Simulation of nitrate loss in tile flow for central Canadian conditions

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McLaughlin, N.A., Rudra, R.P. and Ogilvie, J.R. 2006. **Simulation of nitrate loss in tile flow for central Canadian conditions**. Canadian Biosystems Engineering/Le génie des biosystèmes au Canada **48**: 1.41 - 1.54. The EPIC model (version 5300) was applied to three central Canadian locations characterized by different soil types, fertilization regimes, cultural practices, and climatic conditions to evaluate its versatility and ability to accurately simulate tile flows and nitrate loads. The model was calibrated using data at one site and validated using observed data from all three sites. The simulation results indicate that the EPIC model performs well in quantifying various components of the water and nitrogen budgets over long term periods (several years). However, the EPIC simulations are less accurate for short term periods (months) and during peak flow events. The major limitations in applying the EPIC model for short term periods and peak events were the daily time step and its limited capacity to properly represent seasonal variations in soil hydraulic properties and preferential flow conditions. The problem with the EPIC nitrate load prediction is its limited capability to predict temporal variability of nitrogen cycling processes, which may be linked to the deficiencies in simulation of changes in the soil moisture conditions. **Keywords:** nitrate, tile drainage, simulation, water quality, pollution, models.

Le modèle EPIC (version 5300) a été utilisé en considérant trois régions du centre canadien caractérisées par différents types de sol, plans de fertilisation, pratiques culturales et conditions climatiques dans le but d'évaluer sa flexibilité ainsi que sa capacité à simuler de manière précise le drainage sous-terrain et les charges en nitrate. Le modèle a d'abord été calibré en utilisant des données recueillies sur un site avant d'être validé en utilisant les données observées sur les trois sites. Les résultats de simulation indiquent que le modèle EPIC permet d'obtenir de bons résultats quantitatifs pour différentes composantes hydriques et du bilan d'azote sur de longues périodes de temps (plusieurs années). Cependant, les simulations EPIC sont moins précises sur de courtes périodes (mois) de même que durant les périodes de forts débits. Les principales limites de l'utilisation du modèle EPIC pour les périodes de courte durée et les évènements à forts débits venaient de l'incrément de temps d'un jour et de ses capacités limitées à représenter correctement les variations saisonnières des propriétés hydraulique du sol et les conditions d'écoulement préférentiel. Les problèmes dans les prédictions de la charge de nitrate d'EPIC sont ses capacités limitées à prédire la variabilité temporelle des processus du cycle de l'azote, ce qui peut être lié à l'incapacité durant la simulation à changer les conditions de teneur en eau du sol. **Mots clés**: nitrate, drainage souterrain, simulation, qualité de l'eau, pollution, modèles

INTRODUCTION

There have been many cases in Ontario where groundwater and surface water pollution were linked to excessive manure and litter disposal (Rudolph et al. 1998; Gillham 1991; Frank et al. 1991). Watershed studies over the last few decades have also indicated a steady increase in nitrate concentrations in Ontario surface water since the 1960's, of which the highest levels have occurred in watersheds under agricultural land use (Fleming and Fraser 1999). A survey of 183 wells in Ontario during 1986-1987 showed that 15% of the wells exceeded the drinking water standard of 10 mg/L of NO_3-N (Frank et al. 1991). Goss et al. (1998) observed that at least 37% of domestic wells in Ontario did not meet standard levels for one type of contaminant (coliform, nitrate, or herbicides).

Nitrogen transport in the soil water system depends on both nitrogen and soil water dynamics. Field-scale water balance and water quality models have proven useful tools for agricultural management (Ramanarayanan et al. 1997). The EPIC (Erosion Productivity Impact Calculator) model (Williams 1990) has been previously used as a manure management tool (Ramanarayanan et al. 1997; Edwards et al. 1994). Due to ease of adaptation to different environmental conditions, the EPIC model has also been applied to various Canadian conditions to simulate crop yield, soil erosion, hydrological processes, and nutrient transport (Roloff et al. 1998a, 1988b, 1988c; Purveen et al 1997; Beckie et al. 1995; Touré et al. 1994; Moulin and Beckie 1993). In particular, some Canadian studies have investigated EPIC's ability to simulate soil water and nitrogen dynamics. Beckie et al. (1995) and Roloff et al. (1998a) evaluated EPIC's ability to simulate soil N concentrations and soil water content for long-term spring wheat rotations in semi-arid prairie Canadian regions. Both studies found that EPIC overestimated soil water content in the soil profile. In terms of soil NO_3-N concentrations, Beckie et al. (1995) found that EPIC simulation results were reasonably accurate, while Roloff et al. (1998a) found that EPIC generally underestimated soil NO_3-N concentrations. In another study, Roloff et al. (1998b) evaluated the sensitivity of EPIC's output functions in central Canadian conditions and found that leached NO_3-N was EPIC's most sensitive output function and exhibited the highest variability. Few studies have evaluated EPIC's ability to simulate nitrogen losses in tile flow. Chung et al. (2001, 2002) evaluated EPIC's tile flow and NO_3-N loss predictions for different cropping systems in Minnesota and Iowa, respectively. Both studies found that although long-term water and NO_3-N leaching trends were acceptable, EPIC did not accurately simulate tile flow and NO_3-N losses during peak events. Due to limited investigations in Canada, the objective of this study was to evaluate the performance of the EPIC model in predicting nitrate movement in tile flow for Central Canadian conditions and to determine its potential uses as a nutrient management tool.

Table 1a. Summary of the Lennoxville site field data: General information.

Site location	Lennoxville, Québec
Plot size	45 m^2 *
Slope	5%
Study period	1990-1992
Dominant soil type	Coaticook silty loam (*Typic Fragiaquept*)
Cropping management	Continuous silage corn cropping

*Plots were hydrologically isolated from one another, including both surface water and groundwater.

Table 1b. Summary of the Lennoxville site field data: Precipitation.

Year	Total annual (mm)	Percent of long term mean annual (%)
1990	1184	114
1991	1023	99
1992	1056	102

Table 1c. Summary of Lennoxville site field data: Soil characteristics.

Parameter	Soil depth (mm)			
	0 - 200	200 - 380	380 - 660	660 - 1200
Hydrologic group	C			
Sand (%)	3	36	37	15
Silt (%)	80	45	40	40
Organic matter (%)	5	0 - 1	0 - 1	0 - 1
Bulk density (Mg/m^3)	1.10 - 1.54	1.55 - 1.65	1.50 - 1.65	1.50 - 2.01
pH	4.8	5	5.8	6.6
Estimated field capacity (m^3/m^3)	0.30 - 0.40			
Estimated wilting point (m^3/m^3)	0.05 - 0. 15			

Table 1d. Summary of the Lennoxville site field data: Fertilizing practices.

Fertilizer types	Hog manure and inorganic fertilizer (NH_4NO_3)
Timing of application	(i) Hog manure: • Spring application of hog manure (HS): May 21-25 (at planting) • Fall application of hog manure (HF): October 1-30 (ii) Inorganic fertilizer (IF): May 21-25 (at planting)
Treatment application rates	(i) IF: 180 kg N/ha (ii) IF-2HS: 540 kg/ha (iii) IF-2HF: 540 kg/ha (iv) IF-HS-HF: 540kg/ha
Crop N requirements	180 kg N/ha
Application depth	• Hog slurry: surface applied • NH_4NO_3: incorporated to 200 mm

Table 1e. Summary of the Lennoxville site field data: Collected data.

Runoff	• Daily flow • Nitrogen loads
Tile flow	• Daily flow • Nitrogen loads

MATERIALS and METHODS

Field site description

The EPIC model (version 5300) was evaluated using field data from three experimental sites in central Canada: a site in Lennoxville, Québec, a site in Ottawa, Ontario, and a site in Woodslee, Ontario. The details of the studies for the Lennoxville site are provided by Gangbazo et al. (1999) and G. Gangbazo (Researcher, Ministère de l'environnement et de la faune, Québec, QC) for the Ottawa site by Patni et al. (1996, 1998), and for the Woodslee site by Tan et al. (1993), Ng et al. (2000) and C.S. Tan (Researcher, Greenhouse and Processing Crops Research Centre, Agriculture and Agri-Food Canada, Harrow, ON). A brief description of these experiments is presented in Tables 1a-e, 2a-e, and 3a-e.

The EPIC Model

An illustration of the nitrogen fate and transport system simulated within the EPIC model is presented in Fig. 1. EPIC simulations are based on a daily time step and consider different cultural practices, soil management, and fertilizer application on nitrogen fate and transport. EPIC's hydrological partition at the soil surface is based on the SCS Curve Number technique. Daily percolation through the soil profile is based on a piston flow approach:

$$Q_i = \left(SW_i - FC_i\right)\left(1 - e^{-\frac{\Delta t}{TT_i}}\right) \qquad (1)$$

where:

Q_i = percolation rate for layer i (mm/d),
SW_i = soil water content at start of Δt time interval (24 h),
FC_i = field capacity of soil layer i (mm), and
TT_{ti} = travel time through the layer i (d).

EPIC simulates lateral flow simultaneously with daily percolation using Eq. 2.

$$QR_i = \left(SW_i - FC_i\right)\left(1 - e^{-\frac{\Delta t}{TT_{Ri}}}\right) \qquad (2)$$

where:

QR_i = lateral flow rate for soil layer i (mm/d), and
TT_{Ri} = lateral flow travel time (d).

Table 2a. Summary of the Ottawa site field data: General information.

Site location	Ottawa, Ontario
Plot size	450 m x 315 m (14.2 ha)*
Slope	0.2%
Study period	1990-1994
Dominant soil type	Dalhousie loam (*Typic Haplaquent*)
Cropping management	Continuous silage corn cropping under no tillage (NT) and conventional tillage (CT) regimes

*Plots were hydrologically isolated from one another, including both surface water and groundwater.

Table 2b. Summary of the Ottawa site field data: Precipitation.

Year	Total annual (mm)	Percent of long term mean annual (%)
1991	810	93.8
1992	907	105
1993	1020	118
1994	907	105

Table 2c. Summary of Ottawa site field data: Soil characteristics.

Parameter*	Soil depth (mm) 0 - 100	100 - 350	350 - 650	650 - 1000
Hydrologic group	C			
Sand (%)	45.0 - 74.8	39.2 - 69.4	12.8 - 51.2	13.6 - 22.5
Silt (%)	18.5 - 37.5	22.8 - 45.2	33.2 - 64.5	52.3 - 60.4
Organic matter (%)	1.40 - 3.43	1.32 - 2.91	1.93 - 2.64	2.41 - 2.77
Bulk density (Mg/m^3)	1.30 - 1.36	1.35 - 1.44	1.25 - 1.33	1.23 - 1.30
pH	5.1 - 5.7	5.4 - 5.9	5.5 - 5.7	5.8 - 6.0
Estimated field capacity (m^3/m^3)	0.25 - 0.37	0.20 - 0.39	0.37 - 0.46	0.43 - 0.44
Estimated wilting point (m^3/m^3)	0.18 - 0.27	0.13 - 0.34	0.30 - 0.38	0.38 - 0.39

*The range of values represent the range in values measured in different plots.

Table 2d. Summary of the Ottawa site field data: Fertilizing practices.

Fertilizer types	Starter fertilizer (N P K: 8-32-16); anhydrous ammonia (NH_3)
Timing of application	(i) Starter fertilizer: at planting (May 5 - 8) (ii) Anhydrous ammonia: at 6th leaf stage (June 13 - 25)
Treatment application rates	(i) Starter fertilizer: 9 - 12 kg N/ha (depending on initial soil N) (ii) Anhydrous ammonia: 100 - 140 kg N/ha (depending on initial soil N)
Crop N requirements	130 kg N/ha
Application depth	(i) Starter fertilizer was banded during seeding: 200 mm (ii) Anhydrous ammonia: injection to 200 mm

Table 2e. Summary of the Ottawa site field data: Collected data.

Tile flow	• Daily flow • Nitrogen loads

Finally, tile drainage is simulated in the tile drained soil layer as:

$$RT = \frac{SW - WP}{DRT} \tag{3}$$

where:

RT = tile flow (mm/d),
SW = soil water content in soil drainage layer (mm),
WP = soil water content at wilting point of soil drainage layer (mm), and
DRT = drainage retention time (d).

This algorithm assumes that all available water (SW - WP) is drained through the drain tile over a period of DRT days.

NO_3-N and sediment-bound nitrogen are transported with runoff, while NO_3-N is also leached with percolating water. Nitrogen transformations (denitrification, mineralization, volatilization, immobilization, nitrogen uptake, fixation) are also simulated continuously within the soil matrix. More detailed description of EPIC's algorithms are presented by Williams (1990).

Input parameters for the EPIC Model

The data required for the EPIC input files are grouped into four categories: (i) field description and soil data, (ii) agronomic/management data, (iii) climatic data, and (iv) computational options. A detailed description of these input parameter categories has been given by Sharpley and Williams (1990).

The soil is characterized for each soil layer based on field capacity, permanent wilting point, bulk density, saturated hydraulic conductivity, organic matter content, percent sand and clay content, soil pH, and initial crop residue.

The agronomic/management practices are organized within a schedule of events and include cropping practices (i.e., planting, harvest), fertilization practices, change in curve number, and tillage practices. The potential heat unit (PHU) parameter within the cropping practice module used to describe plant uptake is considered to be one of the most sensitive variables in terms of crop yield and nitrogen leaching (Roloff et al. 1998b) and requires local adjustment (Williams et al. 1989).

Table 3a. Summary of the Woodslee site field data: General information.

Site location	Whelan Experimental Farm, Woodslee, Ontario
Plot size	15 m x 67 m (1005 m^2)*
Slope	< 1%
Study period	1992-1994
Dominant soil type	Brookston clay loam (*Typic Argiaquoll*)
Cropping management	Continuous corn cropping with the following tillage systems: (i) Moldboard plow (MP) only. (ii) Moldboard plow and ryegrass intercropping (MP-IC) (iii) Soil saver (SS): disking to 150 mm depth only, and (iv) Soil saver tillage with intercropped ryegrass (SS-IC)

*Plots were hydrologically isolated from one another, including both surface water and groundwater.

Table 3b. Summary of the Woodslee site field data: Precipitation.

Year	Total annual (mm)	Percent of long term mean annual (%)
1992	968	122
1993	688	87
1994	703	89

Table 3c. Summary of Woodslee site field data: Soil characteristics.

Parameter*	Soil depth (mm) 0 - 250	250 - 450	450 - 800	800 - 1200
Hydrologic group	D			
Sand (%)	20.1 - 49.8	22.7 - 53.0	22.0 - 59.3	19.3 - 37.9
Silt (%)	29.6 - 46.6	21.6 - 39.2	14.0 - 42.2	36.0 - 45.7
Organic matter (%)	5	2.1	0.4	0.6
Bulk density (Mg/m^3)	1.44	1.56	1.57	1.57
pH	5.7	6.8	7	7.9
Estimated field capacity (m^3/m^3)	0.34 - 0.42	0.29 - 0.40	0.36	0.35
Estimated wilting point (m^3/m^3)	0.13 - 0.22	0.12 - 0.20	0.23	0.23

*The range of values represent the range in values measured in different plots.

Table 3d. Summary of the Woodslee site field data: Fertilizing practices.

Fertilizer types	Starter fertilizer (N P K: 8-32-16); urea (NH_3)
Timing of application	(i) Starter fertilizer: at planting (May 12 - 17) (ii) Anhydrous ammonia: at 6^{th} leaf stage
Treatment application rates	(i) Starter fertilizer: 11 kg N/ha (ii) Anhydrous ammonia: 140 - 190 kg N/ha (depending on initial soil N)
Crop N requirements	190 kg N/ha
Application depth	(i) Starter fertilizer was banded during seeding: 200 mm (ii) Urea: incorporated at 200 mm

Table 3e. Summary of the Woodslee site field data: Collected data.

Tile flow	• Daily flow • Nitrogen loads

method produces better results for drier conditions (Roloff et al. 1998b).

Different researchers have debated the accuracy of the tile drainage module used to predict NO_3-N losses in tile outflow in the EPIC model. Chung et al. (2001, 2002) indicated that the simple tile drainage function used in EPIC underestimated the NO_3-N losses in the tile outflow. However, preliminary investigations in this study indicated that EPIC's drainage module is reasonable for application in central Canadian conditions. The simulated tile drainage represented 91 - 100% of the water leached below the root zone. Such high volume of drainage is reasonable for the small plots with narrow drain spacing characterized in this study.

Fertilizer application is described in terms of mineral/organic nitrogen fractions and NH_4/mineral nitrogen fraction. The S-curve volatilization rate fitting parameters can be adjusted to reflect expected volatilization rates. In addition, the tillage practices are characterized by tillage depth, mixing efficiency, and surface roughness.

The EPIC model provides a number of computational options to be suitable for local climate conditions. Various options are available for the simulation of potential evapotranspiration. The Penman method was selected for the Lennoxville and Ottawa sites because of the availability of observed climatic data and its proven applicability in a variety of climatic conditions (Benson et al. 1992). At the Woodslee site, the Baier-Robertson method was selected, because this

A detailed description on the adjustment of the values for the parameters described above are presented in McLaughlin (2001).

Temporal variations of the curve number

In central Canada, the runoff trends are seasonal. More than 70% of the streamflow and sediment loads occur during late winter and early spring (Dickinson and Green 1988). To incorporate seasonal variations in runoff and temporal changes in crop growth, the approach outlined by Rawls et al. (1980) was used to adjust the curve number by using Eq. 4.

$$CN_{normal\ peak\ growth} = 2CN_{average} - CN_{fallow} \quad (4)$$

The CN values were further adjusted based on the density of total residue, the residue on the ground and probability of

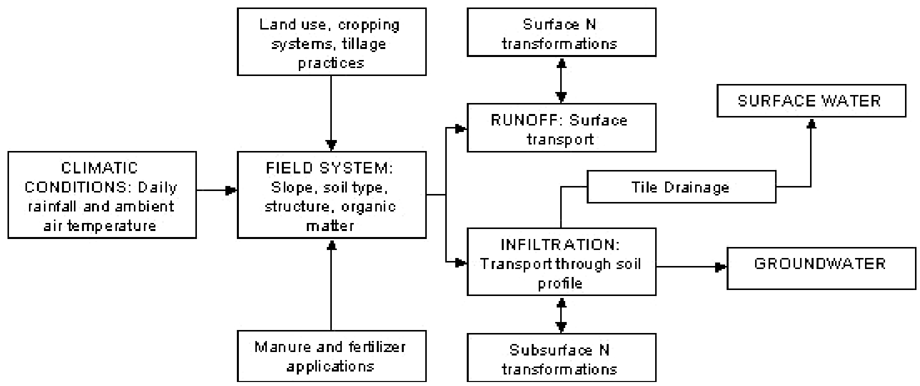

Fig. 1. Schematic representation of nitrogen fate and transport components of EPIC model.

surface crusting (Rawls et al. 1980), the change in vegetative cover (Borah and Ashraf 1990; Madramootoo and Enright 1988), tillage practices and preferential flow (Chung et al. 1999; Yoo and Rochester 1989; Rawls and Richardson 1983; Rawls et al. 1980), winter freezing (McCool et al. 1995), and changes in soil moisture conditions. By adopting these approaches, static seasonal CN values were selected for use within the EPIC model to reflect temporal changes throughout the year. This approach offered flexibility and greater control of the CN value and easier interpretation of output results.

Table 4. Magnitude of base and range values for various parameters used in the sensitivity analysis of the EPIC model.

Parameter	Base value	Range
Bulk density (Mg/m^3)	1.31	1.11 - 1.64
Crop residue (t/ha)	5	2.5 - 7.5
Curve number	80	75 - 83
Drainage duration (d)	1.5	0.4 - 2.2
Evaporation coefficient	2.5	1.5 - 12
Field capacity (m^3/m^3)	0.26	0.195 - 0.325
Wilting point (m^3/m^3)	0.11	0.099 - 0.121
Maximum root depth (m)	1.5	1.0 - 2.0
Soil organic nitrogen (g/t)	1800	1170 - 2340
Potential heat units (°C d)	2000	1600 - 2400
Saturated hydraulic conductivity (mm/h)	15.9	0.5 - 132
Slope gradient (%)	4	3 - 5
Slope length (m)	50	37.5 - 62.5
Tile depth (m)	0.87	0.65 - 1.09

Sensitivity analysis of EPIC

Identification of sensitive parameters can help reduce the efforts undertaken to apply and properly parameterize hydrologic and water quality models. Based on various sensitivity analysis studies of the EPIC model (Benson et al. 1992; Favis-Mortlock and Smith 1990; Roloff et al. 1998b), a number of hydrologic and nitrogen-transport related parameters were examined to quantify their relative sensitivity to runoff and tile-drained water quality and quantity. A list of these variables and their range of applicable values is shown in Table 4. Since the relative sensitivity of these parameters depends upon the climatic conditions and cropping practices of the site, the parameter values were tested within a specific range to best reflect the central Canadian conditions.

The approaches suggested by Cook et al. (1985), Pettapiece (1992), and Saxton et al. (1986) were used to define the ranges of bulk density, permanent wilting point, field capacity, saturated hydraulic conductivity, and organic matter content. The absolute effect of the parameter(s) was quantified by computing the change in the output function (runoff and tile flow and associated nitrate loading) with respect to the changes in the input parameter(s) value while keeping all other parameters constant.

The degree of sensitivity of the objective functions to different input parameters is summarized in Table 5. These data show that generally the curve number, bulk density, field capacity, and organic nitrogen content tend to be the most sensitive parameters.

Table 5. Degree of sensitivity of runoff, tile flow, nitrate loads in runoff, and nitrate loads in tile flow to various parameters.

Objective function	Degree of sensitivity*		
	High	Medium	Low
Runoff	(i) Curve number	(i) Field capacity	(i) Bulk density (ii) Slope gradient
Tile flows	(i) Curve number (ii) Field capacity	(i) Drainage duration	(i) Bulk density (ii) Slope gradient
Nitrate loads in runoff	(i) Curve number (ii) Bulk density	(i) Field capacity	
Nitrate loads in tile flows	(i) Bulk density (ii) Organic nitrogen	(i) Curve number	(i) Drainage duration (ii) Crop residue

*Degree sensitivity definitions (in terms of slopes of sensitivity graphs): high (slope > 0.5), medium (0.25 < slope < 0.5), low (slope < 0.25).

Calibration of EPIC

The first step in the model evaluation process is the calibration of sensitive parameters and evaluation of

Table 6. Calibrated values of most sensitive parameters.

Parameter	Range of values for different soil layers	
	Expected values	Calibrated values
Field capacity (m^3/m^3)	0.30 - 0.40	0.33 - 0.44
Wilting point (m^3/m^3)	0.05 - 0.15	0.09 - 0.15
Bulk density (Mg/m^3)	1.10 - 2.01	1.26 - 1.50
Saturated hydraulic conductivity (mm/h)	0.5 - 20	2.9 - 9.7
Drainage duration (d)	1 - 3	1
Soil organic matter (%)	1.0 - 5.0	1.0 - 5.0
Residue amount (t/ha)	0 - 0.3	0 - 0.3
Curve number	85 - 91	78 - 99

various components of water budget and nitrogen budget. The EPIC model was calibrated on one plot at the Lennoxville site using three years of data. The model was first calibrated for runoff volume and tile outflow, followed by associated nitrate loads.

Validation of EPIC

The next step in the EPIC evaluation was the validation by comparing the simulated results with the observed field measurements at Lennoxville, Ottawa, and Woodslee sites. The comparison between the simulated and observed monthly results was conducted using a statistical approach suggested by Ramanarayanan et al. (1997) and Loague and Green (1991). The statistical approaches used include mean deviation (M_d), determination coefficient (R^2), sorted predicted efficiency (E_s), and unsorted predicted efficiency (E_{NS}). Due to a small sample size of observed data, a paired t-test was also used to determine the significance of the mean deviation between the observed and predicted values. The sorted and unsorted prediction efficiencies were computed by using a relationship suggested by Nash and Suttecliffe (1970). The unsorted and sorted efficiencies can vary between $-\infty$ and 1.0, where 1.0 indicates high correspondence and values lower than zero show no correlation. The sorted efficiency indicates the model's ability to describe the range of results, whereas the unsorted efficiency indicates the closeness of the simulated values with the corresponding observed values. A detailed description of this procedure and the associated relationships are presented by McLaughlin (2001).

RESULTS and DISCUSSION

Calibration at the Lennoxville Site

The parameters identified through sensitivity analysis were adjusted to optimum values to closely match the predicted flow and nitrogen load to the corresponding observations for one plot at the Lennoxville site. Results from this analysis show that the optimum values of the adjusted parameters were generally representative of field conditions (Table 6). The curve number adjustment for the calibration exercise was elaborate due to the sensitivity of tile drainage to curve number adjustments. The calibrated monthly CN values are shown in Table 7 and generally vary between 78 and 99. CN values are generally highest during the spring season and lowest during the summer season. Most CN values are similar to those reported in a different study undertaken nearby (Madramootoo and Enright 1988); however, a value of 99 for the month of July 1990 was greater than expected. This high value is attributed to wetter than normal conditions during July 1990, as described by G. Gangbazo (Researcher, Ministère de l'environnement et de la faune, Québec, QC). The very high adjusted value of the curve number may also reflect EPIC's difficulty in properly simulating runoff from these high intensity events, due to its daily time step and its inability to properly represent soil crusting during high rainfall intensity events (Mualem et al. 1990). Following the CN assessment within EPIC, standard seasonal CN values were established for the validation exercise based on expected seasonal variations in soil moisture and cropping practices (Table 8).

Analysis of computed water budget

After completing the calibration at the Lennoxville site, the EPIC model was applied to the three locations to evaluate the annual water budget (Table 9). At the Lennoxville site, the evapotranspiration constitutes approximately 47% of the average annual precipitation, which agrees with regional climatic data (Fisheries and Environment Canada 1978). Tile flow volumes, which account for 20 - 40% of the total precipitation, are also a reasonable prediction based on local experience.

At the Ottawa site, evapotranspiration represents approximately 56% of the average annual precipitation, which agrees well with the values of 57% provided by Dickinson and Diiwu (2000) for the region. Approximately 80% of the runoff occurred during the spring months, which also agrees with the observations by N. Patni (Researcher, Agriculture and Agri-Food Canada, Argassiz, BC) at this site. The magnitude of tile flow also represents an expected portion (20-40%) of annual average precipitation.

Table 7. Calibrated CN values over the three-year period at the Lennoxville plot calibration exercise.

Year	Jan - Feb	Mar	Apr	May	PD*	Mid June	July	Aug	Mid Sept	Oct	Nov	Dec
1989											91	91
1990	92	94	82	91	90	83	99	78	82	83	82	82
1991	92	93	85	85	85	85	80	78	85	85	85	85
1992	88	94	89	90	88	85	80	78				

*Planting date

Table 8. Temporal variations in CN values for different sites at different dates.

Site	Jan 1	Mar 1	PD*	June 1	July 1	Sept 1	HD†	Nov 1 TD‡
Lennoxville	91	92	88	84	78	84	84	86
Ottawa (CT)	91	93	89	85	81	85	86	89
Ottawa (NT)	91	94	90	82	74	82	84	90
Woodslee (MP)	93	94	92	89	86	89	91	92
Woodslee (MP-IC)	93	94	91	86	81	86	88	91
Woodslee (SS)	93	94	90	87	84	87	89	90
Woodslee (SS-IC)	93	94	87	84	81	84	85	87

*Planting date; †Harvest date; ‡Tillage date

Table 9. Average annual water budgets at the Lennoxville, Ottawa, and Woodslee sites.

Site	Precipitation	Evapotrans-piration	Runoff	Deep percolation	Subsurface flows		Change in soil moisture
Lennoxville	1058.9* [100]	499 [47.1]	172 [16.1]	23.1 [2.2]	375 [35.4]		-8.1 [-0.8]
					Tile drainage	252 [23.8]	
					Other flows	123 [11.6]	
Ottawa (CT)	853.4 [100]	476.3 [55.8]	150.9 [17.7]	22.1 [2.6]	224 [26.2]		-2.4 [-0.3]
					Tile drainage	221 [25.8]	
					Other flows	3 [0.4]	
Woodslee (MP)	878.8 [100]	505.8 [57.6]	178.5 [20.3]	0.0 [0.0]	214 [24.4]		-2.3 [-0.3]
					Tile drainage	202 [23.0]	
					Other flows	12 [1.4]	

*All values in millimeters with percent of precipitation in [ ]

At the Woodslee site, evaporation was approximately 53% of the average annual precipitation, which is reasonable based on previous studies for the region (Rudra et al. 1998, 2000; OMNR 1984). The predicted subsurface flow is however low in comparison to observed flows (C.S. Tan, Researcher, Greenhouse and Processing Crops Research Centre, Agriculture and Agri-Food Canada, Harrow, ON).

Analysis of computed nitrogen budget

The average annual nitrogen budget computed for the three sites is presented in Table 10. These data show that most available nitrogen is taken up by the crops (approximately 24, 103, and 94% of total nitrogen input at the Lennoxville, Ottawa, and Woodslee sites, respectively). A substantial amount of nitrate is also lost with tile flow (approximately 19, 23, and 20% of the total nitrogen input at the Lennoxville, Ottawa and Woodslee sites, respectively).

At the Lennoxville site, the average annual plant uptake of 162 to 186 kg N/ha is slightly higher than expected (Goh and Haynes 1986). However, the elevated rate of nitrogen uptake is explained by the fact that the nitrogen application rate was three times the nitrogen requirements for this treatment (Gangbazo et al. 1999). The increase in soil nitrogen was substantial (increasing on average by 65 kg/ha per year). This type of increase is consistent with similar studies where high rates of nitrogen were used (McAllister 1977; Boschi et al. 1977; Catroux 1981). The predicted rates of gaseous nitrogen losses (volatilization and denitrification) are also reasonable with respect to the literature values (Thompson et al. 1987; Gordon et al. 1988; Pain et al. 1989; Webster and Goulding 1989; Loro et al. 1997). Sediment-bound nitrogen loss was also representative of field measurements (Gangbazo et al. 1992).

At the Ottawa site, the annual average plant uptake of 144 kg N/ha is appropriate (Goh and Haynes 1986). Average denitrification losses of 11 kg N/ha is comparable to observations made by Scharf and Alley (1988). Volatilization rates of 7.5% of total nitrogen input (or 5.7% of applied nitrogen) agrees well with the expected rates from anhydrous ammonia.

At the Woodslee site, plant uptake is also the largest portion of the annual nitrogen budget and represents an annual average of 162 kg N/ha. This amount is reasonable for the region and the method of fertilization (OMAFRA 1994). Simulated nitrogen volatilization rates constitute approximately 26% of total nitrogen input (or approximately 27% of the surface-applied urea nitrogen). These rates are appropriate for

Table 10. Average annual nitrogen budgets at the Lennoxville, Ottawa, and Woodslee sites.

Site	N application rates	Plant uptake	Change in soil N	Denitrification losses	Nitrate in percolation	Nitrate in subsurface flow		Ammonia volatilization	Nitrate in runoff	Sediment N loss
						186 [26.1]				
Lennoxville	729.5* [102]	174 [24.4]	153.4 [21.5]	101.3 [14.2]	6.3 [0.9]	Tile drain N	136 [19.0]	73.8 [10.3]	3.8 [0.5]	15.1 [2.1]
						Other flow N	50.4 [7.0]			
						33.4 [23.8]				
Ottawa (CT)	131.5 [93.7]	144 [102.6]	-61.7 [-43.9]	10.7 [7.6]	3.3 [2.4]	Tile drain N	32.9 [23.4]	7.5 [5.3]	1.5 [1.1]	1.6 [1.1]
						Other flow N	0.5 [0.4]			
						35.3 [20.5]				
Woodslee (MP)	164.3 [95.6]	162 [94.3]	-80.2 [-46.7]	6.4 [3.7]	0.0 [0.0]	Tile drain N	33.8 [19.7]	45.1 [26.3]	2.3 [1.3]	0.9 [0.5]
						Other flow N	1.5 [0.9]			

*All values in kilograms nitrogen per hectare with percent of total nitrogen input in [ ]

soil-surface applied urea given soil surface conditions (Sommer and Jensen 1994; Fox et al. 1996). Denitrification rates of 4% of the total nitrogen input are also appropriate for surface-applied urea (Scharf and Alley 1988).

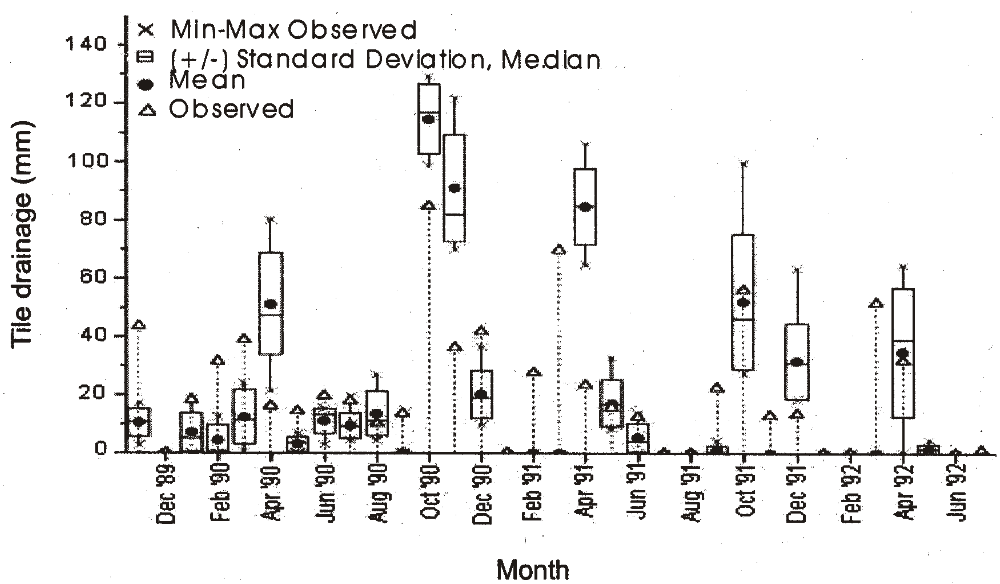

Fig. 2. Comparison of monthly observed and simulated amount of tile flow at the Lennoxville site.

Validation of EPIC

Lennoxville Site Figure 2 presents the comparison of monthly observed and simulated tile outflows using the calibrated parameters and the CN values presented in Table 7. These data show that observed and simulated tile flows follow similar trends, but there is a substantial difference in the flow volumes during the spring and fall seasons. Figure 3 shows the comparison of observed and simulated nitrogen loads in tile flow. The variability in predicted and observed nitrate loads is similar to the variability in predicted tile flows, which indicates that the hydrology dominates nitrate load predictions.

The results of the statistical analysis for the magnitude of tile flows and nitrogen loads in the tile outflows for this site are presented in Table 11. The high sorted efficiency values indicate that the EPIC model generally performed well in simulating the range of tile flow volume and

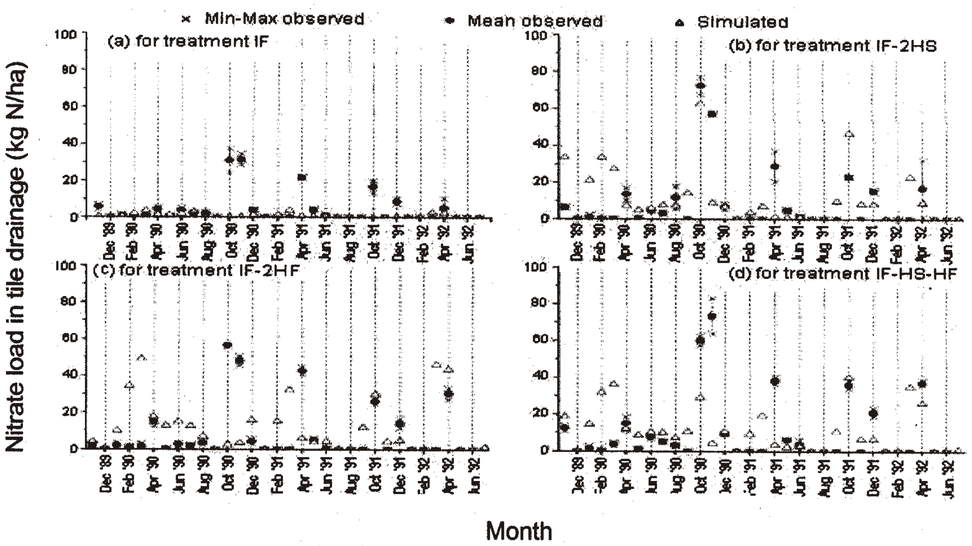

Fig. 3. Comparison of monthly observed and simulated nitrate loads in the tile flow at the Lennoxville site.

nitrogen loads. However, low unsorted efficiency values indicate some discrepancies between the occurrence of simulated and observed tile flow and nitrogen load events.

The discrepancy between monthly observed and predicted tile flow may be partly attributed to problems in properly simulating percolation during freeze-thaw periods and infiltration through partially frozen soils. These conditions may have led to the development of preferential flow conditions and difficulties in describing temporal changes in the soil hydraulic properties. The piston approach used by EPIC's percolation algorithm neglects faster water movement through macropores, the interaction between the macropores and micropores (Diiwu 1997), and upward capillary flow (Warner et al. 1997). The establishment of a static seasonal CN value assumes that the seasonal soil hydraulic conditions remain static, but in central Canadian conditions, soil hydraulic properties have been shown to exhibit significant temporal variability (Gupta 1993; Diiwu 1997). In addition, EPIC's daily time step does not have the ability to accurately simulate changes in water partitioning at the soil surface during high intensity rainfall events.

The discrepancy between predicted and observed nitrate loads may be partly attributed to the overestimation of mineralization following the excessive application of nitrogen. Warner et al. (1997) indicated that EPIC has a tendency to over-predict mineralization when excessive nitrogen rates are applied.

Ottawa Site The results of validation of the EPIC model for tile flows and nitrate loads at the Ottawa site are presented in Figs. 4 and 5, respectively. These data show that for both tillage treatments the model overpredicted the simulated tile flow; however, the simulated and observed tile flow trends were similar. The largest over-predictions generally occurred during the months of March and April (early spring when partially frozen soil conditions exist), which is similar to the trends observed at the Lennoxville site. It is also noted that the observed and simulated tile drainage is generally lower for the no-till treatment (Figure 4). Such observations suggest that the curve number adjustment for no-till treatment reasonably represents the changes in water partitioning at the soil surface. The simulated nitrate loads in tile flow generally followed the trends of tile flows with the largest overestimation occurring again during the months of March and April. The statistical comparisons of the observed and predicted monthly tile flows and nitrogen loads for this site are presented in Table 12. The sorted and unsorted efficiency values indicate that the prediction of the range of tile flow volumes and the timing of events was more accurate for the conventional tillage treatments than for the no-till treatments. Also, the tile flow volumes were predicted more accurately than the nitrate loads. For all treatments, the unsorted efficiency values were low indicating difficulties in accurately estimating the water budget during the spring freshet. Although calibration was not performed at this site, the efficiency statistics describing the monthly tile flows and nitrate loads are similar to those at the Lennoxville site.

Table 11. Statistical analysis of average monthly observed and simulated tile flow and nitrogen loads at the Lennoxville site.

Output	M_d	R^2	Unsorted efficiency	Sorted efficiency
Tile drainage volume	-3.25 NS*	0.38	0.19	0.75
Drain-N (IF)	3.49 S	0.03	-0.19	0.06
Drain-N (IF-2HS)	-2.38 NS	0.26	0.08	0.85
Drain-N (IF-2HF)	-3.36 NS	0.01	-0.9	0.83
Drain-N (IF-HS-HF)	-1.03 NS	0.07	-0.07	0.77

*NS/S - Not significant/significant at 95% confidence level

Table 12. Statistical analysis of the average monthly observed and simulated tile flow and nitrogen loads at the Ottawa site.

Output	M_d	R^2	Unsorted efficiency	Sorted efficiency
Tile drainage - CT†	-5.98 NS*	0.76	0.26	0.63
Tile drainage - NT	-7.25 S	0.69	0.03	0.49
Drain-N - CT	-0.59 NS	0.5	-0.08	0.68
Drain-N - NT	-1.08 NS	0.45	-0.37	0.55

†CT = conventional tillage; NT = no-till treatment
*NS/S - Not significant/significant at 95% confidence level

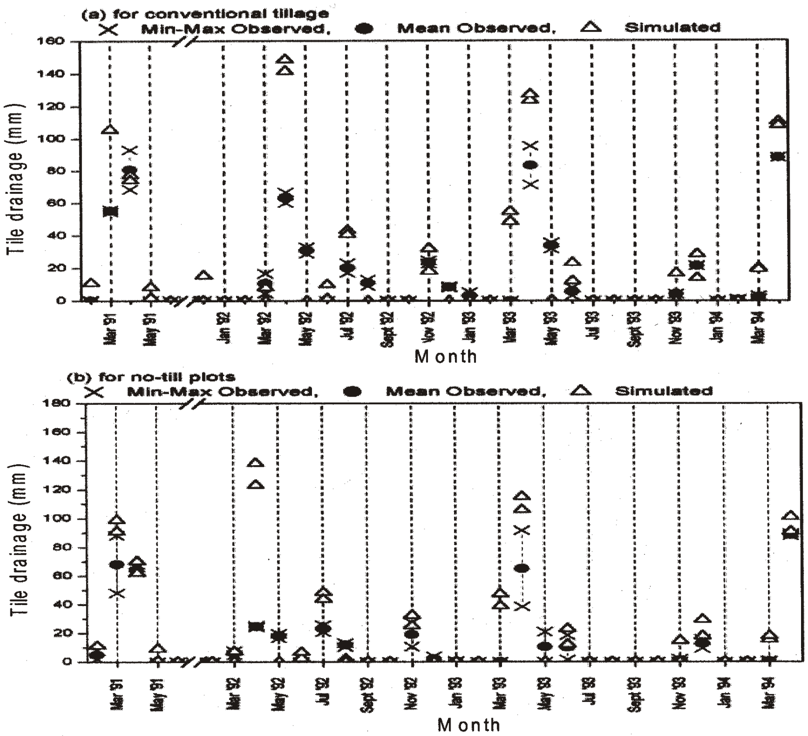

Fig. 4. Comparison of magnitude of monthly observed and simulated tile outflow for conventional and no-tillage treatments at Ottawa site.

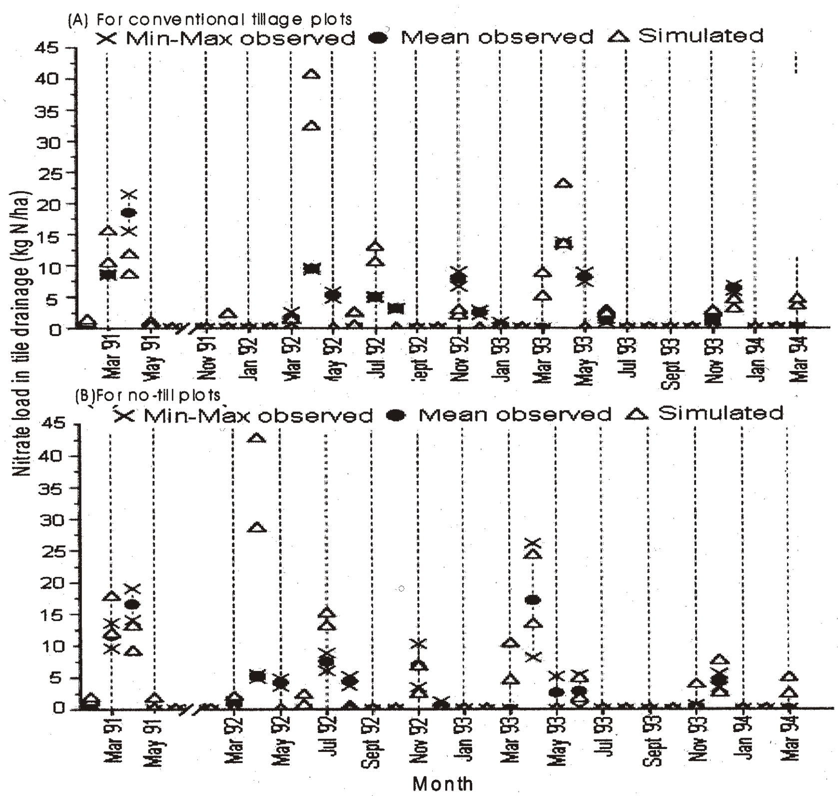

Fig. 5. Comparison of magnitude of monthly observed and simulated nitrate loads in the tile flow for conventional and no-tillage treatments at Ottawa site.

The discrepancy between the monthly observed and predicted tile flow is partly attributed to the weakness in the snowmelt and soil thawing algorithms of the EPIC as indicated in a previous study (Roloff et al. 1998a). The EPIC model predicted the soil thawing and snowmelt conditions too early resulting in an overestimation of tile flow in early spring (March and April) and underestimation of soil moisture later during May and June. In addition, other differences between the observed and predicted tile flow may be attributed to poor representation of the spatial and temporal variation in soil hydraulic properties at this site as observed by Patni and Masse (1992). Observed tile flows in no-till treatments were found to be more variable than in the conventional tillage treatments. Such variability can be attributed to spatial variation in soil hydraulic properties, heterogeneity of soil crust formation, and residue cover at the soil surface.

The simulated nitrate loads in tile flow generally follow the tile flow trends with the largest overestimation occurring in the months of March and April. As with tile flow, simulated and observed nitrate loads generally show more variability in no-till treatment than in conventional till treatment. The poorer unsorted efficiency obtained for nitrate loads than the tile flows suggest difficulty in accurately simulating N dynamics. Previous studies (Chung et. al. 2001; Cavero et al. 1999; Roloff et al. 1998a; Marchetti et al. 1997; Jackson et al. 1994) suggest that EPIC does not accurately simulate the temporal variability of nitrogen transformations (such as denitrification, volatilization, mineralization, immobilization, and plant uptake). These nitrogen transformations are based on empirical equations and are a function of changes in soil moisture conditions, which may not be accurately simulated by the EPIC model (Roloff et al. 1998a; Beckie et al. 1995).

Woodslee Site The results of validation of the EPIC model for tile flows and nitrate loads at the Woodslee site are presented in Figs. 6 and 7, respectively. The data in Figure 6 show that there is a substantial discrepancy between observed and simulated monthly flows for all four treatments throughout the trial period. Figure 6 shows that predicted and simulated monthly nitrate loads were generally underestimated in the spring of 1992 and overestimated in the fall of 1992 and spring of 1994.

The statistical comparison of the observed and predicted monthly tile outflows and nitrogen loads are shown in Table 13. The

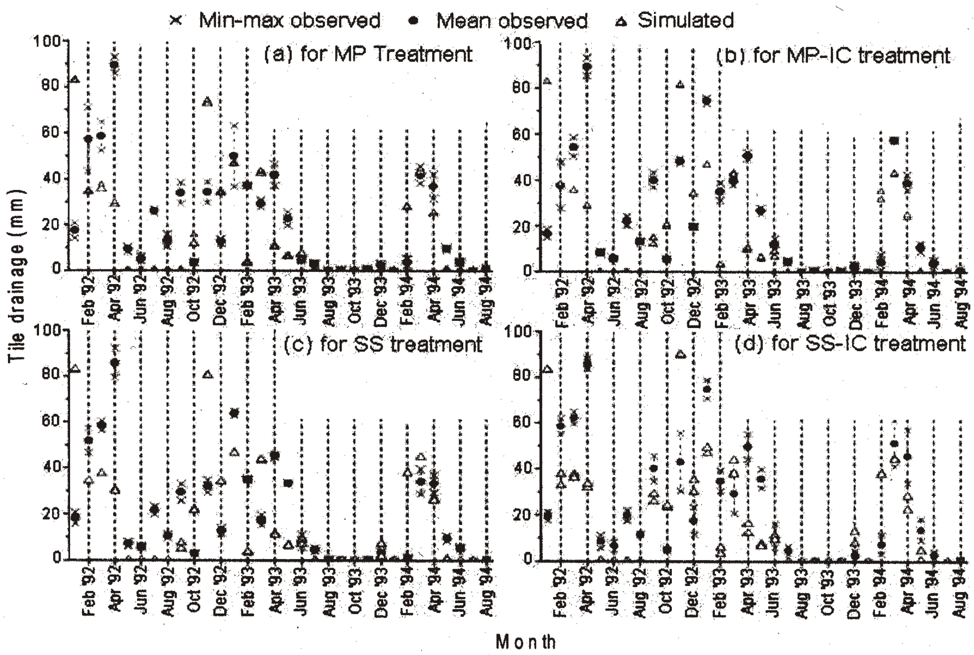

Fig. 6. Comparison of magnitude of monthly observed and simulated tile flow for various tillage treatments at the Woodslee site.

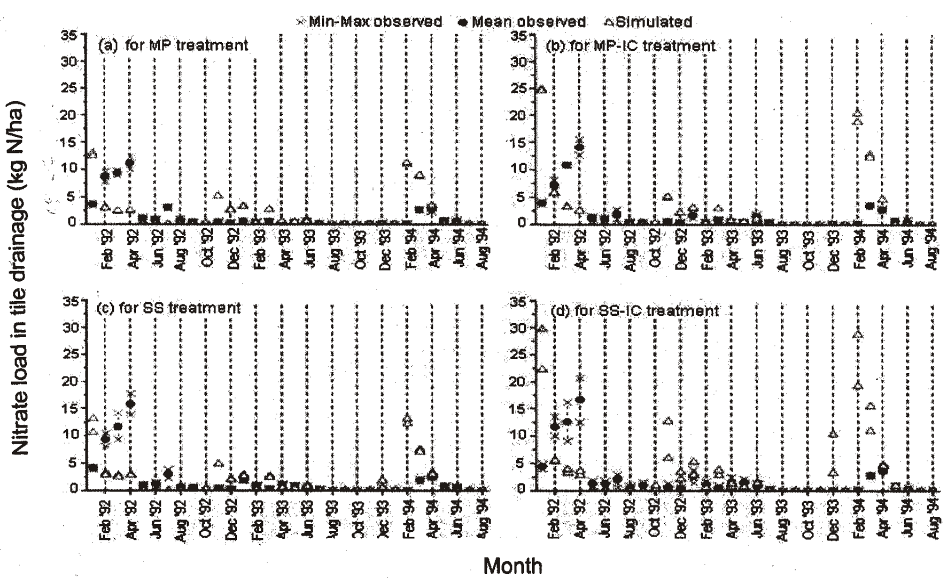

Fig. 7. Comparison of monthly observed and simulated nitrate loads in the tile flow for different tillage and land use treatment at the Woodslee site.

sorted efficiency statistics for the tile outflows suggest relatively accurate prediction of the range of measured flow volumes. However, the low sorted efficiency values suggest that the simulated timing of events do not correspond well with observations. The sorted efficiency for the nitrate load is generally lower for the intercropped treatments. The lower unsorted efficiency values for all treatments indicate that the timing of simulated events do not correlate well with observations.

There is also some difficulty in the prediction of tile outflows during the months of January to April, which may be due to inaccurate quantification of soil hydraulic properties during this period. The soil at the Woodslee site is characterized by cracking clays with a high potential of preferential flow pathway development, which is not well represented in the EPIC model. These preferential flow pathways are promoted by the spring's freeze-thaw cycles (Asare et al. 1993), the previous crop's extensive root structure (i.e. alfalfa), and corn stalk incorporation. Similar limitations of the EPIC model are also reported by Chung et al. (2001).

The nitrate loads were generally underestimated during the spring of 1992 and over-predicted during the spring of 1994. The underestimation in the spring of 1992 may be due to an underestimation in mineralization rates from the previous alfalfa crop residue during the summer of 1991 (Tan et al. 1993), which was not directly included in the initial soil nitrogen input file. The overestimation of the nitrate loads during the spring of 1994 is largely explained by an overestimation of tile drainage volume and an inaccurate representation of interactions between soil nitrogen and water leaching under preferential flow conditions. Under preferential flow conditions, most drainage water leaches through a small portion of the soil pore space, which entrains a smaller percentage of soil nitrate. Poor representation of these conditions resulted in the overprediction of nitrate loads. Also, overpredictions of nitrate loads may also be partly attributed to inaccurate representation of the time-dependent nitrogen cycling processes and the soil moisture conditions as discussed above.

CONCLUSIONS

The results of this study indicate that the EPIC model can be a useful and reliable tool for tile drained water quality, cropping, and nutrient management in central Canadian conditions.

Table 13. **Statistical analysis of the average monthly observed and simulated tile flow and nitrogen loads at Woodslee site.**

Output	M_d	R^2	Unsorted efficiency	Sorted efficiency
Tile drainage (MP)[†]	4.11 NS*	0.25	-0.06	0.88
Tile drainage (MP-IC)	6.42 NS	0.31	0.09	0.88
Tile drainage (SS)	2.24 NS	0.21	-0.17	0.93
Tile drainage (SS-IC)	4.22 NS	0.30	0.08	0.88
Drain-N (MP)	-0.36 NS	0.06	-0.78	0.91
Drain-N (MP-IC)	-1.04 NS	0.05	-2.48	0.26
Drain-N (SS)	0.02 NS	0.04	-0.43	0.90
Drain-N (SS-IC)	-1.31 NS	0.02	-2.19	0.41

[†]MP, MP-IC, SS, and SS-IC designate the outputs from different treatments.
*NS/S - Not significant/significant from paired t-test at 95% confidence level

In the central Canadian conditions, the estimated water and nitrogen budgets were compatible with the long term average local values. In central Canadian conditions the evapotranspiration and subsurface flows are the dominant water budget components, while plant uptake and nitrogen losses in the tile outflows are the dominant nitrogen budget components.

The EPIC model has the potential to simulate long-term nitrogen loss reasonably well but the simulation of the temporal variability of tile outflow and nitrogen loading is somewhat limited. As with many models, EPIC is a useful tool for estimating nitrate losses on a larger time scale such as annually; however, it is erratic on a short time scale, such as a month, a day or on an event. EPIC's limitations are partly attributed to its simple piston-flow percolation approach, daily time step, inaccurate simulation of timing of soil thawing and snowmelt conditions, and empirically based nitrogen transformation functions, which partly depend on the quality of simulated hydrology.

The improvement of the simulation of the temporal variability of soil hydraulic conditions and the incorporation of a preferential flow component are essential to enhance EPIC's tile drainage prediction capability. Improvement in the simulation of soil moisture conditions will also enhance the nitrate loss prediction capability. For application in central Canadian conditions the soil thawing and snowmelt components also require further attention.

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