0.0</td>
<td>0.0</td>
<td>0.004</td>
<td>0.0</td>
</tr>
<tr>
<td>Residue pools (µg/g)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slow pool</td>
<td>450</td>
<td>700</td>
<td>140</td>
<td>310</td>
</tr>
<tr>
<td>Fast pool</td>
<td>700</td>
<td>1000</td>
<td>215</td>
<td>480</td>
</tr>
<tr>
<td>Surface Crust</td>
<td>no</td>
<td>present</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Residue cover (Mg/ha)</td>
<td>3.8</td>
<td>0.6</td>
<td>6.2</td>
<td>5.0</td>
</tr>
</tbody>
</table>

CP=Chisel Plow; MB=Moldboard Plow; NT=No-tillage; RT=Ridge Tillage
Table 4. Summary of input parameters for tile-drain subroutine

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Calibrated or known value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drain spacing</td>
<td>2456 cm</td>
</tr>
<tr>
<td>Drain depth</td>
<td>120 cm</td>
</tr>
<tr>
<td>Depth from drain to imp. layer*</td>
<td>390 cm</td>
</tr>
<tr>
<td>Equivalent depth from imp. layer*</td>
<td>160 cm</td>
</tr>
<tr>
<td>Lateral Hydraulic conductivity*</td>
<td></td>
</tr>
<tr>
<td>Horizon 1</td>
<td>1.55 cm/hr</td>
</tr>
<tr>
<td>Horizon 2</td>
<td>1.05 cm/hr</td>
</tr>
<tr>
<td>Horizon 3</td>
<td>1.18 cm/hr</td>
</tr>
<tr>
<td>Horizon 4</td>
<td>1.00 cm/hr</td>
</tr>
<tr>
<td>Horizon 5</td>
<td>1.00 cm/hr</td>
</tr>
<tr>
<td>Horizon 6</td>
<td>0.95 cm/hr</td>
</tr>
<tr>
<td>Horizon 7</td>
<td>0.90 cm/hr</td>
</tr>
</tbody>
</table>

*Calibrated values

1Adopted from Mirjat (1992)
Table 5. Total seasonal predicted and observed tile flows for 1990, 1991 and 1992

<table>
<thead>
<tr>
<th>Year</th>
<th>Total Rain (cm)</th>
<th>Subsurface drain flows, cm</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>CP</td>
<td>MB</td>
<td>NT</td>
</tr>
<tr>
<td>1990 (JD 100-300)</td>
<td>93.9</td>
<td></td>
<td>18.3</td>
<td>9.0</td>
<td>27.5</td>
</tr>
<tr>
<td>Observed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Predicted</td>
<td></td>
<td></td>
<td>19.3</td>
<td>11.4</td>
<td>28.3</td>
</tr>
<tr>
<td>Percent difference</td>
<td>5.5</td>
<td></td>
<td>26.6</td>
<td>2.9</td>
<td></td>
</tr>
<tr>
<td>1991 (JD 70-200)</td>
<td>59.2</td>
<td></td>
<td>26.4</td>
<td>17.4</td>
<td>31.2</td>
</tr>
<tr>
<td>Observed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Predicted</td>
<td></td>
<td></td>
<td>30.0</td>
<td>18.9</td>
<td>31.3</td>
</tr>
<tr>
<td>Percent difference</td>
<td>13.6</td>
<td></td>
<td>8.6</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>1992 (JD 70-250)</td>
<td>73.2</td>
<td></td>
<td>8.0</td>
<td>6.4</td>
<td>9.2</td>
</tr>
<tr>
<td>Observed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Predicted</td>
<td></td>
<td></td>
<td>8.5</td>
<td>7.9</td>
<td>10.7</td>
</tr>
<tr>
<td>Percent difference</td>
<td>6.2</td>
<td></td>
<td>23.4</td>
<td>16.3</td>
<td></td>
</tr>
</tbody>
</table>

Average of three replications
Table 6. Moisture balance sheet for hydrology component of the model for all the simulation runs for 1990

<table>
<thead>
<tr>
<th>Hydrologic Parameters</th>
<th>Run 1</th>
<th>Run 2</th>
<th>Run 3</th>
<th>Run 4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(CP)</td>
<td>(MB)</td>
<td>(NT)</td>
<td>(RT)</td>
</tr>
<tr>
<td>Total rain (cm)</td>
<td>93.9</td>
<td>93.9</td>
<td>93.9</td>
<td>93.9</td>
</tr>
<tr>
<td>Tile flow (cm)</td>
<td>19.3</td>
<td>11.4</td>
<td>28.3</td>
<td>21.9</td>
</tr>
<tr>
<td>Runoff (cm)</td>
<td>10.7</td>
<td>22.0</td>
<td>3.3</td>
<td>8.4</td>
</tr>
<tr>
<td>Evapotranspiration (cm)</td>
<td>60.4</td>
<td>56.3</td>
<td>59.0</td>
<td>59.8</td>
</tr>
<tr>
<td>Initial soil moisture in the</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>profile(cm)</td>
<td>41.3</td>
<td>41.3</td>
<td>42.3</td>
<td>41.3</td>
</tr>
<tr>
<td>Final soil moisture in the</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>profile (cm)</td>
<td>44.6</td>
<td>45.3</td>
<td>44.7</td>
<td>44.6</td>
</tr>
<tr>
<td>Mass balance error (%)</td>
<td>0.3</td>
<td>0.1</td>
<td>2.0</td>
<td>0.3</td>
</tr>
</tbody>
</table>
Figure 1. A schematic showing how MOIST subroutine interacts with RZWQM
Figure 2. Schematic showing various variables of drain flow subroutine (TDRAIN)

\[ Y = \text{Depth of water table (DTWT), cm} \]

\[ Em = \text{Elevation of water table above drains, cm} \]

\[ Hd = \text{Equivalent depth of impermeable layer from drains (HDRAIN), cm} \]

\[ \text{DEEP} = \text{Depth of saturated zone, cm} \]

\[ S = \text{Drain spacing (SDRAIN), cm} \]

\[ \text{ADEPTH} = \text{Depth of impermeable layer from the surface, cm} \]

\[ Dd = \text{Depth of drains from the surface (DDRAIN), cm} \]
Figure 3. Flow chart for moisture redistributing subroutine MOIST
SUBROUTINE DRAIN

Water table depth input from sub. MOIST

Calculate depth of saturation within the layer

Calculate depth of saturated zone DEEP and effective lateral conductivity

Calculate Hd, equivalent depth

If surface ponding occurs or water table near the surface

Yes

calculate drainage during ponding

No

Calculate drainage flux by Hooghoudt equation

Return

Return

Figure 4. Flow chart for tile drainage subroutine DRAIN
Figure 5. Simulated and observed daily tile flows for Chisel Plow, 1990.
Figure 6. Simulated and observed daily tile flows for Moldboard Plow, 1990.
Figure 7. Simulated and observed daily tile flows for No-Till, 1990.
Figure 8. Simulated and observed daily tile flows for Ridge-Till, 1990.
Figure 9. Simulated and observed daily tile flows for Chisel Plow, 1991
Figure 10. Simulated and observed daily tile flows for Moldboard Plow, 1991
Figure 11. Simulated and observed daily tile flows for No-tillage, 1991
Figure 12. Simulated and observed daily tile flows for Ridge-Tillage, 1991
Figure 13. Simulated and observed daily tile flows for Chisel Plow, 1992
Figure 14. Simulated and observed daily tile flows for Moldboard Plow, 1992
Figure 15. Simulated and observed daily tile flows for No-tillage, 1992
Figure 16. Simulated and observed daily tile flows for Ridge Tillage, 1992
Figure 17. Parameter sensitivity to drain flow volume for the year 1991
Figure 18. Parameter sensitivity to drain flow volume for the year 1991
Abstract

Modified RZWQM was further extended to simulate nitrate-nitrogen (NO₃-N) concentrations and NO₃-N losses with subsurface drain flows. Daily NO₃-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) using the modified RZWQM. Simulations were conducted for the growing seasons of three years (1990 to 1992). Simulated NO₃-N concentrations and losses with subsurface drain flows were compared with the measured data obtained from a water quality research site at Nashua, IA. Predicted NO₃-N concentrations followed more or less the same pattern as that of observed concentrations but coefficient of determination (R²) values (0.18 to 0.37) did not show a strong correlation between observed and simulated NO₃-N concentrations in subsurface drain flows. The model correctly predicted maximum concentrations under MB treatment and minimum under NT for all three years. However, simulated NO₃-N losses were overpredicted (on average 14%) when compared with observed losses. Various NO₃-N transformation processes need to be calibrated as a function of tillage system to improve model performance.
Introduction

It is becoming increasingly evident that chemically intensive agriculture not only creates
environmental pollution by contaminating subsurface soil and water but also results in economic
losses due to subsurface movement of agricultural chemicals. Groundwater contamination by
nitrate-nitrogen (NO₃-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
potentials 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
in reducing 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 enhance NO₃-N movement
(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).

A number of 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 tile
drains. Kanwar et al. (1990) established a field hydrology laboratory to study the effects of four
tillage systems (MB, CP, NT, and RT) on the transport of surface applied chemicals (NO₃-N and
pesticides) through the soil profile to shallow groundwater. Results from this study showed that
NO₃-N concentrations in subsurface drainage water from conventional tillage plots were greater
than in other tillage systems. Their data also indicated that herbicides were moving to groundwater preferentially through macropores. Leeds-Harrison et al. (1992) observed that drain flow and solute load are affected by tillage treatment. Madramootoo and Mousavizadeh (1993) also investigated the effect of three tillage practices (no-tillage, reduced tillage, and conventional tillage) on NO$_3$-N movement to tile drains. They observed greater drain flows in conventionally tilled plots than no-tillage plots. Data on NO$_3$-N concentrations in the tile drains were not reported in the paper.

Although a number of experimental investigations have been conducted to study the transport of agricultural chemicals to tile drains under artificially drained soils, not much work has been done on the simulation of chemical transport to the tile 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 agricultural chemicals. 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 for predicting N-transport, uptake and transformation in artificially drained soils. But these models are not capable of incorporating tillage effects. A mechanistic soil-crop simulation model that emphasizes soil N dynamics and 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.

Therefore, the purpose of this study was to further extend the capability of the modified RZWQM model (Singh, 1994) to predict NO$_3$-N concentrations in tile drains under different tillage
systems. Adding a tile drainage component (Singh, 1994) made this model capable of simulating subsurface drain flows and evaluating the impact of different tillage systems on subsurface drain flows. Following were the specific objectives of this study:

1. Extend the Modified RZWQM model to simulate NO$_3$-N concentration in tile drainage water.

2. 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 different tillage practices and comparing them with observed data from the Nashua Water Quality Site.

**Model Development and Theory**

Following sections describe NO$_3$-N transport processes in RZWQM and were adopted from RZWQM technical documentation (USDA-ARS, 1992).

**NO$_3$-N Transport through Soil Profile in RZWQM**

**Transport of NO$_3$-N within the soil matrix during infiltration**

This section briefly discusses the transport of a non-reactive solute such as NO$_3$-N through the soil profile. For the purpose of chemical transport through soil profile a sequential partial displacement and mixing approach in 1-cm layer increments is used based on the established concept of the miscible displacement. Also, there is a provision for the presence of mobile and immobile flow regions, which introduces another form of preferential chemical transport in the soil matrix. The preferential flow in macropore channels outside the soil matrix is treated separately. For the preferential flow through macropores, the soil matrix is divided into meso- and micropores based on either the input values of these or on the partitioning of the soil water retention curve at a prescribed suction, such as 200 kPa. Initially and during first wetting of a 1-cm depth
increment, the water and chemical in meso- and micro-pores are in equilibrium. After the first time step the miscible displacement of solution in the saturated soil layers, during successive infiltration steps, occurs only in the meso-pores (mobile regions). This approach is similar to the layer model of Adiscott (1977).

An alternative option is to allow diffusion between meso- and micro-pore solutions. The equation for this process is:

\[
\frac{\Delta C_{sol}}{\Delta t} = D_s (C_{micr} - C_{sol})
\]  

where \(C_{sol}\) is the concentration of chemical in the solution (mg/L) in the mesopores, \(C_{micr}\) is the concentration in solution of the micropores, and \(D_s\) is the apparent diffusion coefficient. For each time step, the exchange of chemical is calculated and the concentrations appropriately adjusted at the end of time step.

For each infiltration step, the soil solution is displaced sequentially across 1-cm soil increments in the manner of piston displacement. However, 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). Thus the displacement of 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.

Redistribution of chemicals after infiltration

During the redistribution process, chemicals in the solution move with water from one depth increment to another, including upward movement due to evaporation. At the end of each time step, chemical concentrations in solution and solid phases are adjusted with respect to both
instantaneous equilibrium and kinetic pools. A brief description of modified water redistribution component (incorporating fluctuating water table and subsurface drainage) is presented by Singh (1994).

**Nutrient Processes in RZWQM**

The nutrient processes define carbon (C) and N transformations within the soil profile. 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.

An Organic Matter/Nitrogen submodel (OMNI) which is a major component of the RZWQM, is used for C and N cycling in the soil system. This section presents a brief overview of the OMNI submodel. A detailed discussion on OMNI can be found in RZWQM technical documentation (USDA-ARS, 1992). This submodel combines many features such as crop residue and soil organic matter pools found in existing NO$_3$-N transport models and adds basic principles of chemical rate process theory, soil microbial growth, and environmental interactions. OMNI uses transient rate equations that include Arrhenius temperature response functions and reactive constituent concentrations, and simulate microbial responses to soil oxygen levels, pH, water content, and salinity. The submodel includes direct interactive linkages to related submodels in RZWQM such as soil chemistry, Plant Growth, and Solute Transport models. Linkages such as NH$_4$-N, NO$_3$-N, hydrogen ion concentrations, CO$_2$ partial pressures, and ionic strength are among...
the current primary transfer points.

OMNI simulates all the major N transformations including mineralization-immobilization of crop residues, manure, and other organic wastes; mineralization of soil humus fractions; interpool transfer of C and N; denitrification (production of $N_2$ and $N_2O$); gaseous loss of ammonia, $NH_3$; nitrification of $NH_4$-N to produce $NO_3$-N; production and consumption of methane gas ($CH_4$) and carbon dioxide ($CO_2$), and microbial biomass (MBM) growth and death. In OMNI growth and death of microorganisms drive most of the processes and are a function of environmental variables such as soil temperature and water content, soil pH, soil oxygen levels, and solution concentrations (or activities) of nutrients.

**C and N pools**

In the model, organic matter (OM) is distributed over five computational pools and is decomposed by three microbial biomass populations. The OM pools consist of slow and fast pools for crop residues and other organic amendments; and fast, medium, and slow decaying soil OM, respectively. The fast and medium soil OM pools approximately correspond to the potentially mineralizable N pool ($N_p$) frequently mentioned in the literature. The MBM populations include two heterotrophic groups (soil fungi and facultative bacteria, population 1 and 3), and one autotrophic group (nitrifiers, population 2). Population 1 and 2 are strict aerobes, while population 3 is primarily anaerobic. For computational and conceptual purposes C sink/source compartments for $CO_2$ and $CH_4$ are also included. These gases behave as by-products as well as sources during various parts of the C and N cycle. N concentrations are simulated in organic form as organic residues, soil organic matter, and microbial biomass according to specified OM pool and microbial C:N ratios; in mineral form as $NO_3$-N and $NH_4$-N; as urea fertilizer; and as general N sinks ($N_2$ and $N_2O$).
Soil humus

Soil humus is depleted by microbial decay and built up by the addition of dead biomass and inter-pool transfers. Biomass populations are depleted through death and built up by biomass assimilation/growth during decay of organic matter and nitrification. Growth of heterotrophs occurs primarily by aerobic decay of OM. However, some facultative bacteria grow during denitrifying activity or methane production under anaerobic conditions. The autotrophs grow exclusively as a result of nitrifying activity under aerobic conditions. Urea is converted to NH$_4^+$ by the enzymatic process of hydrolysis. The C source/sink storage increases as a result of MBM respiration, receiving CO$_2$ from aerobic respiration and CH$_4$ from anaerobic respiration. CO$_2$ behaves as a C source during nitrification and CH$_4$ is a C source during OM decay.

Mineralization and immobilization

Mineral N in solution exists as NO$_3^-$N and NH$_4^-$N. NH$_4^-$N is the primary form in the sense that NO$_3^-$N is formed only by microbial oxidation of NH$_4^-$N through the processes of nitrification. Solution NH$_4^-$N may be adsorbed onto the surfaces of soil clays by the process of cation exchange making it temporarily unavailable for leaching. Conversion of organic N to mineral N first produces NH$_4^-$N, then NO$_3^-$N. NO$_3^-$N is removed by the processes of denitrification and immobilization. NH$_4^-$N is formed by the hydrolysis of urea, and by transformations of organic N along mineralizing pathways. Conversely, NH$_4^-$N is removed via NH$_3$ volatilization, nitrification, immobilization, and plant uptake.

There are many processes operating simultaneously on the various N and C species in OMNI. However, only a defining subset of those processes is modeled independently by rate equations. For mass balance consistency, the remaining processes are modeled as functions of specified independent rates.
Simulation of NO$_3$-N Concentrations in the Tile Effluent

As pointed out by Duffy et al. (1975), NO$_3$-N concentrations in the tile 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 of the tile effluent. NO$_3$-N in the tile effluent is calculated as NO$_3$-N flow per unit area to the tile. When the tile flow is zero, the amount of water (and also the chemical) that may actually move is set equal to zero. According to Dutt et al. (1970), the NO$_3$-N concentrations of the tile 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 tile water would be proportional to the NO$_3$-N concentrations in soil layers below the water table. For this purpose, tile drainage per unit thickness (DRN) was calculated for the saturated zone after calculating total tile drainage by the Hooghoudt equation. Moisture contribution from each saturated layer was calculated by multiplying DRN with the thickness of the layer. Since thickness of the layers increased with depth, more moisture was contributed from the layers below the tile lines which is in accordance with the flow net studies of Kirkham (1966).

Total amount of chemical loss from a given soil layer under saturated zone to the tile flow can thus be calculated as follows:

\[
\text{CLOSS}_i = \text{CONC}_i \times \text{DEL}_i
\]

where

- CLOSS$_i$ = Total amount of NO$_3$-N lost to tile flow from layer $i$, $\mu$g/cm$^2$
- CONC$_i$ = Concentration of NO$_3$-N in layer $i$, $\mu$g/cm$^3$
- DEL$_i$ = Total amount of water contributed from layer $i$ to tile flow, cm
Total NO$_3$-N loss in the tile flow for a given time step is then calculated in the following way:

$$TLOSS_j = \sum_{i=1}^{N} CLOSS_i \cdot \Delta T$$ \quad [4]$$

where

- $TLOSS_j =$ Total NO$_3$-N loss in tile flow for time step $j$
- $N =$ Number of soil layers in saturated zone

Average daily NO$_3$-N concentration (ADC) in tile flow is calculated by summing the total losses over the day and dividing by daily tile flow amount:

$$ADC = \frac{\sum_{j=1}^{M} TLOSS_j}{DFLUX}$$ \quad [5]$$

where

- $ADC =$ Average daily NO$_3$-N concentration, $\mu g/cm^3$
- $DFLUX =$ Daily tile flow, cm
- $M =$ Number of time steps in a day

**Model Simulations and Evaluations**

**Initial NO$_3$-N Concentrations, Moisture Content, and Water Table Depth**

The procedure for determining initial soil moisture contents and water table depths has been discussed in the tile flow simulations part of this study (Singh, 1994). NO$_3$-N concentrations in tile 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 initial NO$_3$-N concentrations in the profile were set equal to the NO$_3$-N concentrations measured in late fall of 1990 (October 25, 1990). In order to minimize the difference between the cumulative observed and predicted NO$_3$-N losses with subsurface drain water, initial NO$_3$-N concentrations were adjusted. For 1992, pre-fertilization NO$_3$-N concentration values for the soil profile were available and were used as initial profile concentrations. Initial NO$_3$-N concentrations in the soil profile for 1990, 1991, and 1992 are shown in Tables 4, 5, and 6.

Field Operations

Dates of planting, harvesting, fertilizer application, tillage etc, were input to the model. Tables 1, 2, and 3 show the dates of field operations and amount of fertilizer applied for years 1990, 1991, and 1992, respectively.

Measured NO$_3$-N Concentrations in the Tile Effluent

Data on NO$_3$-N concentrations in the tile effluent were taken from 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, IA. The study site is located on a predominantly Kenyon loam soil with 3 to 4% organic matter. The soils have seasonally high water table and benefit from subsurface drainage. Tile lines 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 line passing through the middle of the plot and there is a tile line at each of the two borders. The middle tile lines of all the plots were intercepted and connected to individual sumps in December 1988 for measuring subsurface drainage (tile flow) and collecting water samples for chemical...
analyses (Kanwar, 1991). For NO$_3$-N sampling, the frequency of sampling averaged three times a week when tile lines were flowing.

**Simulated NO$_3$-N Concentrations in the Tile Flows**

Simulations were conducted by using modified RZWQM to predict NO$_3$-N concentrations in the subsurface drain effluent under four different tillage systems namely CP, MB, NT, and RT for 1990, 1991, and 1992. Figures 1 to 4 show a comparison between the predicted and observed daily NO$_3$-N concentrations in the tile effluent under CP, MB, NT, and RT tillage systems, respectively, for the year 1990. Similar comparisons for 1991 and 1992 have been shown in figures 5 to 8 and figures 9 to 12, respectively. Observed daily NO$_3$-N concentrations in the subsurface drain water represent the average of NO$_3$-N concentrations from three replicate field plots.

NO$_3$-N concentration plots for all three years usually show a good agreement between the range of predicted and observed daily NO$_3$-N concentrations with few exceptions. As NO$_3$-N concentration in the tile effluent is proportional to the NO$_3$-N concentration of the saturated profile, a sudden drop in the NO$_3$-N concentration in the tile flow represented a heavy rainfall decreasing the NO$_3$-N concentration in the drainage water with increased tile flow and vice-versa. Coefficient of determination ($R^2$) values were calculated for the best fit line for simulated versus observed daily NO$_3$-N concentrations in subsurface drain water plots. Figure 2 in Appendix D gives an example of simulated versus observed NO$_3$-N concentration plot drawn to calculate $R^2$. The $R^2$ values are summarized in Table 2 of Appendix D for all three years' simulations. 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. Best fit lines for observed versus simulated NO$_3$-N concentration plots were statistically compared with 1:1 line (see Appendix D for procedure). Except for NT
treatment in 1992, and MB treatment in 1991, best fit lines were significantly different from 1:1 line (Table 2, Appendix D)

Discrepancies between the predicted and observed NO$_3$-N concentrations in the tile water could be due to several reasons. These reasons are: inaccuracies introduced in the hydrologic simulation model causing inaccuracies in the NO$_3$-N concentration of the soil profile and ultimately in the tile flow, inaccuracies introduced in the estimation of initial moisture content and concentrations, unaccounted lateral groundwater flow and NO$_3$-N losses, and unaccounted deep seepage and NO$_3$-N losses, etc. Also, the rate of various NO$_3$-N transformation processes may need to be calibrated in the light of different tillage practices. As mentioned earlier, NO$_3$-N transformation processes are simulated by OMNI component of the main model and rates of all the major transformations are inputs to modified hydrologic component of the model.

Tables 7 and 8 give the total NO$_3$-N losses and average concentrations in the tile effluent for all the three years. Model simulations showed lower NO$_3$-N concentrations in the tile water under NT and RT treatments and higher concentrations under MB and CP treatments for all three years. This was in close agreement with observed NO$_3$-N concentration data. Model-predicted annual NO$_3$-N losses agreed well with the observed NO$_3$-N losses under different tillage systems (overall average percent error being 14 %). For 1990, predicted tillage effects on NO$_3$-N losses in the tile effluent were consistent with the observed tillage effects, i.e., maximum NO$_3$-N loss under NT and minimum 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. Simulated losses did not show any significant change in NO$_3$-N losses under different tillage systems. This was expected because 1992 was a relatively dry year with mostly low-intensity rainfall events. Therefore, preferential flow probably was not generated as much as in 1990 and 1991, thus, minimizing the tillage effects.
on tile flows as well as on \( \text{NO}_3\text{-N} \) losses.

Both observed and simulated tile flow data showed comparable trends in tile flows (maximum tile flow under NT and minimum under MB) and average \( \text{NO}_3\text{-N} \) concentrations (higher concentrations in MB and CP and lower in NT and RT) from year to year. But the trends for the \( \text{NO}_3\text{-N} \) losses were not consistent from year to year indicating again the importance of preferential flow, \( \text{NO}_3\text{-N} \) losses by other pathways (e.g., deep seepage), and spatial variability effects.

\( \text{NO}_3\text{-N} \) Concentrations in the Soil Profile

\( \text{NO}_3\text{-N} \) concentrations were measured in the soil profile on Julian Days (JD) 150, 267, and 297 in 1990 and on JD 119, 176, and 232 in 1992 as a function of tillage systems. For this purpose three 180-cm long soil cores were collected from middle quarter of each plot. These cores were composited after sectioning them into a set of nine samples representing following depths: 0-10, 10-20, 20-30, 30-45, 45-60, 60-90, 90-120, 120-150, and 150-180 cm. Composited samples were analyzed for soil moisture, \( \text{NO}_3\text{-N} \) and pesticide concentrations. A detailed methodology of collecting soil samples and analyzing them is described by Weed (1992).

Model simulated \( \text{NO}_3\text{-N} \) concentration in soil profile were compared with the measured \( \text{NO}_3\text{-N} \) concentration for 1990 and 1992. These data are presented in Figures 13 to 15 for 1990 and in Figures 16 to 18 for 1992, respectively.

Although depth and magnitude of simulated \( \text{NO}_3\text{-N} \) peak concentrations in the soil profile did not match well with observed depths and magnitude of observed \( \text{NO}_3\text{-N} \) concentrations, predicted concentrations were more or less in the same range that of observed concentrations. Model also showed the effect of tillage systems on \( \text{NO}_3\text{-N} \) concentrations in the soil profile. Usually higher soil \( \text{NO}_3\text{-N} \) concentrations occurred under MB and CP treatments and lower soil...
NO$_3$-N concentrations under NT and RT treatments. These trends, in general, agree with the observed tillage effects. Predicted soil NO$_3$-N concentrations were similar for all days except for JD 150, 1990 and JD 176, 1992 and showed peak NO$_3$-N concentrations occurring at bottom depths (120-140 cm) of profile being simulated. NO$_3$-N concentration profiles on JD 150, 1990 and JD 176, 1992 represent concentration profiles 18 and 55 days after fertilizer application (fertilizer was applied on JD 132 in 1990 and on JD 121 in 1992), showing higher soil NO$_3$-N concentration peaks at shallower depths. Simulated soil NO$_3$-N concentration profiles showed a gradually increasing difference between NO$_3$-N concentration profiles for different tillage systems. There was no consistent pattern of this type of behavior 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 tile water flow).

**Sensitivity Analysis**

A sensitivity analysis was performed to determine how the model reacts to the variations in selected hydrologic parameters. Output variable selected to monitor these effects was cumulative NO$_3$-N loss with drain water. Effects of following hydrologic variables/parameters on NO$_3$-N loss with drain flow were considered: initial moisture content of the soil profile, macroporosity, BD, $\Theta_{33kpa}$, lateral Ksat, drain depth, and drain spacing. Since tillage effects are expected to be confined within the surface horizon, sensitivity analysis for following variables was conducted by changing their values for surface horizon (0-25 cm) only: macroporosity, BD, and $\Theta_{33kpa}$. Lateral Ksat, drain depth, and drain spacing were selected because these are important parameters in Hooghoudt equation used to calculate drain flows. The numerical values of the parameters under study were increased by 10 and 20 percent of their experimental or calibrated value. When initial moisture
content of the soil profile was increased by 10 and 20%, initial NO$_3$-N concentrations in the soil profile were adjusted accordingly to have the same amount of NO$_3$-N in the soil profile. The effects of these changes are presented in Figures 19 and 20.

Figure 19 shows that predicted cumulative NO$_3$-N loss with drain water was most sensitive to $\Theta_{3kpa}$ and BD of the surface horizon in comparison to other variables or parameters. For 10 and 20 percent increases in $\Theta_{3kpa}$ for surface horizon respectively, about 16 percent and 45 percent reduction in NO$_3$-N loss with drain water was obtained. Similarly, 10 percent and 20 percent increases in BD for surface horizon, resulted in 14 percent and 45 percent reduction respectively, in cumulative NO$_3$-N loss with drain water. Initial moisture content of the soil profile did not affect total NO$_3$-N loss with subsurface drain water as much as $\Theta_{3kpa}$ and BD. When initial moisture content was increased by 10 percent, about 2 percent increase in cumulative NO$_3$-N loss with drain water was obtained. Similarly, a 20 percent increase in initial moisture content of the soil profile resulted in about 3.5 percent increase in cumulative NO$_3$-N loss with drain water.

Changes in macroporosity in surface horizon did not result in substantial changes in NO$_3$-N loss with drain water, when compared with the changes caused by other variables/parameters. Twenty percent increase in macroporosity of the surface horizon showed about 2 percent increase in cumulative NO$_3$-N loss with drain water. This was expected as 20 percent increase in a macroporosity value of 0.003 m$^3$/m$^3$ represented a macropore volume of 0.0006 m$^3$/m$^3$, which was not enough to cause any substantial change in cumulative NO$_3$-N loss with tile drain water. Lateral Ksat, drain depth, and drain spacing also affected total NO$_3$-N losses with drain flow but not as much as $\Theta_{3kpa}$ and BD. A total of 20 percent increase in lateral Ksat, and drain depth resulted in about 5 percent and 3 percent increase, respectively, in total NO$_3$-N losses with drain water. On the other hand, when drain spacing was increased by 20 percent, about 6 percent decrease in NO$_3$-N loss with drain water was obtained.
Summary and Conclusions

Modified RZWQM was further extended to simulate NO$_3$-N concentrations in the tile water effluent. Daily NO$_3$-N concentrations and losses in the tile flow were simulated as function of tillage systems (CP, MB, NT, RT) for 1990, 1991, and 1992. Simulated NO$_3$-N concentrations and losses were compared with the field measured concentrations and losses to evaluate model's performance. Modified RZWQM, in general, showed a good potential of predicting NO$_3$-N concentrations and losses in the tile effluent under different tillage systems. Simulated daily NO$_3$-N concentrations in tile 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 tile flow under MB and CP treatments and lower under NT and RT treatments for all three years. However, $R^2$ values (0.19 to 0.57) did not show a strong correlation between observed and simulated daily NO$_3$-N concentrations in tile flows. Simulated annual NO$_3$-N losses agreed well with the observed annual NO$_3$-N losses under different tillage systems (average percent error being about 14%). In 1990, predicted tillage effects were consistent with observed tillage effects (i.e., maximum annual NO$_3$-N losses under NT and minimum under MB). But for 1991 and 1992 predicted tillage effects were not always consistent with observed effects. Simulated NO$_3$-N concentrations in the soil profile under different tillage systems were more or less in the same range (maximum and minimum NO$_3$-N concentrations) but depth and magnitude of peak simulated concentrations did not match well with those of observed peaks.

A sensitivity analysis involving various hydrologic parameters showed that bulk density and $\Theta_{33\text{kpa}}$ have more effect on NO$_3$-N losses with subsurface drain water than initial moisture content, macroporosity, lateral Ksat, drain depth, and drain spacing.

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.
For example, accurate measurement of rainfall intensities, initial moisture content, and NO$_3$-N concentrations in the soil profile will certainly improve the model predictions. At the same time, various NO$_3$-N transformation rates need to be calibrated in the light of different tillage practices. NO$_3$-N losses with lateral groundwater flow and deep seepage also need to be accounted.

References


Singh, P. 1994. Adding a tile drainage component in RZWQM and simulating tile drainage under different tillage systems. Paper 2 In Modification of Root Zone Water Quality Model (RZWQM) to simulate the tillage effects on subsurface drain flows and NO3-N movement. Ph.D. dissertation. Iowa State University. Ames, IA.


Table 1. Dates of tillage, planting, chemical application, and harvesting for 1990

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Table 2. Dates of tillage, planting, chemical application, and harvesting for 1991

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Table 3. Dates of tillage, planting, chemical application, and harvesting for 1992

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Table 4. Initial NO₃-N concentrations for simulation runs for all tillage treatments for 1990

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Table 5. Initial NO₃-N concentrations for simulation runs for all tillage treatments for 1991

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Table 6. Initial NO$_3$-N concentrations for simulation runs for all tillage treatments for 1992

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Table 7. Total NO$_3$-N losses with subsurface drain flow for 1990, 1991, and 1992

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<tr>
<th>Year</th>
<th>Total Rain (cm)</th>
<th>NO$_3$-N losses with tile flow (Kg/ha)</th>
<th>CP</th>
<th>MB</th>
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Table 8. Average NO₃-N concentrations in subsurface drain flows for 1990, 1991, and 1992

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<th>NO₃-N conc. in tile flow (mg/L)</th>
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Figure 1. Simulated and observed average NO$_3$-N concentrations in tile flow for Chisel Plow, 1990
Figure 2. Simulated and observed average NO$_3$-N concentrations in tile flow for Moldboard Plow, 1990
Figure 3. Simulated and observed average NO$_3$-N concentrations in tile flow for No-Till, 1990
Figure 4. Simulated and observed average NO$_3$-N concentrations in tile flow for Ridge-Till, 1990
Figure 5. Simulated and observed average NO$_3$-N concentrations in tile flow for Chisel Plow, 1991
Figure 6. Simulated and observed average NO$_3$-N concentrations in tile flow for Moldboard Plow, 1991.
Figure 7. Simulated and observed average NO$_3$-N concentrations in tile flow for No-Till, 1991
Figure 8. Simulated and observed average NO$_3$-N concentrations in tile flow for Ridge-Till, 1991
Figure 9. Simulated and observed average NO$_3$-N concentrations in tile flow for Chisel Plow, 1992
Figure 10. Simulated and observed average $\text{NO}_3^-$ concentrations in tile flow for Moldboard Plow, 1992
Figure 11. Simulated and observed average NO$_3$-N concentrations in tile flow for No-Till, 1992
Figure 12. Simulated and observed average NO$_3$N concentrations in tile flow for Ridge-Till, 1992
Figure 13. Simulated (lines) and observed (points) NO3-N concentrations in soil profile for JD 150, 1990 (error bars show the standard deviation).
Figure 14. Simulated (lines) and observed (points) NO3-N concentrations in soil profile for JD 268, 1990 (error bars show the standard deviation)
Figure 15. Simulated (lines) and observed (points) NO3-N concentrations in soil profile for JD 298, 1990 (error bars show the standard deviation)
Figure 16. Simulated (lines) and observed (points) NO3-N concentrations in soil profile for JD 119, 1992 (error bars show the standard deviation)
Figure 17. Simulated (lines) and observed (points) NO3-N concentrations in soil profile for JD 176, 1992 (error bars show the standard deviation).
Figure 18. Simulated (lines) and observed (points) NO3-N concentrations in soil profile for JD 232, 1992 (error bars show the standard deviation)
Figure 19. Parameter sensitivity to cumulative NO3-N losses with drain water for the year 1991

- Initial moisture content
- Macroporosity of surface horizon
- Bulk density of surface horizon
- 33 kPa moisture content of surface horizon
Figure 20. Parameter sensitivity to cumulative NO3-N loss with drain water for the year 1991.
OVERALL SUMMARY AND CONCLUSIONS

1. Four different tillage systems - moldboard plow (MB), chisel plow (CP), no-tillage (NT), and ridge-tillage (RT) were characterized on the basis of soil physical properties for three different soil types (Floyd, Kenyon, and Readlyn). Three soil physical properties were selected namely, bulk density (BD), saturated hydraulic conductivity (Ksat), and macroporosity (MP). Measured BD, Ksat, and MP data for 50-cm deep soil profile showed no significant effect of tillage systems on these properties in all types of soil except Readlyn. In Readlyn soil, Ksat data at the 7.5-15 cm depth increment showed a significant effect of tillage systems.

2. A subsurface drain flow component was successfully added in RZWQM and the model’s response to tillage treatments was studied by simulating subsurface drain flows under four different tillage systems (CP, MB, NT, and RT) for the growing seasons of three years (1990, 1991, and 1992). The model was calibrated by utilizing 1990 observed tile flow data. Performance of the model was further evaluated by comparing the predicted and observed total seasonal tile flows for the years 1991 and 1992. The modified model in general showed a good agreement between the predicted and observed tile flows ($R^2$ value for observed and simulated tile flow data being about 0.6 on average). Although some discrepancies occurred between the observed and predicted amount of peak tile flows and total seasonal flows, model-predicted trends were consistent with the observed trends i.e., maximum tile flows under NT and minimum under MB treatment.

3. The modified RZWQM was further extended to predict NO$_3$-N concentrations and losses in the subsurface drain effluent. NO$_3$-N concentrations and losses with the tile flow were predicted under MB, CP, NT, and RT systems for the growing seasons of 1990, 91, and 92. Simulated NO$_3$-N concentrations and losses with tile flow were compared with the observed data to evaluate model’s performance. Model-predicted NO$_3$-N concentrations followed on more or less
same pattern as that of observed concentrations but $R^2$ values (0.18 to 0.37) did not show a strong correlation between observed and predicted NO$_3$-N concentrations. The model correctly predicted maximum concentrations under MB treatment and minimum under NT treatment for all three years. However, simulated NO$_3$-N losses were slightly overpredicted (about 14% on average) when compared with observed losses.

4. The modified RZWQM was found to be capable of predicting tillage influences on subsurface drain flows and NO$_3$-N concentrations and losses with the subsurface drain effluent. However, the model predictions could be improved by using better estimates of rainfall intensities, initial soil moisture and NO$_3$-N concentrations in the soil profiles, and lateral groundwater flow component in the model. Various NO$_3$-N transformation processes need to be calibrated in the light of different tillage practices.
RECOMMENDATIONS FOR FUTURE WORK

Although modified RZWQM showed a good potential for simulating subsurface drain flows and NO$_3$-N concentrations in subsurface drain flows under different tillage systems, a number of changes would be necessary to improve predictions of the model and make it more comprehensive.

In its present form, RZWQM uses a variable-thickness layering scheme (ranging from 1 cm at top to 15 cm at bottom) and a time step of 1 h for calculating flow rates. Thicker soil layers at the bottom cause water table depth to be a step function causing abrupt changes in subsurface drain flows. Replacing the current layering scheme with an uniform layering scheme with layers of smaller thickness would result in gradual change in water table depth and more accurate subsurface drain flows. A smaller time step should also increase the accuracy of model predictions.

Another improvement needed in the model would be the incorporation of deep seepage and lateral groundwater flow components to account for NO$_3$-N losses with these flow components.

To make the model more comprehensive, measures of spatial and temporal variability in the soil properties (especially macroporosity) also need to be incorporated. Several researchers have reported that temporal or weather induced variations in soil properties sometimes can be greater than tillage effects. In order to accurately simulate weather and rainfall response, model should be able to mimic these effects.

A considerable difference between simulated and observed NO$_3$-N concentrations in the soil profile under different tillage systems indicated a need for calibrating and validating NO$_3$-N transformation processes as a function of tillage systems.

The model in its present form is not capable of simulation through the winter period. The next research effort should be the addition of freezing-thawing component to the model. This
would permit continuous simulation for several years minimizing the need for input data at the beginning of subsequent years. Long term simulations will also make the model more useful for making planning and management decisions.

Crop rotation is an important management practice. The present capability of the model is to simulate corn growth. Changes are required in plant growth submodel so the model is capable of handling multiple crops and evaluating the effect of crop rotations on water and solute movement through vadose zone.
LITERATURE CITED


ACKNOWLEDGEMENTS

I am deeply indebted to Dr. Ramesh Kanwar, my major professor, for his talented guidance, creative suggestions, and invaluable encouragement throughout the course of this research. I appreciate the great efforts he made helping me in accomplishing the objectives of this research. My gratitude for him is forever.

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My gratitude is due to all my friends especially Dr. Ganesh Wadawadigi, Dr. Binayak Mohanty, Dr. Sandeep Bhatia and Kailash Bhatt for extending their unreserved support during this phase of my educational career.

Finally, I would like to express my deep regards and appreciation for my parents Sri Janardan Singh and Smt. Shashi Singh, and my brothers Shrish and Anshu for their everlasting love and encouragement throughout my educational career. I dedicate this work to my parents and brothers with my heartiest thanks!
### Table 1. $K_{\text{m}}$ (cm/s) measurements for Nashua-Floyd series as a function of tillage and depth.

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<th>Rep 3</th>
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*Sample disturbed or not saturated
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*Samples disturbed or lost
Table 5. Bulk density (g/cm³) measurements for Nashua-Kenyon Series as a function of tillage and depth

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*Sample disturbed or lost
Table 6. Bulk density (g/cm³) measurements for Nashua-Readlyn Series as a function of tillage and depth

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*Sample disturbed or lost*
Table 7. Macroporosity (m$^3$/m$^3$) values for Nashua-Floyd series as a function of tillage and depth

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Table 9. Macroporosity (m³/m³) values for Nashua-Readlyn series as a function of tillage and depth

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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>6.9E-04</td>
<td>5.2E-04</td>
<td>6.1E-04</td>
<td>1.2E-04</td>
</tr>
<tr>
<td>15</td>
<td>4.1E-04</td>
<td>1.4E-04</td>
<td>2.7E-04</td>
<td>1.9E-04</td>
</tr>
<tr>
<td>No-Till</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>1.6E-03</td>
<td>9.5E-04</td>
<td>1.3E-03</td>
<td>4.8E-04</td>
</tr>
<tr>
<td>15</td>
<td>1.1E-04</td>
<td>5.4E-04</td>
<td>3.3E-04</td>
<td>3.0E-04</td>
</tr>
<tr>
<td>Ridge-Till</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>6.8E-04</td>
<td>1.2E-04</td>
<td>4.0E-04</td>
<td>3.9E-04</td>
</tr>
<tr>
<td>15</td>
<td>3.2E-04</td>
<td>1.8E-04</td>
<td>2.5E-04</td>
<td>1.0E-04</td>
</tr>
</tbody>
</table>
APPENDIX B STATISTICAL ANALYSES SUMMARY

An example of analysis of variance (ANOVA) test performed to test significant effects of tillage on soil properties.
Soil Type - Kenyon
Soil Property - Bulk Density
Depth Increment - 2nd (35-42.5 cm)

<table>
<thead>
<tr>
<th>Source of Variance</th>
<th>Degrees of Freedom</th>
<th>Sum of Squares</th>
<th>Mean Squares</th>
<th>F value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>11</td>
<td>0.0415</td>
<td>0.000377</td>
<td></td>
</tr>
<tr>
<td>Rep.</td>
<td>2</td>
<td>0.0118</td>
<td>0.00059</td>
<td>1.96</td>
</tr>
<tr>
<td>Trtmnt.</td>
<td>3</td>
<td>0.0115</td>
<td>0.00038</td>
<td>1.26</td>
</tr>
<tr>
<td>Error</td>
<td>6</td>
<td>0.018</td>
<td>0.0003</td>
<td></td>
</tr>
</tbody>
</table>

Tabulated value of $F_i$ (n1=3, n2=6) = 4.76 at 95% confidence interval
n1 = degrees of freedom in nominator
n2 = degrees of freedom in denominator
From above analysis: $F_i > F$ thus no significant effect of treatment.
Table 1. Summary of ANOVA tests for Ksat for all three types of soils

<table>
<thead>
<tr>
<th>Soil Type: Flyod</th>
<th>SS</th>
<th>MS</th>
<th>( F_{\text{cal}} )</th>
<th>( F_{\text{table}} )</th>
<th>CV (%)</th>
<th>Trtmnt. Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>DI-1</td>
<td>0.00007</td>
<td>0.000025</td>
<td>3.96</td>
<td>9.28</td>
<td>95</td>
<td>NSE</td>
</tr>
<tr>
<td>DI-2</td>
<td>0.00226</td>
<td>0.00075</td>
<td>3.05</td>
<td>5.41</td>
<td>104</td>
<td>NSE</td>
</tr>
</tbody>
</table>

Soil Type: Kenyon

<table>
<thead>
<tr>
<th>Soil Type: Kenyon</th>
<th>SS</th>
<th>MS</th>
<th>( F_{\text{cal}} )</th>
<th>( F_{\text{table}} )</th>
<th>CV (%)</th>
<th>Trtmnt. Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>DI-1</td>
<td>0.00194</td>
<td>0.00064</td>
<td>4.65</td>
<td>4.76</td>
<td>155</td>
<td>NSE</td>
</tr>
<tr>
<td>DI-2</td>
<td>0.00045</td>
<td>0.00015</td>
<td>4.04</td>
<td>5.41</td>
<td>93</td>
<td>NSE</td>
</tr>
</tbody>
</table>

Soil Type: Readlyn

<table>
<thead>
<tr>
<th>Soil Type: Readlyn</th>
<th>SS</th>
<th>MS</th>
<th>( F_{\text{cal}} )</th>
<th>( F_{\text{table}} )</th>
<th>CV (%)</th>
<th>Trtmnt. Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>DI-1</td>
<td>0.00019</td>
<td>0.000063</td>
<td>11.4</td>
<td>5.41</td>
<td>50</td>
<td>SE</td>
</tr>
<tr>
<td>DI-2</td>
<td>0.00011</td>
<td>0.000037</td>
<td>2.37</td>
<td>9.28</td>
<td>67</td>
<td>NSE</td>
</tr>
</tbody>
</table>

\( \text{DI-1} \) = Depth Increment 1 (7.5-15 cm)
\( \text{DI-2} \) = Depth Increment 2 (42.5-50 cm)
SS = Sum of Squares (Tillage)
MS = Mean Squares (Tillage)
\( F_{\text{cal}} \) = Calculated F value
\( F_{\text{table}} \) = Tabulated F value
NSE = No significant effect
SE = Significant effect
CV = Coefficient of variation
Table 2. Summary of ANOVA tests for Bulk Density for all three types of soils

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>DI-1</th>
<th>DI-2</th>
<th>DI-1</th>
<th>DI-2</th>
<th>DI-1</th>
<th>DI-2</th>
<th>DI-1</th>
<th>DI-2</th>
<th>DI-1</th>
<th>DI-2</th>
<th>DI-1</th>
<th>DI-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flyod</td>
<td>0.09942</td>
<td>0.03314</td>
<td>3.25</td>
<td>4.76</td>
<td>8.9</td>
<td>NSE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kenyon</td>
<td>0.0601</td>
<td>0.0201</td>
<td>2.53</td>
<td>4.76</td>
<td>6.5</td>
<td>NSE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Readlyn</td>
<td>0.0066</td>
<td>0.00383</td>
<td>1.26</td>
<td>4.76</td>
<td>3.5</td>
<td>NSE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Legend:**
- DI-1 = Depth Increment 1 (0-7.5 cm)
- DI-2 = Depth Increment 2 (35-42.5 cm)
- SS = Sum of Squares (Tillage)
- MS = Mean Squares (Tillage)
- $F_{cal}$ = Calculated F value
- $F_{table}$ = Tabulated F value
- CV = Coefficient of variation
- NSE = No significant effect
- SE = Significant effect

**Notes:**
- Table 2. Summary of ANOVA tests for Bulk Density for all three types of soils
- Soil Type: Flyod
- Soil Type: Kenyon
- Soil Type: Readlyn
Table 3. Summary of ANOVA tests for Macroporosity for all three types of soils

<table>
<thead>
<tr>
<th></th>
<th>SS</th>
<th>MS</th>
<th>$F_{cal}$</th>
<th>$F_{table}$</th>
<th>CV (%)</th>
<th>Trtmnt. Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Soil Type: Floyd</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DI-1</td>
<td>1.5E-06</td>
<td>4.9E-07</td>
<td>1.55</td>
<td>5.41</td>
<td>110</td>
<td>NSE</td>
</tr>
<tr>
<td>DI-2</td>
<td>4.2E-06</td>
<td>1.4E-07</td>
<td>0.51</td>
<td>5.41</td>
<td>133</td>
<td>NSE</td>
</tr>
<tr>
<td><strong>Soil Type: Kenyon</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DI-1</td>
<td>1.0E-07</td>
<td>3.0E-08</td>
<td>3.04</td>
<td>5.41</td>
<td>43</td>
<td>NSE</td>
</tr>
<tr>
<td>DI-2</td>
<td>2.1E-07</td>
<td>7.0E-08</td>
<td>1.02</td>
<td>5.41</td>
<td>98</td>
<td>NSE</td>
</tr>
<tr>
<td><strong>Soil Type: Readlyn</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DI-1</td>
<td>1.1E-06</td>
<td>3.7E-07</td>
<td>15.3</td>
<td>5.41</td>
<td>23</td>
<td>SE</td>
</tr>
<tr>
<td>DI-2</td>
<td>2.0E-08</td>
<td>1.0E-08</td>
<td>0.17</td>
<td>5.41</td>
<td>71</td>
<td>NSE</td>
</tr>
</tbody>
</table>

DI-1 = Depth 1 (0 cm)
DI-2 = Depth 2 (15 cm)
SS = Sum of Squares (Tillage)
MS = Mean Squares (Tillage)
$F_{cal}$ = Calculated F value
$F_{table}$ = Tabulated F value
NSE = No significant effect
SE = Significant effect
CV = Coefficient of variation
APPENDIX C SOURCE CODE FOR MOIST AND DRAIN

A listing of source code for subroutines MOIST and DRAIN

SUBROUTINE MOIST (SOILHP, TL, NDXN2H, HORTHK, N_HOR, PTRANS, QF, + DTWT, THETA, EVAP, AEVAP, DFLUX, NL, H, AEF, AE, HKBAR, JLUL)
C===================================================================
C PURPOSE: THIS SUBROUTINE SIMULATES MOISTURE REDISTRIBUTION
C AFTER INfiltrATION TAKES PLACE. THIS SUBROUTINE
C IS BASED ON A SIMPLE FINITE DIFFERENCE SOLUTION
C OF RICHARD'S EQUATION.
C
C VARIABLES TYPE DESCRIPTION
C DTWT I/O DEPTH TO WATER TABLE
C H O VECTOR OF NODAL HEAD VALUES
C NL I TOTAL NUMBER OF LAYERS
C TL I THICKNESS OF LAYER (I)
C DEBT I TIME STEP (1 HR)
C THETA I/O VOLUMETRIC WATER CONTENT (DIMENSIONLESS)
C EVAP I EVAPORATION FROM THE FIRST LAYER (CM/HR)
C THF I THETA AT FIELD CAPACITY...SOILHP(7,J)
C THR I THETA AT WILTING POINT...SOILHP(9,J)
C THS I THETA AT SATURATION...SOILHP(6,J)*AEF
C SOILHP I ARRAY OF SOIL HYDRAULIC PROPERTIES
C NDXN2H I V: INDICES RELATING NUMERICAL LAYERS TO
C SOIL HORIZONS
C DEL L A SINK TERM FOR TILE DRAINAGE FROM EACH
C SATURATED LAYER
C HKBAR I VECTOR INTERFACE AVG. COND. VALUES (CM/HR)
C ET I EVAPORATION FROM EACH LAYER 
C =QS(I)*TL(I)
C QS(I) I NODAL PLANT UPTAKE (CM/HR)
C QF(I) O FLOW RATES RETURNED BY MOIST (CM/HR)
C DIFF I SOIL WATER DIFFUSIVITY-f(THETA)
C COND I HYDRAULIC CONDUCTIVITY- f(THETA)
C KS I SATURATED HYDRAULIC CONDUCTIVITY
C INF I INFILTRATION RATE
C DZ(I) L DEPTH OF THE BOTTOM BOUNDARY OF LAYER I (CM)
C DIFF L DIFFERENCE BETWEEN WT DEPTH AND DZ(I) (CM)
C N L NUMBER OF TOPMOST LAYER WHICH HAS WT IN IT
C HTL L HALF OF THE LAYER THICKNESS (CM)
C LUL L NUMBER OF LAST LAYER IN THE UNSATURATED PROFILE
C POR(I) I POROSITY OF LAYER I
C AVD I AVG. DIFFUSION COEFF. FOR LAYER I-1 AND
C I (CM'2/HR)
C AVK I AVG. HYDRAULIC CONDUCTIVITY FOR LAYER I-1
C INT L INTERVALS PER DAY
C EXCESS L THETA(I)-THF(I)
C DEFICIT L THR(I)-THETA(I)
C FLRT(I) L FLOW RATE INTO LAYER I (CM/HR)
C SOILM(I) L SOIL MOISTURE(I)=THETA(I)*TL(I) (CM)
C DX(I) L DISTANCE BETWEEN THE CENTERS OF LAYER I AND I+1
C DV(I) L DRAINABLE VOLUME FROM LAYER I
C DFLUX I TOTAL DRAINAGE FLUX...RETURNED BY "DRAIN" (CM/HR)
C DRN L DUMMY VARIABLE FOR DFLUX
C MAXHOR I MAX NUMBER OF HORIZONS
C HORTHK I THICKNESS OF EACH HORIZON
C BP(I) I BUBBLING PRESSY-TO CALCULATE NODAL 'K'
C
C CALLED FROM: REDIST
C
C PROGRAMMER: PIYUSH SINGH
C
C==================================================================
C

IMPLICIT DOUBLE PRECISION (A-H, O-Z)
PARAMETER (MXNOD=40, MAXHOR=12)
DIMENSION TL(MXNOD), THF(MXNOD), THR(MXNOD), ET(MXNOD),
+ QS(MXNOD), QF(MXNOD), FLRT(MXNOD+1), DZ(0:MXNOD), EV(MXNOD),
+ DX(MXNOD), SOILHP(13, MAXHOR), THETA(MXNOD), SOILM(MXNOD),
+ THS(MXNOD), EXCESS(MXNOD), DEFICIT(MXNOD), DV(MXNOD),
+ XNED(MXNOD), OSM(MXNOD), DEL(MXNOD), HORTHK(MAXHOR),
+ H(MXNOD), HKBAR(MXNOD), BP(MXNOD), AVK(MXNOD)
INTEGER NDXN2H(MXNOD)
LOGICAL FIRST
SAVE FIRST
DATA FIRST/.TRUE./

C IF FIRST DAY OF THE SIMULATION.....CHECK THE WATER TABLE DEPTH
AND DETERMINE THICKNESS OF UNSATURATED ZONE
IF (FIRST) THEN
  DO 5 I=1, NL
    JH=NDXN2H(I)
    THF(I)=SOILHP(7, JH)
    THR(I)=SOILHP(9, JH)
    THS(I)=SOILHP(6, JH)*AEF
    BP(I)=SOILHP(1, JH)
  CONTINUE
  DZ(0)=0.0D0
  DZ(1)=TL(1)
  DO 10 I=2, NL
    DZ(I)=DZ(I-1)+TL(I)
  CONTINUE
  FIRST=.FALSE.
  DO 15 I=1, NL
    DIFF=DTWT-DZ(I)
    IF (DIFF.LT.0.0D0) THEN
      N=I
      LUL=I-1
      DIFF=-DIFF
      HTL=0.5D0*TL(I)
      IF (DIFF.LT.HTL) THEN
        N=I+1
        LUL=I
      END IF
      GO TO 150
    ELSE IF (I.EQ.NL) THEN
      LUL=NL
      N=NL+1
    END IF
  CONTINUE
150 DO 20 I=N, NL
    THETA(I)=THS(I)
    SOILM(I)=THETA(I)*TL(I)
  CONTINUE
END IF

C CALCULATE SOIL MOISTURE MOVEMENT IN THE UNDISTURBED SOIL PROFILE
C CALCULATE FLOW INTO FIRST LAYER
C ...
C FIRST CALCULATE EVAP. AND TRANS. FROM EACH ALYER......
DO 22 I=1, LUL
  EV(I)=-EVAP/LUL
  ET(I)=-PTRANS/LUL
22 CONTINUE

C .......CALCULATE ET FROM UNSATURATED LAYERS
IF (LUL.LE.0) THEN
LUL=1
END IF

DO 25 1=1,LUL
SOILM(I)=THETA(I)*TL(I)
25 CONTINUE

DO 30 1=1,NL
OSM(I)=SOILM(I)
30 CONTINUE

JLUL=LUL
JN=N

CALCULATE AVG. HYDRAULIC CONDUCTIVITY

DO 3232 I=1,NL-1
CARG1=H(I)
CARG2=H(I+1)
AVK(I)=(POINTK(CARG1,BP(I))+POINTK(CARG2,BP(I+1)))*0.5D0
HKBAR(I)=AVK(I)
3232 CONTINUE

CALCULATE FLOW RATES.............

......IF EVAPORATION MORE THEN AVAILABLE MOISTURE
SET IT EQUAL TO HALF OF AVAILABLE MOISTURE

IF (EVAP..GT.((THETA(1)-THR(1))*TL(1))) THEN
EVAP=(THETA(1)-THR(1))*TL(1)
END IF

FLRT(1) = -EV(1)

DO 35 I=1,LUL
SOILM(I)=SOILM(I)+FLRT(I)
THETA(I)=SOILM(I)/TL(I)
35 CONTINUE

IF LAST LAYER IN UNSATURATED ZONE... MAKE ITS OUTFLOW EQUAL
TO ZERO.....OR SET DEEP PERCOLATION TO ZERO

IF (I.EQ.LUL) THEN
FLRT(I+1)=0.0D0
ELSE IF (THETA(I).GT.THF(I)) THEN
EXCESS(I)=(THETA(I)-THF(I))*TL(I)
FLRT(I+1)=EXCESS(I)
ELSE IF (THETA(I).LT.THR(I)) THEN
DEFICIT(I)=(THR(I)-THETA(I))*TL(I)
ET(I+1)=ET(I+1)+ET(I)
EV(I)=0.0D0
FLRT(I+1)=-DEFICIT(I)
ELSE
ARG1=THETA(I)
ARG2=THETA(I+1)

ELSE
AVD = (DIFN(ARG1) + DIFN(ARG2)) * 0.5D0

DX(I) = 0.5D0 * TL(I) + 0.5D0 * TL(I+1)

FLRT(I+1) = (AVD * (THETA(I) - THETA(I+1))) / (DX(I) + AVK(I))

IF FLRT(I+1) IS NEGATIVE (UPWARD) AND MORE THAN THE MOISTURE DEFICIT IN THE Ith LAYER THEN SET IT EQUAL TO MOISTURE DEFICIT OF Ith LAYER

IF (FLRT(I+1) .LT. 0.0D0) THEN
  XMORE = ABS(FLRT(I+1)) - (THF(I) - THETA(I)) * TL(I)
  IF (XMORE .GT. 0.0D0) THEN
    FLRT(I+1) = -(THF(I) - THETA(I)) * TL(I)
  END IF
END IF

END IF

UPDATE SOIL MOISTURE CONTENT OF THE LAYERS

IF (I.EQ.1) THEN
  SOILM(I) = SOILM(I) - FLRT(I+1) - ET(I)
  THETA(I) = SOILM(I) / TL(I)
ELSE
  SOILM(I) = SOILM(I) - FLRT(I+1) - ET(I) - EV(I)
  THETA(I) = SOILM(I) / TL(I)
END IF

IF MOISTURE CONTENT GOES BELOW WILTING POINT, PUT BACK THE EV AND ET BACK INTO THE LAYER......

IF (THETA(I) .LT. THR(I)) THEN
  SOILM(I) = SOILM(I) + EV(I)
  THETA(I) = SOILM(I) / TL(I)
  EV(I) = 0.0D0
END IF
IF (THETA(I) .LT. THR(I)) THEN
  SOILM(I) = SOILM(I) + ET(I)
  THETA(I) = SOILM(I) / TL(I)
  ET(I) = 0.0D0
END IF

CONTINUE

AET = 0.0D0
AEVAP = 0.0
DO 40 I = 1, LUL
  AET = AET + ET(I)
  AEVAP = AEVAP + EV(I)
40 CONTINUE

IF THE WATER CONTENT OF THE LAST LAYER IN UNSATURATED ZONE BECOMES MORE THAN THE FIELD CAPACITY THEN RAISE THE WATER TABLE UP THIS LAYER

IF (THETA(LUL) .GT. THF(LUL)) THEN
  EXTRA = (THETA(LUL) - THF(LUL)) * TL(LUL)
  DO 45 I = NL, N - 1
    XNEED(I) = (THS(I) - THETA(I)) * TL(I)
    IF (EXTRA .LE. XNEED(I)) THEN
      SOILM(I) = SOILM(I) + EXTRA
      THETA(I) = SOILM(I) / TL(I)
      EXTRA = 0.0D0
    ELSE
      SOILM(I) = SOILM(I) + XNEED(I)
      THETA(I) = SOILM(I) / TL(I)
      EXTRA = EXTRA - XNEED(I)
    END IF
 45 CONTINUE
SOILM(LUL) = THF(LUL) * TL(LUL) + EXTRA
THETA(LUL) = SOILM(LUL) / TL(LUL)
IF (THETA(LUL) .GT. (THS(LUL))) THEN
EXTRA = (THETA(LUL) - THS(LUL)) * TL(LUL)
SOILM(LUL) = THS(LUL) * TL(LUL)
THETA(LUL) = SOILM(LUL) / TL(LUL)

IF (LUL.EQ.1) THEN
  HEAD = EXTRA
  LUL = 0
  N = 1
  GO TO 125
ELSE
  DO 50 I = LUL + 1, 1, -1
  XNEED(I) = (THS(I) - THETA(I)) * TL(I)
  IF (EXTRA.LE.XNEED(I)) THEN
    SOILM(I) = SOILM(I) + EXTRA
    THETA(I) = SOILM(I) / TL(I)
    EXTRA = 0.0
    IND = I
    GO TO 100
  ELSE
    SOILM(I) = SOILM(I) + XNEED(I)
    THETA(I) = SOILM(I) / TL(I)
    EXTRA = EXTRA - XNEED(I)
    IF (I.EQ.1) THEN
      HEAD = EXTRA
      LUL = 0
      N = 1
    END IF
  END IF
50 CONTINUE
100 IF (THETA(IND).GT.THF(IND)) THEN
  LUL = IND - 1
  N = IND
ELSE
  LUL = IND
  N = IND + 1
END IF
END IF
ELSE IF (THETA(LUL).GT.THF(LUL)) THEN
  LUL = LUL - 1
  N = N - 1
ELSE
  GO TO 125
END IF
END IF

C C C
C CALCULATE DRAINAGE FLUX BELOW THE WATER TABLE AND ADJUST WT HEIGHT
C C
125 DTWT = DZ(LUL)
CALL TDRAIN (DTWT, DFLUX, HORTHK, NHOR)
C
DSEEP = 0.0
DRN = DFLUX + DSEEP
DO 55 I = N, NL
  DEL(I) = DRN / (DZ(NL) - DZ(LUL)) * TL(I)
55 CONTINUE
IF (DRN.GT.0.0) THEN
  DO 60 I = N, NL
    DV(I) = (THETA(I) - THF(I)) * TL(I)
    IF (DRN.LE.DV(I)) THEN
      SOILM(I) = SOILM(I) + DRN
      THETA(I) = SOILM(I) / TL(I)
      INDX = I
    GO TO 300
  ELSE
    SOILM(I) = SOILM(I) - DV(I)
    THETA(I) = SOILM(I) / TL(I)
    DRN = DRN - DV(I)
  END IF
60 CONTINUE
CONTINUE
N = INDX  
LUL = INDX - 1  
END IF  
DTWT = DZ(LUL)

RECALCULATE FLOW RATES IN AND OUT OF THE LAYERS

DO 65 I = 1, JLUL  
   FLRT(I+1) = FLRT(I) - SOILM(I) + OSM(I) - ET(I)
65 CONTINUE
   FLRT(NL+1) = DSEEP
DO 70 I = NL, JN+2, -1  
   FLRT(I) = FLRT(I+1) + DEL(I)
70 CONTINUE
   FLRT(JN+1) = FLRT(JN+2) + 2.0*D0*DEL(NL)

DO 75 I = 1, NL  
   QF(I) = FLRT(I+1)
75 CONTINUE
CALL WCHEAD(THETA, H, SOILHP, NL, NDPXN2H, MAXHOR)
RETURN

FUNCTION TO CALCULATE DIFN. COEFF. AS A FUNCTION OF THETA (CM^2/HR)

DOUBLE PRECISION FUNCTION DIFN(X1)
IMPLICIT DOUBLE PRECISION (A-H,0-Z)
DIFN = 10.0**(-4.0+13.067D0*X1)/24.0D0
RETURN
END

FUNCTION TO CALCULATE UNSATURATED COND. AS A FUNCTION OF THETA (CM/HR)

DOUBLE PRECISION FUNCTION COND(X2)
IMPLICIT DOUBLE PRECISION (A-H,0-Z)
COND = 10.0**(-8.0+21.15D0*X2)/24.0D0
RETURN
END

SUBROUTINE TDRAIN(DTWT, DFLUX, HORTK, NHOR)

PURPOSE: CALCULATE EFFECTIVE LATRAL HYDRAULIC COND. (CM/DAY) AND  
DRAINAGE FLUX (CM/DAY) AS A FUNCTION OF WATER TABLE. THIS  
SUBROUTINE DOES NOT MODIFY THE DEPTH OF WATER TABLE

VARIABLES DEFINITIONS:

<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>TYPE</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>DTWT</td>
<td>I/O</td>
<td>DEPTH TO WATER TABLE (CM)</td>
</tr>
</tbody>
</table>
| ADEPTH   | I    | ACTUAL DEPTH OF IMPERMEABLE LAYER  
FROM SURFACE (CM) |
| ABOVE    | L    | DEPTH OF THE TOP OF THE LAYER CONSIDERED |
| DZ       | L    | DEPTH OF THE BOTTOM OF THE LAYER CONSIDERED |
| DEPTH    | I    | EFFECTIVE DEPTH TO THE IMPERMEABLE LAYER |
| SDRAIN   | I    | DRAIN SPACING |
| DDRAIN   | I    | DEPTH OF THE DRAIN FROM SURFACE |
| DC       | I    | DRAINAGE COEFFICIENT |
| CONK     | I    | LATERAL HYDRAULIC COND. OF THE LAYER (CM/DAY) |
| DFLUX    | I    | DRAINAGE FLUX (CM) |
| GEE      | I    | FACTOR -G- IN KIRKHAM'S EQUATION |
| STOR     | I    | SURFACE STORAGE |
| STORRO   | I    | SURFACE STORAGE THAT MUST BE FILLED BEFORE  
SURFACE WATER CAN MOVE TO DRAIN (CM) |
HORTHK I LOWER DEPTH OF HORIZON I FROM SURFACE

NHOR I NUMBER OF HORIZONS

CALLED FROM: REDIST1

PROGRAMMER: PIYUSH SINGH

IMPLICIT DOUBLE PRECISION (A-H,O-Z)
PARAMETER (MAXHOR=12)
DIMENSION DZ(MAXHOR),W(MAXHOR),HORTHK(MAXHOR)
COMMON/TILE/ADEPTH, DEPTH, GEE, S DRAIN,
+ DDRAIN, DC, CONK(MAXHOR), STOR, STORRO, HDRAIN
Y=DTWT

C CALCULATE DEPTH OF SATURATION WITHIN THE LAYER
C
IF (Y.GT.ADEPTH) THEN
Y=ADEPTH
END IF
DO 5 I=1,NHOR
   DZ(I)=HORTHK(I)
5 CONTINUE
ABOVE=0.0DO
DO 10 I=1,NHOR
   IF (Y.GT.DZ(I)) THEN
      W(I)=0.0DO
   ELSE
      W(I)=DZ(I) -Y
      X=DZ(I)-ABOVE
      IF (W(I).GT.X) THEN
         W(I)=X
      END IF
      ABOVE=DZ(I)
   END IF
10 CONTINUE
C CALCULATE EFFECTIVE SATURATED LATERAL HYDRAULIC CONDUCTIVITY
BETWEEN WATER TABLE
SUM=0.0DO
DEEP=0.0DO
DO 20 I=1,NHOR
   SUM=SUM+W(I)*CONK(I)
   DEEP=DEEP+W(I)
20 CONTINUE
C CALCULATE EFFECTIVE SATURATED LATERAL HYDRAULIC CONDUCTIVITY
IN THE CASE WATER TABLE IS NEAR IMPERMEABLE LAYER
IF ((DEEP.LE.0.0001D0).OR.(SUM.LE.0.0001D0)) THEN
   SUM=CONK(1)*DZ(1)
   DEEP=DZ(1)
   DO 40 I=2,NHOR
      SUM=SUM+CONK(I)*(DZ(I)-DZ(I-1))
      DEEP=DZ(I)
40 CONTINUE
END IF
CONE=SUM/DEEP
HDMIN=DEPTH-DDRAIN
IF (HDRAIN.LT.HDMIN) THEN
   HDRAIN=HDMIN
END IF
C CALCULATE DRAINAGE DURING PONDING
IF ((DTWT.LT.0.5D0).AND.(STOR.GT.STORRO)) THEN
DFLUX = 12.5663D0 * CONE * (DEPTH - HDRAIN + STOR) / (GEE * SDRAIN)
ELSE
CALCULATE DRAINAGE FLUX BY HOOCHOUDT EQUATION
EM = DEPTH - Y - HDRAIN
IF (EM .LT. 0.0D0) THEN
  DFLUX = 0.0D0
ELSE
  DFLUX = 4.0D0 * CONE * EM * (2.0D0 * HDRAIN + EM) / SDRAIN**2
END IF
IF (DFLUX .GT. DC) DFLUX = DC
IF (DFLUX .LT. 0.0D0) DFLUX = 0.0D0
END IF
RETURN
END
APPENDIX D  STATISTICAL EVALUATION OF MODEL PREDICTIONS

Procedure for calculating 95% confidence interval (CI) for slope and intercept of best-fit line determined for simulated versus observed data:

CI for slope:

$$CI_{slope} = \beta_1 \pm t_{n-2,\alpha/2} \left[ S/\sqrt{S_{xx}} \right]$$

CI for intercept:

$$CI_{intercept} = \beta_0 \pm t_{n-2,\alpha/2} \left[ S\sqrt{\sum X^2}/nS_{xx} \right]$$

where

- $\beta_1$ = Slope of the best fit line
- $\beta_0$ = Intercept of the best fit line
- $t_{n-2,\alpha/2}$ = Value of the Student’s t distribution at degrees of freedom $n-2$ and confidence level of $\alpha/2$ (0.025)
- $S/\sqrt{S_{xx}}$ = Standard error of estimation of slope
- $S\sqrt{\sum X^2}/nS_{xx}$ = Standard error of estimation of intercept
- $n$ = number of observations

Reference:

Figure 1. Observed versus predicted daily tile flows plotted to determine best fit line and coefficient of determination.
Figure 2. Observed versus predicted NO3-N concentrations in tile effluent plotted to determine best fit line and coefficient of determination
Table 1. Slope of the best fit line (M), Y-intercept (C), and coefficient of determination (R^2) values calculated for simulated and observed subsurface drain flows (a 95% confidence interval is also given for the values of M and C)

<table>
<thead>
<tr>
<th>Year of Run</th>
<th>Treatments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CP</td>
</tr>
<tr>
<td>1990</td>
<td>M' = 0.63 ± 0.06</td>
</tr>
<tr>
<td></td>
<td>C = 0.04 ± 0.14</td>
</tr>
<tr>
<td></td>
<td>R^2 = 0.67</td>
</tr>
<tr>
<td>1991</td>
<td>M' = 0.77 ± 0.14</td>
</tr>
<tr>
<td></td>
<td>C = 0.09 ± 0.18</td>
</tr>
<tr>
<td></td>
<td>R^2 = 0.69</td>
</tr>
<tr>
<td>1992</td>
<td>M' = 0.80 ± 0.16</td>
</tr>
<tr>
<td></td>
<td>C = 0.01 ± 0.08</td>
</tr>
<tr>
<td></td>
<td>R^2 = 0.64</td>
</tr>
</tbody>
</table>

*Significantly different from the slope (M=1.0) of 1:1 line

**Significantly different from the intercept (C=0) of 1:1 line

Table 2. Slope of the best fit line (M), Y-intercept (C), and coefficient of determination (R^2) values calculated for simulated and observed NO\textsubscript{3}-N concentrations in subsurface drain flows (95% confidence interval is also given for the values of M and C)

<table>
<thead>
<tr>
<th>Year of Run</th>
<th>Treatments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CP</td>
</tr>
<tr>
<td>1990</td>
<td>M' = 0.73 ± 0.2</td>
</tr>
<tr>
<td></td>
<td>C = 19.2 ± 27.3</td>
</tr>
<tr>
<td></td>
<td>R^2 = 0.43</td>
</tr>
<tr>
<td>1991</td>
<td>M' = 0.65 ± 0.2</td>
</tr>
<tr>
<td></td>
<td>C = 17.1 ± 26.1</td>
</tr>
<tr>
<td></td>
<td>R^2 = 0.46</td>
</tr>
<tr>
<td>1992</td>
<td>M' = 0.45 ± 0.18</td>
</tr>
<tr>
<td></td>
<td>C = 7.3 ± 12.0</td>
</tr>
<tr>
<td></td>
<td>R^2 = 0.19</td>
</tr>
</tbody>
</table>

*Significantly different from the slope (M=1.0) of 1:1 line

**Significantly different from the intercept (C=0) of 1:1 line