Comparison of Simulated and Measured Nitrate Losses in Tile Effluent

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ABSTRACT

A hydrologic and nitrate-transport simulation model was developed and used to simulate the major water and nitrogen-transport processes occurring in a typical agricultural watershed during the crop growth period. Data from a tile drainage experiment were used to evaluate the simulation model. Predicted values of tile flow volumes and nitrate concentrations in the tile effluent were compared with the measured data and, although variable, were encouraging. Deviations between predicted and measured nitrate losses in the tile effluent existed on a daily basis but usually were small when considered over the entire crop growth period.

INTRODUCTION

Nitrogen is essential to the growth and development of all crop plants. Statistics show that the use of nitrogen fertilizers has increased in this country at the rate of 4% a year for the 1969-79 period (ACS 1980). Most of the nitrogen used in the Midwest is on corn. Dibb and Walker (1979) reported that the average nitrogen application rate for producers planning to achieve high yields in the Midwest was in the excess of 224 kg/ha. The current agricultural practice is to economize on the time and application of nitrogen fertilizer by making a single application to meet the demands of the crop for the entire year. Bartholomew and Clark (1965) have pointed out that only 50% of the fertilizer applied is beneficially recovered in any one cropping year. The remaining nitrogen either goes out of the system through leaching, wash-off and volatization or stays in the soil profile for possible later use.

Nitrogen leached out of the root zone may reduce the quality of groundwater or surface water and present environmental, economic, and energy-conservation concerns. Baker et al. (1975) found that, even with modest fertilizer application rate of 112 kg/ha annually on corn in rotation with unfertilized soybeans, the concentrations of nitrate in the tile drainage water exceeded 10 ppm (NO_3-N) and the losses averaged around 30 kg/ha annually. Watts and Martin (1981) found that about 30-35 kg/ha of nitrate was lost through leaching when 168 kg/ha of N was applied to irrigated corn. Gase et al. (1978) measured the nitrate concentrations and losses in tile drainage water from plots receiving 21, 112, 224, and 448 kg/ha/year for 3 years in continuous-corn. They did not find any effect of differential fertilization on nitate losses in the first year, but for the second and third years, nitrate losses increased with the level of fertilization. Losses for the third year were 19, 25, 59, and 120 kg/ha, respectively. This shows that nitrate losses in drainage water will increase with the increased rate of fertilization which is expected with increased intensity of farming. The use of artifical drainage to remove excess water from cropland may enhance N movement; however, artifical drainage is an absolute necessity to farm some of the nation's most productive soils. Without artifical 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 computer simulation model was developed (Kanwar, 1981) to help determine the effects of farm management practices and weather on nitrate levels in tile effluent and to quantify the nitrogen fertilizers that may leach out of the root zone. Other nitrogen simulation models that have been reported in the literature are by Frere et al. (1970); Dutt et al. (1972); Beek and Fressel (1973); Reuss and Cole (1973); Hagin and Amberger (1974); Mehran and Tanji (1974); Duffy et al. (1975); Saxton et al. (1977); Watts and Martin (1981); Skaggs and Gilliam (1981); Knisel (1980); and Tubbs and Haith (1981). All these models vary considerably in their purpose and format. Except for Dutt et al. (1981) and Duffy et al. (1975), these models cannot be applied directly to a tile-drained area. Therefore, it was decided to develop an improved nitrogen simulation model for a tile-drained small agricultural watershed by using some of the ideas and submodels from Duffy et al. (1975).

The overall objectives of this paper are to present some of the key processes used to build the nitrogen simulation model, input data needs, and to compare the predicted values of nitrogen leached out of the root zone with actual data. This paper also explains some of the difficulties experienced in calibrating some of the processes used in the model, especially surface runoff and deep percolation because of the lack of adequate physical data. Although the model was developed for a particular location, it could be applied to other locations having similar field conditions.

MODEL DEVELOPMENT

Simulation Model

A computer simulation model was developed to simulate the soil-plant-water-nitrogen system (Fig. 1) in a typical tile drained agricultural field. The study site was located at the Agronomy and Agricultural Engineering Research Center near Ames, Iowa. The

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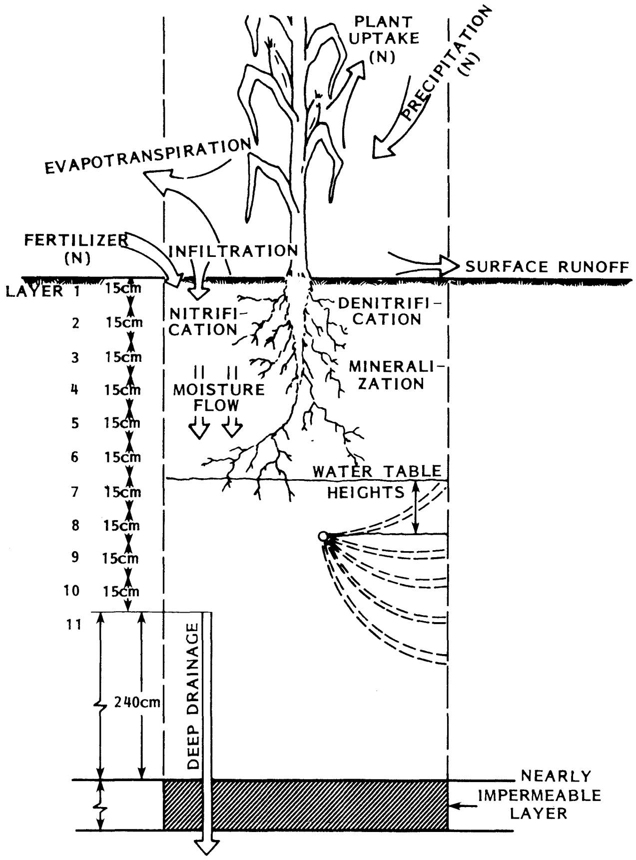

Fig. 1—Water and nitrogen processes represented in the soil-plant-water-atmosphere system.

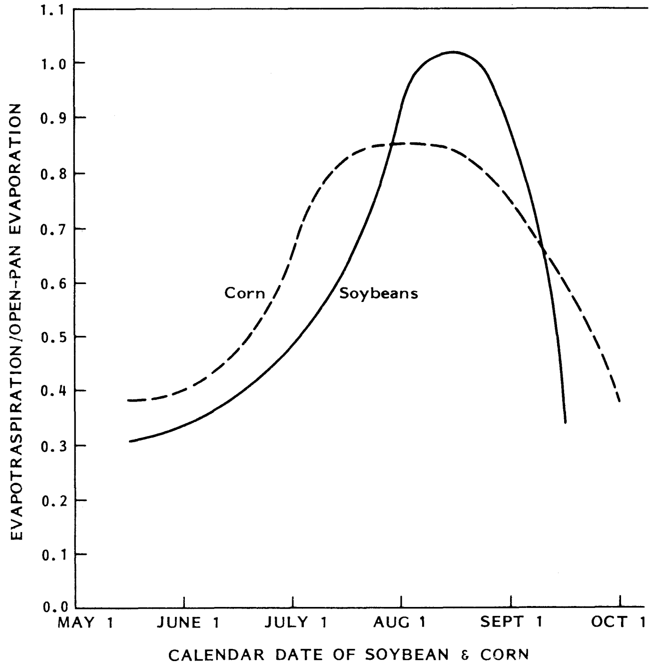

Fig. 2—Ratio of evapotranspiration of corn and soybeans to open-pan evaporation throughout the growing season.

experimental data on daily tile flow rates and the concentration of nitrate in the tile effluent from an 0.4 ha area were available for nine years (1970-1978) for model calibration and testing. The model simulates the biophysiochemical transformation of various nitrogen forms in the soil, nitrogen uptake, and nitrogen flow due to mass flow, dispersion, and diffusion. Water flow in the saturated and unsaturated soil zones and evapotranspiration also are simulated along with loss of water and nitrate from the root zone.

Because we are interested in root zone, the top 150 cm of the soil profile are modeled in detail. The soil profile is divided into 11 horizontal layers, the first 10 layers starting from the soil surface being each 15 cm deep, and the final layer extending from 150 cm to 390 cm below the surface. Within each layer, the soil properties, water content (volume of water per volume of soil), and nitrate concentrations are considered uniform.

Weather Input Data

Most of the weather data needed were available for the entire growing season. Daily rainfall and other data such as open-pan evaporation, wind velocity, air temperature, and soil temperature were collected at a location about 1 km from the experimental site used for model calibration and testing. Daily rainfall and daily pan evaporation data were used as intput into the model. The model calculates the evapotranspiration by the method of Shaw (1963). For some years, the pan evaporation data were not available for the complete months of April and November. Therefore, a fixed amount of evapotranspiration (0.035 cm/day for April and 0.07 cm/day for November) was used for part of these two months.

Crop Data

The planting and harvesting days for the crops, distribution of root system as a function of time, the crop development ratios, and crop stress factors as a function of soil moisture are required as inputs for the model. May 15 and May 22 were taken as planting days and October 15 and September 22 were taken as harvesting days for corn and soybeans, respectively. Ratios of evapotranspiration of crops to open-pan evaporation are given in Fig. 2 (R. H. Shaw, Agronomy Dept., ISU, unpublished paper, 1981). Data on moisture-stress factors and distribution of root system were taken from Shaw (1963) and are given in Figs. 3 and 4.

Corn and soybean growth-rate functions used in the model are simular to the one used by Duffy et al. (1975). Table 1 shows the distribution of root system of corn as a function of day of the year.

Soil-Moisture Data

The data on initial soil water content, field capacity, wilting point, diffusivity, unsaturated and saturated hydraulic conductivities, and initial water-table depth are needed as inputs for the model. Data on field capacity and wilting point were taken from Shaw et al. (1972). Other soil moisture data were taken from the literature. The saturated hydraulic conductivity was estimated on the basis of model calibration.

Unsaturated Flow

The unsaturated soil water flow is assumed to move only in the vertical direction. The following equation is used [Beek and Frissel, 1983].

$$v_i = -D_i(\theta)\frac{d\theta i}{dx} + K_i(\theta) \quad [1]$$

where v_i is flow rate of water, $D_i(\theta)$ is the diffusivity of

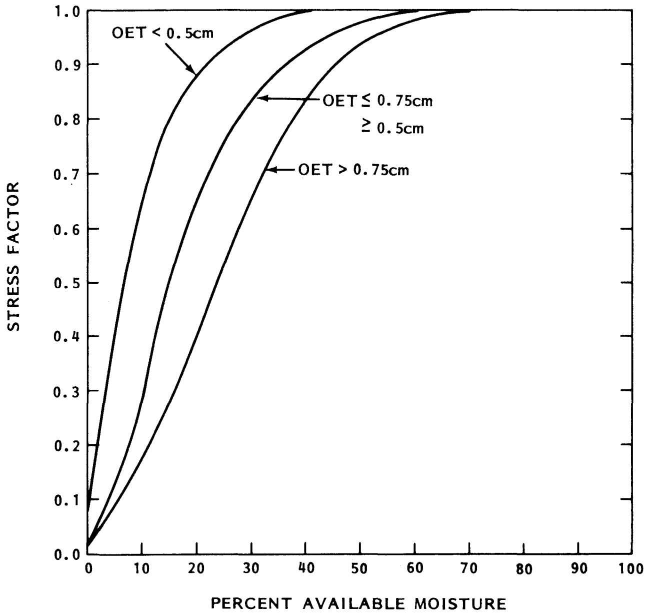

Fig. 3—Relative evapotranspiration rates for different atmospheric demand rates prior to August 1. Stress factor is equal to the ratio of actual evapotranspiration to open-pan evaporation (OET).

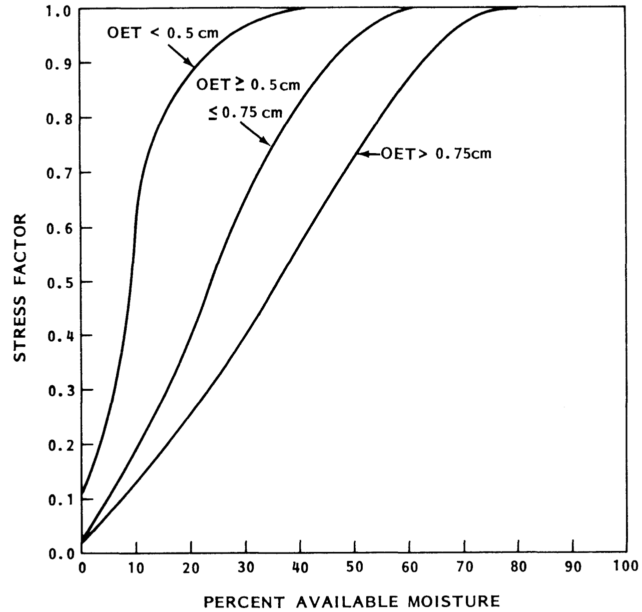

Fig. 4—Relative evapotranspiration rates for different atmospheric demand rates after August 1. Stress factor is equal to the ratio of actual evapotranspiration to open-pan evaporation (OET).

TABLE 1. DISTRIBUTION OF ROOT SYSTEM OF CORN AND PERCENTAGE OF ET THAT COMES FROM EACH LAYER OF SOIL AS USED IN THE MODEL

Soil depth, cm	Percent of ET that comes from each layer									
	Day of the year									
	135-158	158-164	164-177	177-184	184-191	191-199	199-206	206-213	213-265	265-
0-15	100	50	40	34	30	30	30	30	30	30
15-30		50	40	34	30	30	30	30	30	30
30-45			20	16	20	10	10	7.5	7.5	5
45-60				16	10	10	7.5	7.5	7.5	5
60-75					10	10	7.5	7.5	5.0	5
75-90						10	7.5	7.5	5.0	5
90-105							7.5	5.0	5.0	5
105-120								3.0	5.0	5
120-135								2.0	3.0	5
135-150									2.0	5

soil layer i, $K_i(\theta)$ is the conductivity of soil layer i, $(\theta)_i$ is water content of soil in layer i, and x is the soil depth. The relationships between $D_i(\theta)$ and $K_i(\theta)$ are functions of moisture content and, indirectly, functions of depth. The values of conductivities used in the model were taken from Campbell and Johnson (1975), and values of diffusivities were taken from Staple (1969) for Webster silty-clay-loam soil. The rate of flow (infiltration) into the first layer, v_1, is the precipitation on that day less surface runoff.

Surface Runoff

Surface runoff is calculated by the Mockus (1972) curve number technique. This method was selected because required inputs are generally available and it relates runoff to soil type, land use, and management practices. Runoff is predicted for daily rainfall by using the SCS equation.

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \quad [2]$$

where Q is the daily runoff, P is the daily rainfall, and S is a retention parameter related to soil water content with the equation:

$$S = \left(\frac{UL - SM}{UL}\right) Smx \quad [3]$$

where SM is the soil water content in the root zone, UL is the upper limit of soil water storage in the root zone, and Smx is the maximum value of S which is estimated by using equation:

$$Smx = \frac{1000}{CN_I} - 10 \quad [4]$$

where CN_I is the curve number for the moisture condition I CN. An estimate of the moisture condition II CN was obtained as determined by Mockus (1972).

Saturated Flow

Two kinds of saturated flows have been assumed in this model, one flowing into the tile and, the second, flowing vertically down beneath the tile as deep percolation, although actually the deep percolation flow can be lateral as well as vertical (Skaggs and Gilliam, 1981). Tile flow is calculated according to the Hooghoudt's steady-state equation modified by Bouwer

TABLE 2. SUMMARY OF INPUT PARAMETERS FOR THE MODEL

Parameters	Calibrated or known value
Drain spacing	3658 cm
Drain depth	120 cm
Depth from drain to impermeable layer*	270 cm
Saturated hydraulic conductivity*	15 cm/day
Thickness of nearly impermeable layer*	2000 cm
Curve Number II	81
Vertical hydraulic conductivity of impermeable* layer*	0.10 cm/day
Hydraulic head in groundwater aquifer*	1950 cm
Drainable porosity	0.07
Percent depressional area near the tile*	0.03
Labyrinth factor used to compute nitrate flow by diffusion*	0.8
Diffusion coefficient of nitrate in water*	1.0 cm^2 /day
Dispersion coefficient of nitrate in water*	4 cm
Rate of nitrification of fertilizer	80% within 20 days 20% after 20 days
Rate of denitrification*	0.003 mg N/cm^2 /day
Rate of mineralization	4/15 to 6/3 0.003 mg N/cm^2 /day 4/1 to 4/14 and 6/4 to 10/31 0.00115 mg N/cm^2 /day

* Parameters that were calibrated

and van Shilfgaarde (1963). Deep percolation has been considered to occur in the model through the nearly impermeable layer in the vertical direction only and was estimated by an application of Darcy's law as given by equation:

$$V_S = K_V \frac{H - (T + d + m)}{T} \quad [5]$$

where V_s is the vertical seepage, K_v is the hydraulic conductivity of the nearly impermeable layer of thickness T, H is the hydraulic head of the groundwater aquifer, d is the distance between the tile and impermeable layer, and m is the mean water-table elevation above the drains. The various drainage parameters used in the model are summarized in Table 2.

Water Content

The quantity of water in the soil is expressed on a volume basis. In the model, the water content can vary between a wilting point (15-bar water content) and saturation point. The water content above the water table is assumed to vary from 15-bar to 1/3-bar water content. The water table is assumed to move in discrete steps of 15 cm (from the top of one layer to the top of adjacent layer above or below) except below 150 cm where it can vary continuously. The values for the 15-bar and 1/3-bar moisture contents were taken from Shaw et al. (1972).

Nitrogen Inputs

Fertilizer application time and rate data are needed as input to the model April 1 of each year is set as the starting day for the model simulation; therefore, the beginning nitrate concentrations for all the soil layers considered in the model are needed as inputs on this date.

NITROGEN TRANSFORMATIONS, TRANSPORT AND UPTAKE

Transformations

The microbiological nitrogen transformations considered in this model are nitrification of NH_4-N to NO_3-N, mineralization of organic-N to NH_4-N, immobilization of NH_4-N and NO_3-N as organic-N, and denitrification of NO_3-N to gaseous forms. In the model, 80% of the fertilizer nitrogen is considered to nitrify linearly within 15 days, and the remaining fertilizer is assumed to nitrify at a very slow rate of 0.005 mg N/day/cm^2 until all is used (Feigin et al., 1974). A total of about 70 kg N/ha annually is used as input in the top 30 cm of the soil profile because of mineralization, which seems to be a reasonable amount (Bartholomew and Clark, 1965) and comparable to one used by Watts and Martin (1981). If nitrate is present and the soil moisture exceeds field capacity in the top 30 cm of the soil, the denitrification rate (based on trial and error estimation) is assumed to be equal to 0.003 mg N/cm^2/day; otherwise, it is zero.

Nitrogen Transport

In the model, the movement of nitrogen in the soil is considered only when it is in the nitrate form since nitrate is soluble and negatively charged. Other forms of nitrogen is not considered, although, soluble organic nitrogen movement is possible (Bottcher et al., 1981). Beek and Frissel (1973) considered that nitrate flow in the soil is caused by mass transport, diffusion, and dispersion. They represented these nitrogen movements as follows:

Diffusion is a function of the concentration gradient of nitrate between layers and was described by the following relationship.

$$FLRTD = DIF * Tort * \frac{[(\theta_{i-1} + \theta_i)]}{2} \frac{[(NO_3 - N)_{i-1} - (NO_3 - N)_i]}{\ell}$$

where

FLRTD = flow rate of nitrate due to diffusion, mg N/day/cm^2
DIF = diffusion coefficient for nitrate in water, cm^2/day
TORT = toruosity factor (0.8]
$(NO_3\text{-}N)_i$ = nitrate concentration in layer i, mg N/cm^3
ℓ = thickness of layer i, cm

The flow rate of nitrates due to dispersion is proportional to the absolute flow rate of water and concentration gradient according to the following equation:

$$FLRTS = v_1 * DISP * [(NO_3\text{-}N_{i-1})\text{-}(NO_3\text{-}N)_i]/\ell$$

where

FLRTS = flow rate of nitrate due to dispersion, mg N/day/cm^2

v_i = absolute value of the water flow rate in layer i, cm/day

DISP = dispersion coefficient (0.7 cm for coarse sand and 7 cm for loess)

Water flows from layer to layer and carries nitrate with it. However, water flowing through macropores may mix incompletely with the nitrate in a given layer, therefore a weighting factor is used. Mass flow is represented in the model by the following relationship.

$$MFL = v_i * (NO_3\text{-}N)_{i+1} * WF$$

where

v_i = water flow rate, cm/day

WF = weighting factor, $\leqslant 1$

The total flux of nitrate for each layer is the sum of the flow rates due to mass flow of water, diffusion, and dispersion.

Nitrogen Uptake

It is assumed that nitrate is taken up by the crop with water that is eventually transpired. Thus, the nitrogen uptake by plants is calculated as:

$$(DNTUP)_i = (ET)_i * (NO_3\text{-}N) * (F)_i$$

where

$(DNTUP)_i$ = rate of nitrogen uptake from layer i, mg N/cm^2

$(F)_i$ = a factor for approximating the amount of transpiration from layer i

$(ET)_i$ = evapotranspiration from layer i

Part of the nitrogen uptake in soybeans comes from nitrogen fixed from the atmosphere. The rate of nitrogen fixation is to be proportional to the rate of root growth as follows:

$$(NITUP)_s = DRTGR * k_f$$

where

$(NITUP)_s$ = nitrogen fixation rate, mg N/day/cm^2

k_f = constant (0.011 is used as a trial value)

DRTGR = root growth rate, cm/day

MODEL CALIBRATION AND TESTING

Experimental Site

The model was calibrated and tested by using data from field experiments conducted at the Iowa State University Agronomy and Agricultural Engineering Research Center near Ames, Iowa.

The experimental study site was on a Clarion-Webster soil with a maximum slope of 2%. The drainage system consisted of subsurface 10.2-cm diameter drains spaced 36.6 m apart. The observations were made from one plot having an area of about 0.42 ha. Surface drainage was only fair, with some shallow depressions near the tile.

To provide access to the tile line, a sump 152 cm deep was placed to intercept the drain tile, which was at a depth of 120 cm. A float-activated stage recorder was installed in conjuntion with a calibrated flume to provide the time depth records. The data on daily tile flow rate and the concentrations of nitrate in the tile effluent (sampled from daily to once every three days) were collected for 9 years (1970-1978). The details and results of the field experiments have been reported by Baker et al. (1975), and Baker and Johnson (1981). Because of frozen conditions, little tile flow occurred during December, January, February and most of March. Therefore, evaluations were based on data from the period April 1 to November 30. Sampling by Baker† provided seven sets of field data on profile nitrate concentrations for the years from 1974 to 1978. There data were used for initializing the profile nitrate concentrations.

Calibration

The hydrology component of the model was calibrated by using the tile flow data from the year 1974, a normal year when there was sustained tile flow. The nitrogen component was calibrated by using the data for 1976 as the profile nitrate concentration data were available for this year to meet the model input needs. The criterion used for calibrating the model was to minimize the difference between the measured and predicted cumulative tile flow from April 1 to November 30. A trial-and-error procedure was used to define the parameter. Each parameter was varied within a reasonable range while all other parameters were kept constant. This procedure was continued until an acceptable value for the parameter was obtained. A list of various calibrated parameters is given in Table 2.

Fig. 5 shows the daily measured and predicted values of tile flow from April 1 to November 30 for the 1974 calibration year. There is generally good conformity between measured and predicted values although discrepancies exist for some days. The model predicted peak flows on the same day that they occurred and also predicted zero flow within a few days of when the tile stopped flowing in July. When the tile started flowing again on October 31, the model also predicted tile flow on the same day. Even though the soil is a very complex, heterogeneous porous media, the model predictions are encouraging. Final calibration values used resulted in the difference between total measured and predicted tile water flows being 6%. Although further calibration could have reduced this difference, this was not deemed worthwhile as the errors in the physical flow measurements are in this range.

Testing

To test the ability of the model to predict the system response, the model was tested with data from 1970 to 1978, excluding 1974, the calibration year and 1971 and 1977 when oats were grown because crop development ratios are not available for oats.

The daily observed and predicted data from April 1 to November 30 for 1973 (wet year), 1976 (dry year) and 1978 (normal year) are shown in Figs. 6 through 8. These figures show that predicted values of tile flows and their nitrate concentrations compare reasonable well with the measured values on a daily basis, although discrepancies exist for some periods. Discrepancies between the measured and predicted values may be due in part to incorrect estimation of evapotranspiration in that period, errors in the assumed values for soil properties for the soil in the field, and lack of good information of intitial

†Data from the file of J. L. Baker, Agricultural Engineering Dept., Iowa State University, Ames—September, 1979.

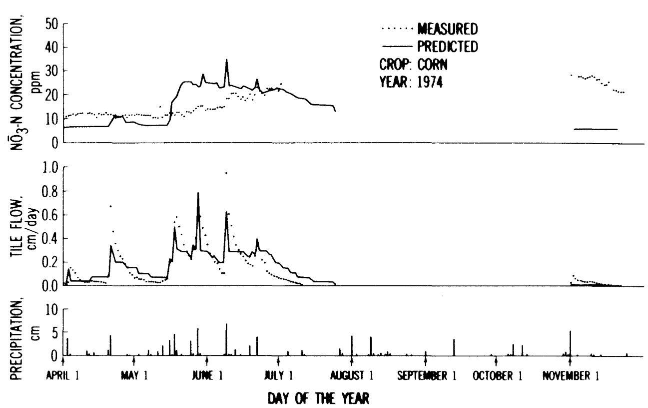

Fig. 5—Precipitation, measured and predicted tile flow and NO_3-N concentrations of the tile water for 1974.

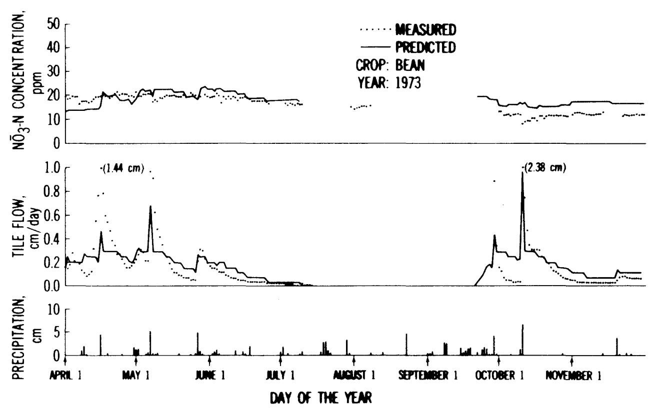

Fig. 6—Precipitation, measured and predicted tile flows and NO_3-N concentrations of the tile water for 1973 (wet year).

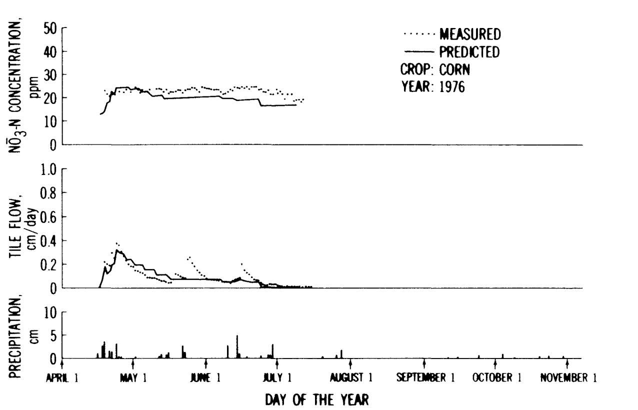

Fig. 7—Precipitation, measured and predicted tile flows and NO_3-N concentrations of the tile water for 1976 (wet year).

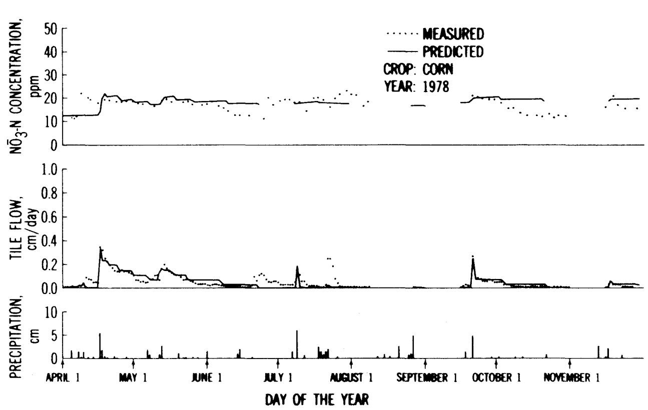

Fig. 8—Precipitation, measured and predicted tile flows and NO_3-N concentrations of the tile water for 1978 (normal year).

TABLE 3. COMPARISON OF MEASURED AND PREDICTED ANNUAL TILE FLOW AND NITRATE DISCHARGE FOR 7 YEARS

				TILE FLOW			NITROGEN LOSS		
Year	Crop	Fertilizer application rate, kg/ha	Precipitation, cm	Measured, cm	Predicted, cm	Error, %	Measured, kg/ha	Predicted, kg/ha	Error, %
1970	corn	112	84.50	9.37	10.77	+14.9	14.9	18.5	+24.2
1972	corn	112	83.16	17.03	15.80	- 7.2	40.9	29.9	-26.9
1973	soybean	0	93.01	30.31	31.33	+ 3.4	50.0	57.7	+15.4
1974*	corn	100	86.21	19.21	20.28	+ 5.6	30.1	38.5	-18.2
1975	soybean	0	64.01	15.92	15.27	- 4.1	38.5	31.9	-18.2
1976	corn	90	43.18	8.10	7.62	- 5.9	20.9	16.4	-21.5
1978	corn	90	83.49	11.07	10.00	- 9.7	20.6	19.0	+ 7.7
Average		72	76.79	15.86	15.87	+ 0.1	30.84	30.47	- 1.2

* Calibration year.
1971 and 1977 planted to oats

conditions, all to which the model is quite sensitive.

The comparisons of the measured and predicted tile flows and total nitrogen losses for various years are given in Table 3. These comparisons indicate that predicted annual tile flows are within 15% of the measured flows. The agreement between predicted and measured flows is very good for wet and dry years. When we compare the averages of measured and predicted flows for all the 7 years, the agreement looks excellent.

The comparison between the predicted and measured annual NO_3-N discharges indicate that predicted were always within 33%. When discharges were averaged over the 7-year period, an error of only 1.2% was observed between measured and simulated values. From Table 3, it is also quite evident that an equivalent of 42% of the applied nitrogen was discharged through tile drainage on an annual basis. The largest nitrogen discharge was observed in 1973, which was the wettest year.

Most of the representations of processes used in the nitrogen simulations were empirical; errors in these representations could be responsible for some of the discrepancies in the predicted values. There were discrepancies each year at the beginning of the simulation process that resulted from lack of field data for the soil profile initialization. It is also reccognized that true steady-state conditions seldom exist under field situations. Year-to-year environmental variations occur, but these tend to cancel out in the long term. In spite of steady-state conditions assumed within each time span (1 day in this model), the model has the capability to reasonably estimate the long-term nitrogen loss with tile drainage water.

SUMMARY

A nitrogen simulation model was developed and evaluated by use of field data. The model predictions agreed reasonably well with the measured values of tile drainage water and nitrate losses in the tile effluent. The difference between measured and predicted values indicates that the hydrology of the area is not completely understood in the present form of model and/or that some of the soil moisture properties estimated do not reflect the actual field conditions. But on the whole, the model provides satisfactory simulation results.

Experimentally determined soil-water properties would improve hydrologic predictions. Hydrologic activity in levels below the tile needs to be studied to obtain better simulation results. The processes of nitrification, mineralization, nitrogen uptake, and denitrification need better representation.

Measured as well as predicted data indicate that an equivalent of nearly half of the applied fertilizer nitrogen is being discharged with tile drainage water. As farmers decide to apply more fertilizers to obtain higher yields, large leaching losses of nitrates can be expected to occur, an economic as well as an environmental concern. Models such as that discussed here can help in the development of improved nitrogen management to decrease losses.

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