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Modelling nitrate losses in drainage water using DRAINMOD 5.0

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Abstract

The appropriateness of the DRAINMOD-N computer model for the southwestern Quebec region was assessed by comparing field data and simulated results. Four years of field data were collected from a 4.2 ha field research facility located at St. Emmanuel, Que. The experimental layout contrasted two different fertilizer and water table treatments in a split plot design. Nitrogen fertilizer was applied at rates of 120 and 200 kg N/ha. The water table was either maintained at 0.6 m by a subirrigation (SI) system or was under free drainage (FD) at a drain depth of 1.0 m. The model was calibrated using data from 1996 to 1997. Simulated output for 1998 and 1999 were compared to measured values based on the mean residual error (MRE), coefficient of efficiency ($C_{eff} = 1.0$ represents a perfect match; $C_{eff} \leq 0$ a poor match) and other statistical parameters. Except for FD plots in 1998 (MRE $= -0.225$ m, $C_{eff} = -0.198$), water table depths (WTDs) were predicted to 0.17 m (23%) with C_{eff} ranging from 0.035 to 0.846. DRAINMOD correctly predicted the pattern, but underestimated the magnitude of daily drainflow in both years. On a monthly basis total drain flow was underestimated by up to 5 mm in 1998 and 1.2 mm in 1999. Except for the 1998-SI plots ($C_{eff} = -0.021$) simulations were excellent ($C_{eff} > 0.8$). With the exception of two FD-year-N combinations, DRAINMOD overestimated leached nitrogen by 0.01–1.09 kg ha^{-1} month^{-1} (0.02–5.01%). Nitrate leaching predictions were poor in 1998 ($-0.20 > C_{eff} > -7.83$), but good to excellent in 1999 ($0.95 > C_{eff} > 0.56$). The poor performance in 1998 compared to 1999 is attributed to significant rainfall events occurring soon after surface fertilizer application in 1998, but not in 1999. DRAINMOD largely overpredicted monthly total denitrification. Predictions were poor in 1999 ($-0.25 > C_{eff}$) and very poor in 1998 ($-139.7 > C_{eff}$) and mostly attributable to poor

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simulation of June and July, the peak months of measured denitrification. DRAINMOD performed well in the prediction of hydrological parameters, but fared less well in terms of nitrate leaching and denitrification.

Keywords: Drainage; Water table management; Subirrigation; Modelling; Nitrogen; Environment; Leaching; DRAINMOD

1. Introduction

Both surface and ground waters are adversely affected by the influx of nutrients from agricultural lands. While, subsurface drainage removes excessive water and improves plant growth, it increases the leaching of nutrients. Nitrate–nitrogen (NO_3^-–N) is particularly susceptible to leaching due to its solubility in water and is often applied in large quantities as ammonium fertilizer.

Subsurface drainage systems are used to alleviate crop-water stress caused by high water tables, especially in humid regions with fine textured soils. Across North America this practice has been used effectively to enhance crop growth by lowering water tables. Approximately 2 million ha of cropland in the provinces of Ontario and Quebec are subsurface drained, mostly for corn (*Zea mays* L.) and soybean (*Glycine max* (L.) Merr.) production.

Nitrates are water soluble and are susceptible to transport (via leaching) into adjacent surface waters. This creates water quality problems by accelerating eutrophication and by increasing the concentration of NO_3^-–N in surface and well waters above acceptable drinking water standards. NO_3^-–N concentrations as high as 40 mg/l have been observed in Eastern Canada (Milburn et al., 1990; Madramootoo et al., 1992).

Water table management has been identified as a best management practice to reduce nitrate losses from subsurface drains. This occurs through two mechanisms: by reducing the volume of drain flow and by promoting the anaerobic conditions needed for denitrification, which effectively reduces dissolved NO_3^-–N levels.

Field measurements must often be performed to assess the effects of water and agronomic management practices on nutrient transport. Such work is costly and time-consuming. Computer models make use of nutrient transport equations and algorithms to assess water quality without the costly field measurements. Such models are based on theoretical equations and need to be verified against field measurements in order to evaluate the accuracy and viability of the given method. A number of computer simulation models are available for the analysis of water quality parameters for lands under subsurface drainage. Numerous field scale and more recently, watershed scale models exist. These include, the soil and water assessment tool (SWAT, a watershed scale model), the root zone water quality model (RZWQM) and DRAINMOD-N. DRAINMOD is a field scale model that has gained acceptance over the years since its development in the 1970s (Skaggs, 1978) as a design and management tool for subsurface drainage systems. The original DRAINMOD program was developed to assess the performance of drainage and water table management systems in soils with poor drainage and to be a management aid for existing drainage systems. Approximate methods are used to quantify the hydrologic components, including subsurface drainage, subirrigation, infiltration, evapotranspiration (ET) and surface runoff (Skaggs, 1982). DRAINMOD performs a daily water balance in the soil profile and uses rainfall and ET data to model drainage systems. Equations by Hooghoudt, Kirkham and Ernst are used to calculate drainage and subirrigation rates while infiltration rates are predicted by the Green and Ampt equation. Water table depth (WTD), drainage rates, surface runoff and ET are calculated on a continuous basis. Four water management modes are available: (i) conventional drainage: the subsurface drainage system has a free outlet; (ii) controlled drainage: the water level in the outlet rises to the level set by the weir height (i.e. the outlet is submerged); (iii) subirrigation: water is pumped back into the subsurface drain system to increase moisture in the root zone during dry periods; and (iv) combined system mode: the user can change between conventional drainage, controlled drainage and subirrigation over the course of the simulation period.

Modules were later added that extended the model's capabilities to include the simulation of salt transport and soil salinity (Kandil et al., 1992, 1993) as well as nitrogen transport and N-transformation based on a simplified version of the nitrogen cycle (Brevé et al., 1992). They make use of modifications in DRAINMOD to compute soil-water fluxes (Skaggs et al., 1991; Kandil et al., 1992, 1993) and are most applicable for mobile constituents such as nitrogen and salts. Since this study was completed a further modification of DRAINMOD has allowed it to account for freezing, thawing and snowmelt (Wan, 1999).

The current DRAINMOD-N was a further development of the original DRAINMOD that included the above modules (Brevé et al., 1997a,b). The soil nitrogen module simulates the movement and transformation of nitrogen in agricultural fields with drainage systems. DRAINMOD-N is a 'quasi-two-dimensional' model that simulates the movement and fate of nitrogen in shallow water table soils with artificial drainage. It is 'quasi' because the nitrogen movement component considers only vertical transport in the unsaturated zone, while both vertical and lateral transport is considered in the saturated zone. The model uses an explicit numerical solution to the advective-dispersive-reactive equation to simulate NO_3^-–N movement below the soil surface. Nitrogen concentrations are predicted in the soil profile, as well as in surface and subsurface drainage waters. This is valuable for determining the effects of water table management and fertilizer rates on nitrogen loading from agricultural fields.

The primary objective of this study was to assess the DRAINMOD-N computer model for the southwestern Quebec region by comparing field data with simulated results. The effects of N fertilization rate and water table management on nitrate leaching were simulated.

2. Materials and methods

2.1. Field measurements

2.1.1. Site description

Data were collected at an instrumented, 4.2 ha field-scale experimental site located in Soulanges County, Que., about 30 km west of the Macdonald Campus of McGill University (Fig. 1). Site design and instrumentation are described fully in Tait et al. (1995).

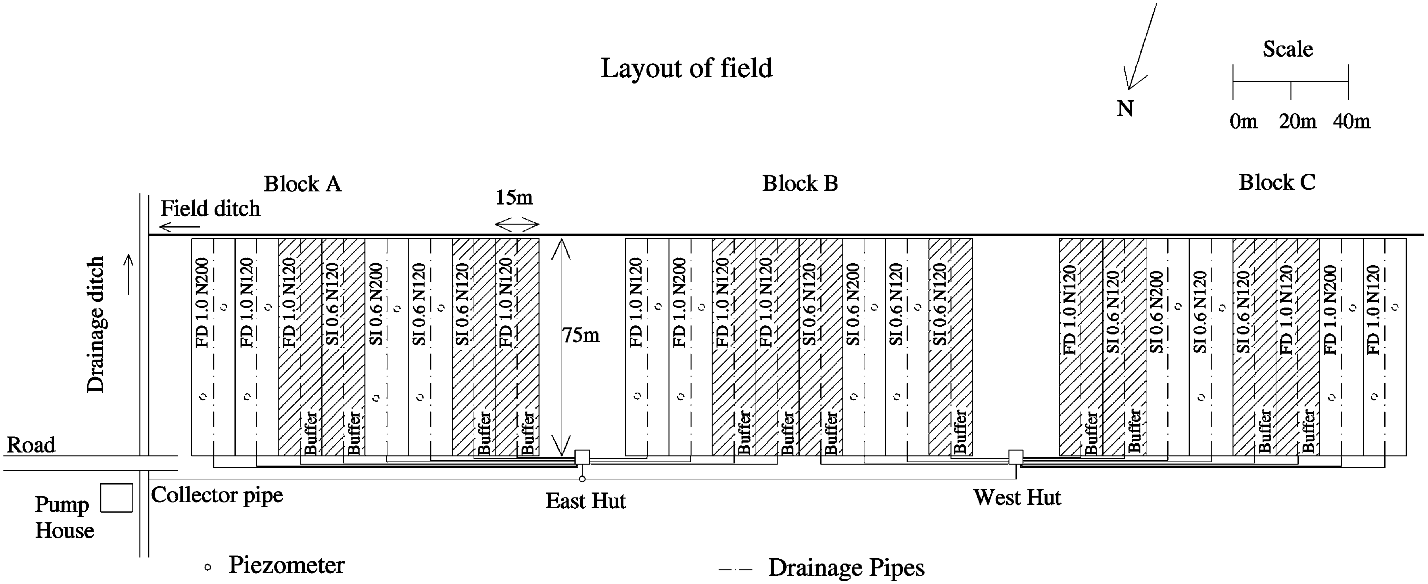

Fig. 1. Field layout.

The upper soil layer (0–0.25 m) was a Soulanges very fine sandy loam (fine, silty, mixed, non-acid, frigid Humaquept), underlain by layers of sandy clay loam (0.25–0.5 m in depth) and clay (0.5–1.0 m depth). Surface slope of the field was about 0.5%. Lateral subsurface drains were situated 15 m apart on a 0.3% slope at a maximum depth of 1.0 m. Each of the three 0.9 ha blocks was monocropped to corn and comprised eight possible treatment plots, 15 m wide by 75 m long.

2.1.2. Treatments imposed

WTD was the main plot factor and fertilizer level the subplot factor in a thrice-replicated split-plot design. In each of the three blocks, two water table treatments were applied: free drainage at a WTD of 1.0 m (FD) and subirrigation at a WTD of 0.6 m (SI). Subirrigation was implemented in the last week of May and shut off in the last week of September. Nitrogen fertilizer was applied in a split dose: 23 kg N ha^{-1} banded as ammonium phosphate (18-46-0) at planting (8 May 1998, 4 May 1999) and 97 or 177 kg N ha^{-1} broadcast as ammonium nitrate (34-0-0) roughly 1 month after planting (8 June 1998, 10 June 1999), resulting in rates of 120 kg N ha^{-1} (N_{120}) or 200 kg N ha^{-1} (N_{200}), respectively. A more detailed description of the fieldwork and plot assignations is presented elsewhere (Madramootoo et al., 1999; Elmi et al., 2000).

2.1.3. Measurements

WTD were measured three times per week in each of the plots in 1996–1999. Water table observation wells (perforated, 12-mm-diameter polyethylene pipes with a geotextile sleeve) were installed to a depth of 1.4 m on the north and south sides of each plot. A water sensor was used to monitor the depth of the water table and WTD averaged for each plot. The wells were installed immediately after planting (mid-May) and were removed in mid September when the SI plots were returned to FD to facilitate field operations.

Drain flow was measured by a tipping bucket device (Tait et al., 1995). The frequency of water sampling was set according to the volume of drainage flow. A 0.5 l sample was taken for every 1000 l of drain flow in 1998 (a very wet year) and for every 500 l of drained flow in 1996, 1997 and 1999. Samples were stored in 20 l bottles, forming composite samples and 20 ml sub-samples were subsequently removed manually and analysed in the lab for NO_3^-–N according to a colorimetric method modified from Keeney and Nelson (1982). In general, water samples were analysed every 2 weeks during dry periods and at least twice a week during wet periods. While ponding occurred on a few occasions, after the end of the snowmelt (about 1 April) no surface runoff was measured during the growing season in any of the plots, from the installation of the plots in 1992 through the years presented herein.

In both 1998 and 1999, denitrification in the top 0.45 m soil layer was measured weekly to bi-weekly from late May to early October according to the methods described by Elmi et al. (2000). Given the preponderance of the applied fertilizer N and organic matter in the 0–0.15 m soil layer, measured denitrification in this layer accounted for over 95% of the denitrification measured from 0 to 0.45 m depth. Preliminary experiments had shown no detectable denitrification activity in the heavy clay layers below this depth.

2.2. Model inputs

2.2.1. The soil utility

To facilitate the input of soils data, DRAINMOD contains a soil utility program. Soil-water characteristic data are required for each layer of the soil profile. Rooting depths and saturated hydraulic conductivities for each layer were taken from Mousavizadeh (1992). From this information, DRAINMOD calculates the relationship between WTD and drained volume and between WTD and maximum steady upward flux. The Green-Ampt infiltration parameters are also calculated as a function of WTD when the infiltration event begins. The soil water characteristic curves were measured for the research site using pressure plate apparatus (Mousavizadeh, 1992).

2.2.2. Precipitation, temperature and ET

Hourly precipitation was required for DRAINMOD's hydrologic component. Hourly rainfall data were collected at the research site. Table 1 shows the monthly precipitation measured at the site at the Coteau du Lac weather station, located about 500 m from the experimental site, for the period of April to November, when drainflow was measured.

The user is given the option of using observed ET data or applying daily maximum and minimum temperatures for the calculation of ET based on the Thornwaite equation. Temperature data for 1998 and 1999 were collected from the nearby weather station. Data for 1996 and 1997 were taken from the St. Anne-de-Bellevue weather station, about 30 km from the research site. Thornwaite ET was calculated based on latitude $45^{\circ}18'$ and an average heat index of 40, computed with data from 1998 to 1999. The ET for the months from planting to harvest (May to September) are presented in Table 2.

The ET data generated by DRAINMOD were verified using the Baier–Robertson and Blaney–Criddle methods. Barnett et al. (1997) compared several ET prediction equations for a nearby site in Quebec and found that the Baier–Robertson equation performed the best with respect to adjusted pan evaporation values on a seasonal basis. To improve model accuracy, daily inputs were thus scaled using a monthly factor (available as an

Table 1
Monthly precipitation from the Environment Canada, Côteau-du-Lac weather station

Month	Precipitation (mm)		
	1998	1999	Mean 1961–1990
April	33.4	25.0	73.5
May	69.6	53.2	68.3
June	229.8	94.6	82.5
July	128.4	103.6	85.6
August	101.0	64.8	100.3
September	80.8	168.6	86.5
October	66.2	107.4	72.5
November	53.0	31.4	92.1
Total (April to November)	762.2	648.6	661.3

Table 2
Monthly evapotranspiration (mm) by the Baier–Robertson method

Month	ET			
	1996	1997	1998	1999
May	52	50	57	59
June	97	106	98	102
July	145	151	148	137
August	93	87	107	81
September	33	36	43	37
Total (May to September)	420	430	453	416

option in DRAINMOD) so that the generated monthly totals matched those calculated by the Baier–Robertson equation.

2.3. Simulating nitrogen transport with DRAINMOD-N

Certain parameters required calibration for the nitrogen component of the model. A sensitivity analysis performed on DRAINMOD-N (Brevé et al., 1997b) showed that the NO_3^-–N loss in the subsurface drains is most sensitive to the standard rate coefficients for denitrification and mineralization; mildly sensitive to N content in the crop; and practically insensitive to NO_3^-–N content in rainfall and dispersivity. A value of 2.5×10^{-5} per day was used for the coefficient of mineralization, K_{min}. Values for the coefficient of denitrification, K_{den}, were in 1.08 and 3.5 per day for the FD and SI plots, respectively. Values cited in the literature for K_{min} range from 10^{-5} to 10^{-4} per day, while values for K_{den} range from 0.004 to 1.08 per day (Johnson et al., 1987), so the values that were used in the model should be considered more as fitting parameters than as representative physical values.

Elmi et al. (2000) measured denitrification on a seasonal basis. By knowing these values it was possible to back-calculate K_{den}. The equation for denitrification used in DRAINMOD-N is:

$$\Gamma_{den} = K_{den} f_{\theta_{den}} f_{temp} f_z \theta \, [NO_3^{-}-N] \quad (1)$$

where Γ_{den} is the denitrification rate [M L^{-3} T^{-1}], $\Gamma_{den} = 0$ for $\theta > \theta_{den}$; K_{den} the denitrification rate constant (T^{-1}); $f_{\theta_{den}}$, f_{temp}, f_z are dimensionless soil water content, temperature and depth adjustment factors, as further defined in Madramootoo et al. (1999), [NO_3^-–N] content in the soil profile [M L^{-3}]; θ the volumetric soil moisture content [L^3 L^{-3}], θ_{den} the threshold soil moisture content below which denitrification does not occur [L^3 L^{-3}].

The range for each individual parameter in the above equation was examined. Two different values of K_{den} were calculated for both the CD and FD treatments, the maximum value encountered and the average value (the average value based on the seasonal averages of each of the individual parameters). Table 3 presents the input data required for drainage system design, nitrogen parameters and crop information.

Table 3
DRAINMOD-N input parameters

Parameter	Value
Drainage system components	
Drain depth (m)	1.0
Drain spacing (m)	15
Effective radius (mm)	3.5
Actual distance to impermeable layer (m)	5.0
Equivalent depth from drain to impermeable layer (m)	1.5
Drainage coefficient (mm per day)	10
Saturated hydraulic comductivity (m s^{-1})	5.3×10^{-6}
Kirkham's coefficient, *G*	12.77
Initial depth to water table (m)	0.85
Irrigation pump capacity (mm per day)	100
Maximum surface storage (mm)	15
Kirkham's depth for flow to drains (mm)	2.5
Nitrogen subroutine	
Soil dispersivity	5
Soil tortuosity	1
Soil diffusion coefficient	1×10^{-6}
Net mineralization rate constant (per day)	2.5×10^{-5}
Denitrification rate constant (per day)	1.08
Continuous days of saturation for denitrification (day)	2
Nitrogen in yield (%)	1.5
Fertilizer application (kg/ha)	120 or 200
Volumetric soil moisture content at wilting point	0.14
Bulk density (Mg/m^3)	1.55
Threshold soil moisture content for fertilizer dissolution	0.218
Soil temperature adjustments	Yes
Initial [NO_3^-] in the soil	10 mg/l at 1 m
[NO_3^-] of rain (mg/l)	0.5
Initial [organic N] (mg/l)	2
Crop information	
Planting date	4 May
Length of growing season (day)	130
Latest planting date without yield loss	14 May
Days required to prepare seedbed and plant	5
First stage reduction factor	0.88
Days to use first stage reduction factor	40
Second stage reduction factor	1.667
Rooting depth (m)	0.3
Lower limit of water content in root zone	0.13
Limiting WTD (m)	0.3
Weir settings	1.5 m for FD, 0.6 m for SI

The model was run in combined system model, beginning 1 April of each year, when the spring snowmelt was completed. WTD was measured at 0.85 m from the soil surface and soil nitrate concentration at drain depth was based on measured nitrate in the drainflow water (Table 3). For the SI plot simulations, the model was switched over to subirrigation mode on 15 May when the subirrigation system was turned on and turned back to conventional drainage mode in mid-September when the subirrigation system was turned off to facilitate field operations and crop drying.

2.4. Statistical analysis

Simulated and observed values were compared on a monthly total, seasonal total, or daily basis. Mean residual error (MRE); absolute deviation (AD); average relative percent error (ARPE); and coefficient of efficiency (C_{eff}) (James and Burges, 1982) were calculated as:

$$\mathrm{MRE} = \frac{\sum_{i=1}^{i=n} - O_i}{n} \tag{2}$$

$$\mathrm{AD} = \frac{\sum_{i=1}^{i=n} |S_i - O_i|}{n} \tag{3}$$

$$\mathrm{ARPE} = \frac{\sum_{i=1}^{i=n} S_\mathrm{i} - \mathrm{O_i}}{\sum_{i=1}^{i=n} \mathrm{O_i}} \tag{4}$$

$$C_{\mathrm{eff}} = \frac{\sum_{i=1}^{i=n} (O_i - \bar{O})^2 - \sum_{i=1}^{i=n} (S_i - O_i)^2}{\sum_{i=1}^{i=n} (O_i - \bar{O})^2} \tag{5}$$

where O_i is individual observed value, S_i individual simulated value, $\bar{O}$ mean observed value and n the number of paired observed–simulated values.

The MRE gives information as to whether the model is over or underpredicting; ARPE expresses this on a percentage basis, while AD is an indicator of quantitive dispersion between the observed and simulated values. The C_{eff} evaluates the error relative to the natural variation in the observed values. A C_{eff} of 1.0 represents a perfect prediction, while a value of zero represents a prediction no better than the random variation in the observed data, increasingly negative values indicate increasingly poorer predictions.

3. Results and discussion

3.1. WTDs

As measured WTD was not affected by nitrogen fertilisation treatment (data not shown), the DRAINMOD and field results were only compared for SI versus FD. Measured and predicted WTD are presented for the period of late May to early September of 1998 and 1999 (Figs. 2 and 3) during which the SI treatment was imposed, but the simulation of WTD began on 1 April, from an initial measured value of 0.85 m from the soil surface. In general, for both years and for both SI and FD, DRAINMOD simulated the pattern of water table fluctuations fairly well (Figs. 2 and 3). Overall, the water tables were predicted within 0.046 m (or 7.5%) for SI and 0.225 m (37%) for FD plots (Table 4). The AD ranged from 0.15 to 0.25 m. Chang et al. (1983) reported an MRE of as low as 0.06 m, while others have calculated values ranging from 0.081 to 0.190 m (Skaggs, 1982; Workman and Skaggs,

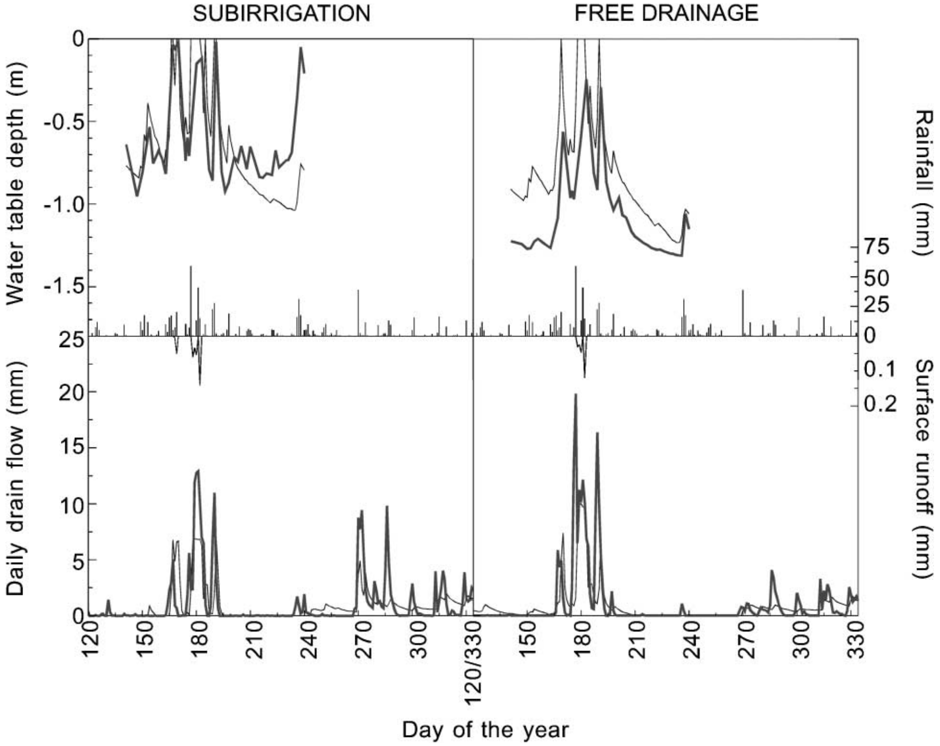

Fig. 2. Rainfall and observed (narrow line) and DRAINMOD-predicted (bold line) WTDs, surface runoff and drain flow for 1998. Observed surface runoff was zero in all cases.

Table 4
Comparison of simulated and observed WTDs and drainage fluxes

Statistical parameter	Treatment			
	Subirrigation (0.6 m)		Free drainage (1.0 m)	
	1998	1999	1998	1999
WTD (m)				
MRE	0.046	−0.011	−0.225	−0.174
AD	0.192	0.148	0.254	0.174
ARPE	7.505	−1.501	−36.99	−23.08
C_{eff}	0.169	0.035	−0.198	0.846
n	32	40	32	40
Monthly drain flow (mm)				
MRE	5.000	0.217	3.583	1.172
AD	12.73	5.602	7.983	3.682
ARPE	22.88	0.833	16.48	9.229
C_{eff}	−0.021	0.957	0.8294	0.963
n	6	6	6	6

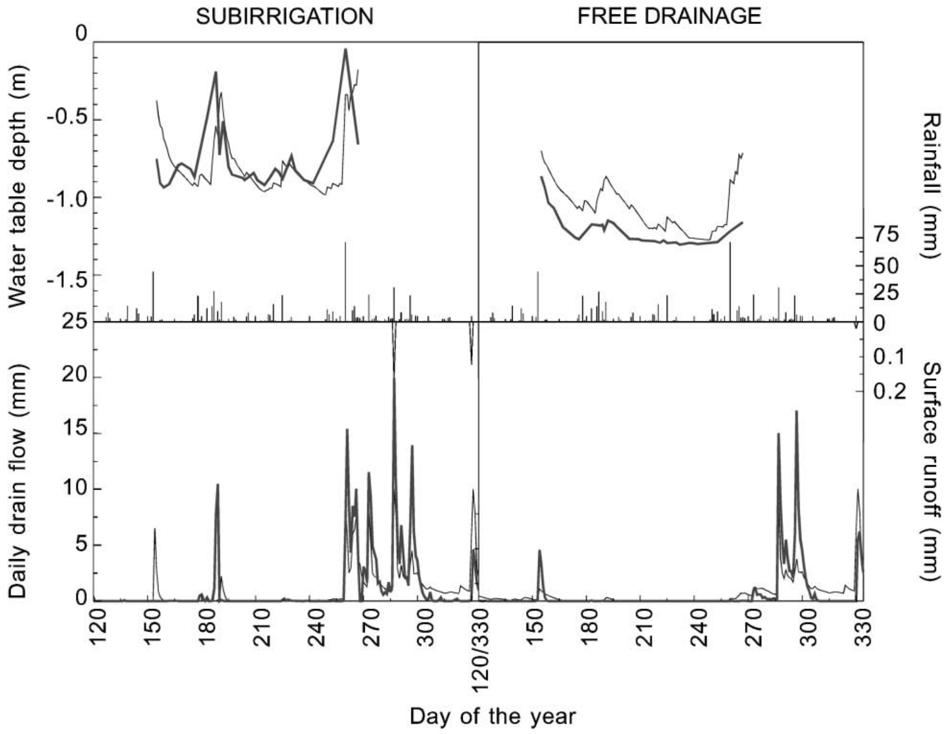

Fig. 3. Rainfall and observed (narrow line) and DRAINMOD-predicted (bold line) WTDs, surface runoff and drain flow for 1999. Observed surface runoff was zero in all cases.

1989; Mackenzie, 1993). As DRAINMOD predicts the WTD midway between drains and measurements were taken at a number of different locations roughly one- or three-quarters of the way between drains it would natural for the model's estimates to slightly overestimate WTD. However, over both seasons, DRAINMOD predicted a shallower than measured WTD under FD. For SI plots, DRAINMOD predicted a slightly shallower than measured WTD in 1999, but a deeper one for 1998 (Table 4, Figs. 2 and 3). Many measurements on site over a period of 9 years have shown the variation in WTD from over the drain to the midpoint between drains to rarely exceed 50 mm. The C_{eff} shows both 1998 and 1999 WTD predictions for SI to be acceptable ($0 < C_{\text{eff}} < 0.8$). In 1998, the WTD prediction for FD plots was poor ($C_{\text{eff}} < 0$), but in 1999 the prediction was excellent ($C_{\text{eff}} > 0.8$). Thus, with the possible exception of FD-1998, DRAINMOD predicted WTD fairly accurately.

3.2. Drain flow

As measured monthly drain flow (May to October) was not affected by nitrogen fertilisation treatment (data not shown), the DRAINMOD and field results were only compared for the two SI versus FD. In general, for both years and for both SI and FD, DRAINMOD simulated the pattern of daily drain flow and its peak flows fairly well, though generally underestimating drain flow (Figs. 2 and 3). Overall, the monthly drain flows were predicted to within 5.0 mm (or 22.9%) in 1998 and within 1.2 mm (9.2%) in 1999 (Table 4). The AD ranged from 3.7 mm (FD-1999) to 12.7 mm (SI-1998). Over both seasons, DRAINMOD underpredicted monthly drain flow (positive MRE and ARPE), particularly in 1998 compared to 1999 (Table 4). The underprediction of runoff could occur if the model predicted surface runoff at times when the WTD was at or near the surface. While no surface runoff was measured in either year, some surface runoff was predicted by the model (Figs. 2 and 3). Predicted runoff was less than 0.2 mm d^{-1}. This amount of surface runoff is not sufficient to explain the underprediction of drain flow. Monthly drain flow predictions for SI-1998 were poor ($C_{eff} < 0$), while excellent ($C_{eff} > 0.8$) for all other year-WTD treatment combinations. The greater error for SI-1998 might be related to the fact that two distinct periods of multiple flow peaks (late June to early July and late September to early October) occurred, whereas for the other year-WTD treatment combinations, peak flow were generally concentrated in one or the other period (Figs. 2 and 3). Overall, DRAINMOD predictions of monthly drainflow were near perfect in 1999 ($C_{eff} > 0.95$), but mixed in 1998.

3.3. Nitrate losses

The monthly total NO_3^-–N load in drainage water (June to November) was affected by both WTD treatment and N fertilisation level, which were interacting factors (not shown). Consequently, comparisons between DRAINMOD-predicted and measured monthly NO_3^-–N loads were done for all year-WTD-N fertilisation combinations. With the exception of FD-N200-1998 and FD-N120-1999, DRAINMOD overestimated NO_3^-–N loads by 0.01 to 1.09 kg ha^{-1} $month^{-1}$ (0.02–5.01%) (Tables 5 and 6). For the same treatment combinations, the magnitude of the MRE and ARPE and the AD were consistently greater in 1998 than in 1999 (Table 6). These greater errors in 1998 are reflected in poor C_{eff} values ($-0.20 > C_{eff} > -7.83$) compared to good to excellent C_{eff} values in 1999 ($0.56 < C_{eff} < 0.95$). In 1998, large rainfall events occurred soon after the second surface fertilizer application (8 June). Both June and July had well above average rainfall. However, September to November had below average rainfall (Table 1). Consequently, the majority of nitrate leaching occurred early in the season rather than during the fall months. Comparatively, in 1999 the situation was reversed. May precipitation was below average whereas June and July rainfall only slightly above average, while September rainfall was close to twice the average. October rainfall was 40% over average. Thus it appears that DRAINMOD had difficulty estimating leaching occuring early in the season under higher than average precipitation, but fared better when leaching was limited to the fall months. Perhaps, the fact that the leached nitrogen in 1998 may have come directly from applied granular fertilizer or from nitrate in the very top soil layer, as compared to 1999, when the nitrate would have had the whole season to become distributed through the soil profile, explains why DRAINMOD made poorer predictions in 1998 than 1999.

3.4. Denitrification

The monthly total denitrification (June to September) was affected by both WTD treatment and N fertilisation level, which were interacting factors. Consequently, comparisons

Table 5
Comparison of simulated and observed monthly total nitrate–nitrogen losses (kg ha^{-1} month^{-1}) to subsurface drains

Year and month	NO_3^-–N losses (kg ha^{-1} month^{-1})							
	Free drainage				Subirrigation			
	N_{120}		N_{200}		N_{120}		N_{200}	
	Observed	Simulated	Observed	Simulated	Observed	Simulated	Observed	Simulated
1998								
June	0.35	3.90	0.260	7.250	1.43	3.60	3.50	6.80
July	0.58	0.097	0.530	0.100	1.35	0.64	6.20	1.00
August	0.028	0.002	0.026	0.0115	0.037	1.00	0.062	1.00
September	0.086	0.34	0.091	0.350	0.058	0.066	0.033	0.076
October	0.305	0.070	0.305	0.073	0.44	0.10	0.54	0.1
November	0.180	0.073	0.120	0.076	0.36	0.175	0.58	0.21
1999								
April	0.150	0.140	0.360	0.142	0.0315	0.117	0.0105	0.118
May	0.00054	0.036	0.0041	0.035	0.00105	1.04	0.00036	1.04
June	0.17	0.105	0.370	0.108	0.0088	0.75	0.0032	0.76
July	0.0019	0.008	0.0076	0.008	0.11	0.035	0.115	0.036
August	0.00074	1.00	0.00195	1.00	0.004	1.005	0.00024	1.005
September	0.025	0.0720	0.037	0.0725	0.265	0.405	0.450	1.185
October	2.03	0.82	3.30	1.075	0.645	0.405	1.00	1.12
November	0.049	0.72	0.0163	2.05	0.0066	0.35	0.019	0.55

between DRAINMOD-predicted and measured monthly total denitrification were done for all year-WTD-N fertilisation combinations. DRAINMOD predictions of monthly total denitrification were extremely poor in 1998 and poor in 1999 (Tables 7 and 8). Errors ranged from 14.09 to 35.16 kg ha^{-1} month^{-1} (5.16–16.67%), whereas in 1999 errors ranged from 0.54 to 5.49 kg ha^{-1} month^{-1} (1.48–7.22%). In 1998, the relative error (ARPE) was greater for FD plots than SI plots, regardless of fertilization level, whereas in 1999 the

Table 6
Statistical comparison of simulated and observed monthly total NO_3^-–N losses (kg ha^{-1} month^{-1}) to subsurface drains

Statistical parameter	Treatments							
	1998				1999			
	N_{120}		N_{200}		N_{120}		N_{200}	
	FD	SI	FD	SI	FD	SI	FD	SI
MRE	0.15	0.49	−0.46	1.09	−0.06	0.12	0.01	0.35
AD	0.58	0.77	1.54	1.33	0.25	0.19	0.51	0.37
ARPE	0.25	1.95	−0.26	5.01	−0.23	0.97	0.02	1.85
C_{eff}	0.02	−0.59	−0.16	−4.88	0.86	0.95	0.56	0.77

Table 7
Comparison of simulated and observed monthly denitrification (kg ha^{-1} $month^{-1}$) to subsurface drains

Year and month	Denitrification (kg ha^{-1} mol^{-1})							
	Free drainage				Subirrigation			
	N_{120}		N_{200}		N_{120}		N_{200}	
	Observed	Simulated	Observed	Simulated	Observed	Simulated	Observed	Simulated
1998								
June	3.15	48.0	4.10	93.0	9.0	81.0	11.3	152.0
July	1.0	12.5	1.32	20.05	1.93	2.10	2.05	2.65
August	0.76	1.8	0.405	1.83	1.125	1.56	1.08	1.47
September	0.58	1.8	0.53	2.05	1.96	2.15	1.37	2.25
1999								
June	1.50	3.20	1.35	3.22	2.1	9.4	2.05	9.6
July	5.6	1.93	1.63	1.96	3.8	2.8	6.4	3.0
August	0.074	1.40	0.086	1.40	1.8	1.2	1.153	1.2
September	0.045	2.80	0.041	2.80	1.0	4.85	0.68	18.3

opposite was the case. The C_{eff} values presented in Table 6 for various groupings of months show the same trend.

C_{eff} values (June to September) in 1998 were extremely poor ($C_{eff} < -139.70$) and while better in 1999, still very poor ($C_{eff} < -0.25$). However, if the month of June was not considered in the calculation of the C_{eff}, values were much improved, particularly in 1998 where C_{eff} for SI plots were excellent ($C_{eff} > 0.9$). Comparatively, removing the month of September from the calculation of the C_{eff} worsened the values. However, in both years, the majority of denitrification occurred in June (compared to July to September), so the fact that DRAINMOD performs better for non-peak months limits its applicability to accurately simulate NO_3^-–N leaching.

Table 8
Statistical comparison of simulated and observed denitrification (kg ha^{-1} $month^{-1}$) for the months of June, July, August and September 1998 and 1999

Statistical parameter	Treatments							
	1998				1999			
	N_{120}		N_{200}		N_{120}		N_{200}	
	FD	SI	FD	SI	FD	SI	FD	SI
MRE	14.09	17.92	26.61	35.16	0.54	2.42	1.48	5.49
AD	14.09	17.92	26.61	35.16	2.22	3.27	1.48	7.22
ARPE	10.08	5.16	16.67	9.03	0.32	1.04	1.96	2.04
C_{eff} (June to September)	−98.99	−139.70	−860.12	−280.09	−0.25	−14.06	−5.08	−17.00
C_{eff} (July to September)	−503.04	0.98	−123.05	0.91	−0.02	−2.77	−4.35	−14.76
C_{eff} (June to August)		−148.30	−982.47	−309.27	−0.10	−15.53	−2.27	−2.67

$n = 4$ for all statistical parameters, except C_{eff} (July to September) and C_{eff} (June to August), where $n = 3$.

4. Summary and conclusions

The primary objective of this study was to validate the DRAINMOD-N computer model for the southwestern Quebec region, comparing field data collected over 1996–1999 with simulated results. The effects of management practices, such as subirrigation and controlled drainage on nitrate leaching were examined in the modelled output.

The hydrologic component of the model generally performed well for water table and drained volume predictions. The leached NO_3^-–N component gave good results for 1999, but poor results for 1998, generally overestimating nitrate leaching in both years. The prediction of denitrification was very poor in both years, particularly in 1998. The higher errors in 1998 can be, at least in part, attributed to heavy rains soon after fertilizer application, followed by an average to dry fall. Overall, while one can recommend DRAINMOD-N as an accurate tool for the simulation of field-scale hydrological parameters in the southwestern Quebec region, its simulation of N-cycle components requires improvement, particularly in the instance of heavy rains occuring soon after fertilizer application, an event which has been shown, in many instances, to be the main runoff and nutrient loss event of a growing season. The denitrification function of DRAINMOD-N also needs to be improved.

One improvement to the nitrogen component of DRAINMOD-N would be to include the newly discovered anaerobic microbial anammox process ($NH_4^- + NO_2^- \rightarrow N_2 + 2H_2O$), which occurs primarily in waste water treatment plants. This process has been observed in sewage effluent-irrigated lands and closely related planctomycetes have been isolated from soil (Kuenen and Jetten, 2001). They showed experimental evidence suggesting that an association of anaerobic anammox organisms with aerobic nitrifying organisms at an oxic–anoxic interface, such as would occur at the water table, could allow for the removal of ammonium and nitrite from the anoxic region. While such a process has never been demonstrated in the field or incorporated into soil N-cycle simulations, it could hypothetically account for some of the discrepancies in soil N modelling.

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