NRC Research Press
ARTICLE

Modeling agricultural land drainage under spring snowmelt conditions with DRAINMOD

J. Morrison, C.A. Madramootoo, and M. Chikhaoui

Abstract: There are few computer models that can simulate winter freeze–thaw conditions and spring snowmelt hydrology for agricultural tile drained lands. DRAINMOD, which is used widely to simulate tile drainage flows, has not been extensively applied during colder periods in eastern Canada. This study analyzes the performance of DRAINMOD for surface runoff and subsurface drainage predictions in southern Quebec during spring snowmelt. The model was tested with five years of field data. DRAINMOD was found to be adequate in predicting spring snowmelt hydrology, except for subsurface drainage at one site. It was found that soil characteristics had a major influence on model performance.

Key words: DRAINMOD, agricultural drainage, hydrological modeling, spring snowmelt, cold climate conditions.

Résumé : Il existe peu de modèles informatiques qui simulent le gel/dégel d'hiver et l'hydrologie de la fonte des neiges printanière pour les terres agricoles ayant un réseau de drainage par canalisation souterraine. Le modèle DRAINMOD, largement utilisé pour simuler les écoulements des réseaux de drainage par canalisation souterraine, n'a pas été utilisé de manière extensive durant les périodes froides dans l'Est du Canada. La présente étude analyse le rendement de DRAINMOD à prédire de drainage sous la surface et l'écoulement de surface dans le Sud du Québec durant la fonte des neiges printanière. Le modèle a été validé en utilisant cinq années de données de terrain. DRAINMOD s'est révélé être adéquat pour prédire l'hydrologie de la fonte des neiges printanière, sauf pour le drainage sous la surface à un seul site. Les caractéristiques des sols influencent grandement le rendement du modèle. [Traduit par la Rédaction]

Mots-clés : DRAINMOD, drainage agricole, modélisation hydrologique, fonte des neiges printanière, conditions climatiques froides.

Introduction

Artificial drainage is a widely practiced agricultural water management intervention in the humid, cold climate conditions of eastern Canada. The primary function of subsurface or tile drainage systems is to remove excess soil water from intensively cultivated fields (Fausey et al. 1987); this may be either to accommodate a longer growing season by facilitating earlier field operations, or to remove excess water from the root zone during the growing season (Skaggs and Van Schilfgaarde 1999). The economic benefits of agricultural land drainage are well documented, and extensive research has been conducted to optimize drainage design, assess environmental impacts, and monitor hydrological and water quality changes arising from the practice (Chikhaoui et al. 2006; Skaggs et al. 1995).

Field data collection is one approach for assessing the performance of a drainage system; however, this method is costly and long-term monitoring studies are difficult to sustain. Computer modeling has thus become a reliable complementary tool for simulating the hydrological and water quality processes of various drainage designs and management scenarios under a wide range of environmental conditions. Several hydrological simulation models have been developed to predict surface and subsurface flow in different regions. These include: DRAINMOD (Skaggs 1976), EPIC (Williams et al. 1984), GLEAMS (Leonard et al. 1987), WEPP (Nearing et al. 1989), ADAPT (Warld et al. 1988), and SWAT (Arnold et al. 1993). Each model is unique and they all require extensive input data for successful calibration and subsequent use.

Limited studies have been conducted to evaluate these models for the cold climate conditions of eastern Canada, specifically southern Quebec (Turcotte et al. 2005). Cold climate hydrology presents a challenge for drainage modeling. It is important that the hydrological model effectively simulates winter freeze–thaw conditions and spring snowmelt, which is often the major hydrological event of the year (Enright and Madramootoo 2004). Accurately modeling spring snowmelt is crucial because it is usually also the major nutrient transport event of the year (Jamieson 2001; Jamieson et al. 2003). The ability to correctly predict these peak events allows for appropriate actions to be taken in mitigating or managing subsequent water quality and environmental impacts (Sands et al. 2003).

DRAINMOD version 6.1 was chosen to simulate field drainage in this study. It is a process-based, field-scale model widely used in North America to simulate outflows from subsurface tile drainage systems. It has been successfully used for different soil types and crop conditions (Helwig et al. 2002; Sands et al. 2003; Wang et al. 2006). DRAINMOD is also reported to have a simpler calibration process (Sands et al. 2003). More recent versions of DRAINMOD include components for snow accumulation and melting, and soil freeze–thaw processes for use in cold climates (Luo et al. 2000, 2001).

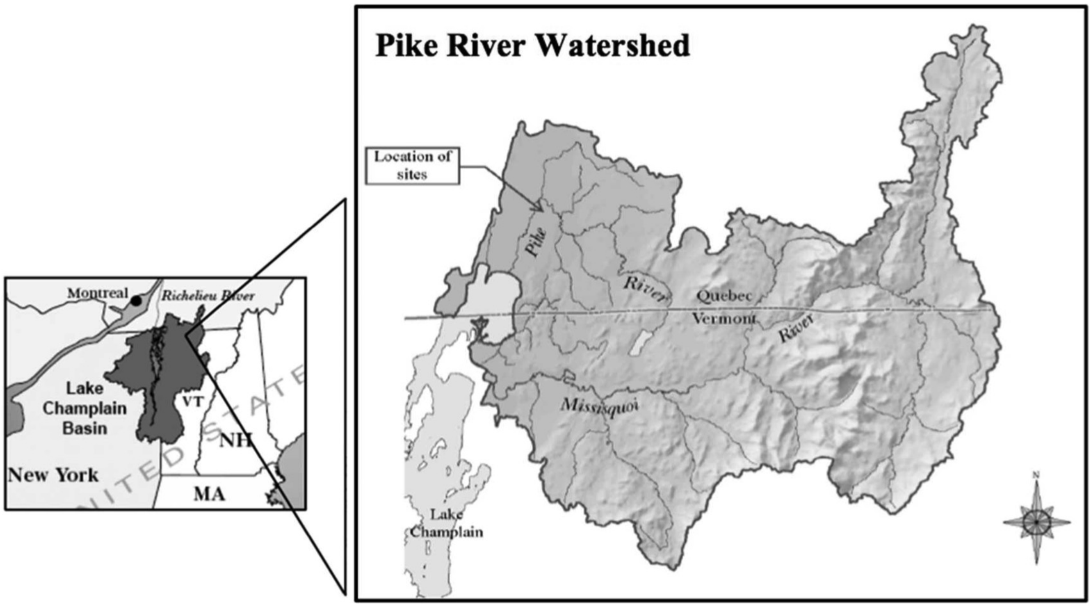
Overall good DRAINMOD performance in simulating subsurface drainage in cold climate conditions has been demonstrated by Dayyani (2010), Luo et al. (2001), and Sands et al. (2003). Luo et al.

Received 28 August 2013. Accepted 29 January 2014.

J. Morrison, C.A. Madramootoo, and M. Chikhaoui.* Brace Centre for Water Resources Management, McGill University, Macdonald Campus, 3 Stewart Park, 21 111 Lakeshore Road, Ste. Anne de Bellevue, QC H9X 3V9, Canada.
Corresponding author: J. Morrison (e-mail: jane.morrison@mail.mcgill.ca).
*Current affiliation and address: Institute of Agronomy and Veterinary Hassan II, P.O. Box 6608, 10101 Rabat, Morocco.

Can. J. Civ. Eng. **41**: 275–284 (2014) dx.doi.org/10.1139/cjce-2013-0416

Fig. 1. Site locations relative to the Pike River watershed.



(2001) analyzed DRAINMOD's performance in predicting water table depth and subsurface flow rate at three sites in cold climate locations. Unlike the work conducted in this study, Luo et al. (2001) did not measure surface runoff, there was no specific snowmelt analysis, and subsurface flow rate was examined rather than runoff volume. Sands et al. (2003) compared the performance of DRAINMOD to another hydrological model, ADAPT, within a cold climate. This study conducted a thorough analysis of both models' performance under several scenarios. Although, the analysis was only conducted over the two year calibration period and there was no exclusive data set used to validate the models. Furthermore, the study only analyzed the models' ability in predicting subsurface drainage, and surface runoff was not considered. Dayyani (2010) examined the performance of DRAINMOD in simulating subsurface drainage in a cold climate, pairing it with the WARMF model to simulate surface runoff. However, the study did not involve a lengthy discussion on snowmelt predictions. In studies by both Sands et al. (2003) and Dayyani (2010) only one experimental field site was examined, therefore discussions did not consider the effects of specific field properties on model performance.

The main objectives of this paper are therefore to (*i*) evaluate the hydrological predictions of DRAINMOD for surface runoff and subsurface drainage under the cold climate conditions of southern Quebec; (*ii*) compare the effectiveness of DRAINMOD in predicting flows during spring snowmelt to the entire year; and (*iii*) examine the effects of the different properties of two field sites on model performance. An emphasis is placed on subsurface drainage as this aspect of the cold climate drainage process is less understood.

Materials and methods

Site description

The data used in this study was collected from monitoring stations installed in October 2000 at the edge of two tile-drained agricultural fields located in the Pike River watershed, about 70 km southeast of Montreal, Quebec (Fig. 1). These two fields, characterized as Site A and Site B, are situated on privately-owned farms and are located approximately 3 km apart. Site A is located on a dairy farm with a surface drainage area of 6.0 ha, a subsurface drainage area of 5.9 ha and a land slope of 2.6%. Site B is located on the farm of a swine and cash crop producer, and has a surface drainage area of 6.9 ha, a subsurface drainage area of 7.8 ha and a land slope of 0.8%.

Both sites have a conventional, parallel tile drainage system that consists of buried plastic corrugated laterals of 11 cm diameter, and outlets of 21 cm diameter to a surface ditch. The system was installed with a trenchless plow in a systematic pattern. The outlets are made of corrugated plastic pipe for Site A and clay pipe for Site B. Lateral tile spacing is 13 m at Site A and 10 m at Site B, and the average tile drain depth at both sites is 1 m.

Soil classification of the sites was obtained from local soil surveys. The soil at Site A is a Rubicon sandy loam, exhibiting fair internal drainage with sand and clay contents of 59% and 10%, respectively. The soil types at Site B are: Sainte Rosalie clay loam (70%), Suffield clay loam (20%), and Bedford sandy clay loam (10%). The internal drainage of this soil is imperfect and contains 22% sand and 40% clay. Both soils are characterized by a granular structure. Saturated hydraulic conductivity values were obtained from the regional soil quality inventory (MAPAQ 1990) and verified by a physicochemical analysis of soil samples (Abou Nohra 2006). Soil characteristics are presented in Table 1.

Site A was cultivated in corn, alfalfa, clover, and grass, and Site B was cultivated in corn, barley and soybeans. The cropping sequence for both sites is presented in Table 2. The growing season typically lasts from early–mid-May to early–mid-October. Conventional tillage with a mouldboard plough was practiced in the fall at both sites for all study years, except Site A in 2004 and Site B in 2005. The fields were not irrigated. Although the sites were instrumented in October 2000, data from 2001 was unusable as a result of an equipment malfunction and was excluded from this study.

Data collection

The 30-year climatic normal annual precipitation recorded at Environment Canada's Philipsburg weather station located approximately 9 km from the sites is 1096 mm, with an annual snowfall equivalent of 204 mm. Rainfall was measured at each site using a tipping bucket rain gage (Texas Instruments TE525M, 0.1 mm tip) and air temperature was recorded using a thermistor (Campbell Scientific 107). The estimated total annual potential evapotranspiration for the region is 600 mm (Gollamudi et al. 2007). This region has an average annual temperature of 6.8 °C and a frost-free period of 155 d (Jamieson et al. 2003). Based on data from Environment Canada, the average temperature during the growing season at Philipsburg station is 16.1 °C.

Table 1. Site characteristics and DRAINMOD inputs.

	Site A			Site B		
Soil characteristics:						
Layer	1	2	3	1	2	3
K_s (cm/h)	3.6	1.3	0.9	2.9	0.2	0.1
Depth (cm)	0–30	30–60	60–100	0–30	30–60	60–100
Soil texture	Sandy loam	Loam	Silt loam	Sandy loam	Clay loam	Silty clay loam
System design:						
Depth of drain (cm)	100			100		
Spacing between drains (cm)	1300			1000		
Effective radius of drain (cm)	0.35			0.35		
Impermeable depth (cm)	700			700		
Drainage coefficient (cm/d)	1			1		
Initial water table depth (cm)	50			50		
Max. subirrigation pump capacity (cm/d)	0			0		
Max. surface storage (cm)	0.5			0.5		
Kirkham's depth for flow to drains (cm)	0.25			0.25		
Soil temperature:						
Computational depth functions (ZA/ZB)	2.5			2.5		
	1.2			1.2		
Soil thermal conductivity functions (TKA/TKB)	0.4			0.4		
	1.3			1.3		
Rain–snow dividing temp. (°C)	0			0		
Snowmelt base temp. (°C)	2			2		
Snowmelt coefficient (mm/d)	5			5		
Critical ice content (cm^3/cm^3)	0.2			0.2		
Snow density (kg/m^3)	100			100		
Phase lag for air temp. sine wave (h)	8			8		
Soil temp., bottom of profile (°C)	7.2			7.2		

Table 2. Tillage and crop rotations in the experimental fields.

	Crop		Tillage	
Year	Site A	Site B	Site A	Site B
2002	Corn	Barley	Conventional	Conventional
2003	Corn	Corn	Conventional	Conventional
2004	Alfalfa and clover	Corn	None	Conventional
2005	Alfalfa and clover	Corn	Conventional	None
2006	Alfalfa and grass	Soybeans	Conventional	Conventional

The two experimental fields were intensively monitored for surface runoff and subsurface drainage outflows, as well as for various water quality parameters. The instrumentation, data collection and sampling methodology used during the study period were identical for both sites.

Surface runoff was continuously measured at the outlet of each field using H-flumes with two water level sensors. The primary sensor was an SR50 ultrasonic depth sensor (Campbell Scientific Inc., Utah, USA) and the secondary (backup) sensor was a Keller-173 pressure transducer (Campbell Scientific Inc., Utah, USA). Surface runoff volumes were calculated based on a rating curve, specific to the flume specifications. Similarly, outflows from the subsurface drainage systems was continuously recorded. Two sensors were installed at both sites: the primary sensor was a ProSonic DMU 93 ultrasonic flow meter (Endress and Hauser Canada Ltd., Ontario, Canada) and the secondary (backup) sensor was an IF-200 fixed insertion flow meter (Global Water Instrumentation Inc., California, USA). All meteorological and hydrological data was measured at 5 s intervals and stored as means or totals over 15 min periods on a CR21X datalogger (Campbell Scientific Inc., Utah, USA).

The sites were also equipped with soil temperature thermocouples and barometric pressure data loggers for year-round water level monitoring. All field data collected was checked rigorously for accuracy; a complete dataset was available for the study period, except for 2001. Further information regarding surface runoff and subsurface discharge sampling procedures at these sites can be found in Eastman et al. (2010), Enright and Madramootoo (2004), and Gollamudi et al. (2007).

Model description

DRAINMOD is a deterministic hydrologic field scale model developed by Skaggs (1978), which simulates surface runoff, subsurface drainage, evapotranspiration, infiltration and water table fluctuations. It has been used successfully for a range of spatial scales, and soil and crop conditions (Dayyani 2010, Helwig et al. 2002; Luo et al. 2001 and Sands et al. 2003). The model uses a water balance protocol of the soil profile, located midway between adjacent tile drains and from the impermeable layer up to the soil surface. The water balance equation is given by:

$$(1) \qquad \Delta V_a = D + \mathrm{ET} + \mathrm{DS} - F$$

where ΔV_a is the change in air volume (cm), D is the lateral drainage (cm), ET is the evapotranspiration (cm), DS is the deep seepage (cm), and F is infiltration (cm).

The model uses Hooghoudt's equation to calculate subsurface drainage rates, which is based on the Dupuit-Forchheimer assumptions with a correction factor for convergence near the drains (Van Schilfgaarde 1974). When there is surface ponding due to the water table rising to the surface, the drainage rate is estimated using the equation derived by Kirkham (1957). Surface runoff is computed from a water balance at the ground surface:

$$(2) \qquad P = F + \mathrm{RO} - \Delta S$$

where P is precipitation (cm), F is infiltration (cm), RO is runoff (cm), and ΔS is the change in surface water storage (cm).

Infiltration is estimated using the Green-Ampt equation and deep seepage is estimated using Darcy's law. Evapotranspiration data can be input directly, or is estimated using the Thornthwaite (1948) model. When the daily maximum temperature is below a user-input rain/snow dividing temperature value, daily precipitation is regarded as snowfall with a consideration for accumulation. Snowmelt occurs when air temperature rises above a user-input snowmelt base temperature and is determined by the heat flow equation. Frozen soil conditions are simulated by simultaneously solving water and heat flow equations, based on the principles of mass and energy conservation (Luo et al. 2000). During freezing conditions (below zero temperature), ice content is calculated in the soil profile and soil hydraulic conductivity and infiltration are modified accordingly (Sands et al. 2003). A detailed description of DRAINMOD can be found in Skaggs (1978).

Model inputs

Input data required for DRAINMOD includes weather data, drainage design parameters, soil properties, crop information, and management practices. More recent DRAINMOD versions require soil thermal conductivity and snowfall related parameters for modeling fields under cold conditions.

Precipitation and air temperature recorded at the experimental sites were used in the model. The heat index was calculated using monthly climate normals from 1971 to 2000, based on weather data at the Philipsburg station, and the following equations:

$$(3) \qquad i = \left(\frac{T_{\mathrm{a}}}{5}\right)^{1.51}$$

$$(4) \qquad I = \sum_{j=1}^{12} i_j$$

where i is the monthly heat index, T_{a} is the mean monthly air temperature (°C), I is the annual heat index, and j is month (Xu and Singh 2001).

Most drainage design parameters, soil properties, crop information, and soil management practices were measured and available. Because DRAINMOD only allows for one crop type to be considered over the analysis period, corn crops were assumed for all years at both sites. A similar assumption was made for the DRAINMOD simulations carried out by Sands et al. (2003).

Normalized soil water content was calculated using the Brooks and Corey equation (Rawls et al. 1983):

$$(5) \qquad S_{\mathrm{e}} = \left(\frac{\psi_{\mathrm{b}}}{\psi}\right)^{\lambda}$$

where S_{e} is normalized water content, ψ_{b} is bubbling pressure (cm), ψ is suction or pressure (cm), and λ is the pore size distribution index.

Green Ampt parameters for infiltration were calculated using the following equations:

$$(6) \qquad A = K_{\mathrm{s}} \times M \times \mathrm{Sav}$$

$$(7) \qquad B = K_{\mathrm{s}}$$

where A and B are the Green Ampt parameters, K_{s} is saturated conductivity (cm/h), M is drainable porosity, and Sav (cm) is suction at the wetting front.

Furthermore, lateral hydraulic conductivity was calculated as twice the saturated hydraulic conductivity (Singh et al. 2006). Soil thermal conductivity and snowfall related parameters were estimated based on other studies carried out in the region (Gollamudi 2006) and on other DRAINMOD studies in fields with similar cold-climate conditions (Luo et al. 2000).

Although DRAINMOD is capable of estimating ET, input values were obtained using the CROPWAT model version 8.0 (Smith 1992) for improved accuracy. The model was run with the following input parameters: altitude, geographic coordinates, daily minimum and maximum temperature, daily humidity, and daily wind speed. Wind and humidity parameters were obtained from the Frelighsburg weather station, located within 20 km from the fields. Hours of sunlight and radiation were estimated within the CROPWAT model. Reference ET output was based on the Penman–Monteith combination method.

Table 3. Modified NSE values for calibration and validation at both sites.

	Calibration		Validation	
Site	Subsurface drainage	Surface runoff	Subsurface drainage	Surface runoff
A	0.5	0.6	0.6	−0.2
B	0.3	0.5	0.1	0.1

Table 1 provides a summary of the input data used to operate DRAINMOD for the purpose of this study.

Results and discussion

Model calibration

DRAINMOD was run from March 2002 through June 2006. Data from March 2002 through December 2003 was used to calibrate the model. Multiple simulations were conducted to determine sensitive parameters and optimize calibration methodology. Sensitive parameters were determined to be: hydraulic conductivity, soil water content, monthly ET adjustment factors, and surface storage. Final calibrations involved a systematic refinement of these parameters, and a comparison of simulated and observed subsurface drainage and surface runoff at both sites. Model performance was assessed using a modified Nash–Sutcliffe efficiency (NSE) statistic. The calibrations resulted in a significant improvement in model performance.

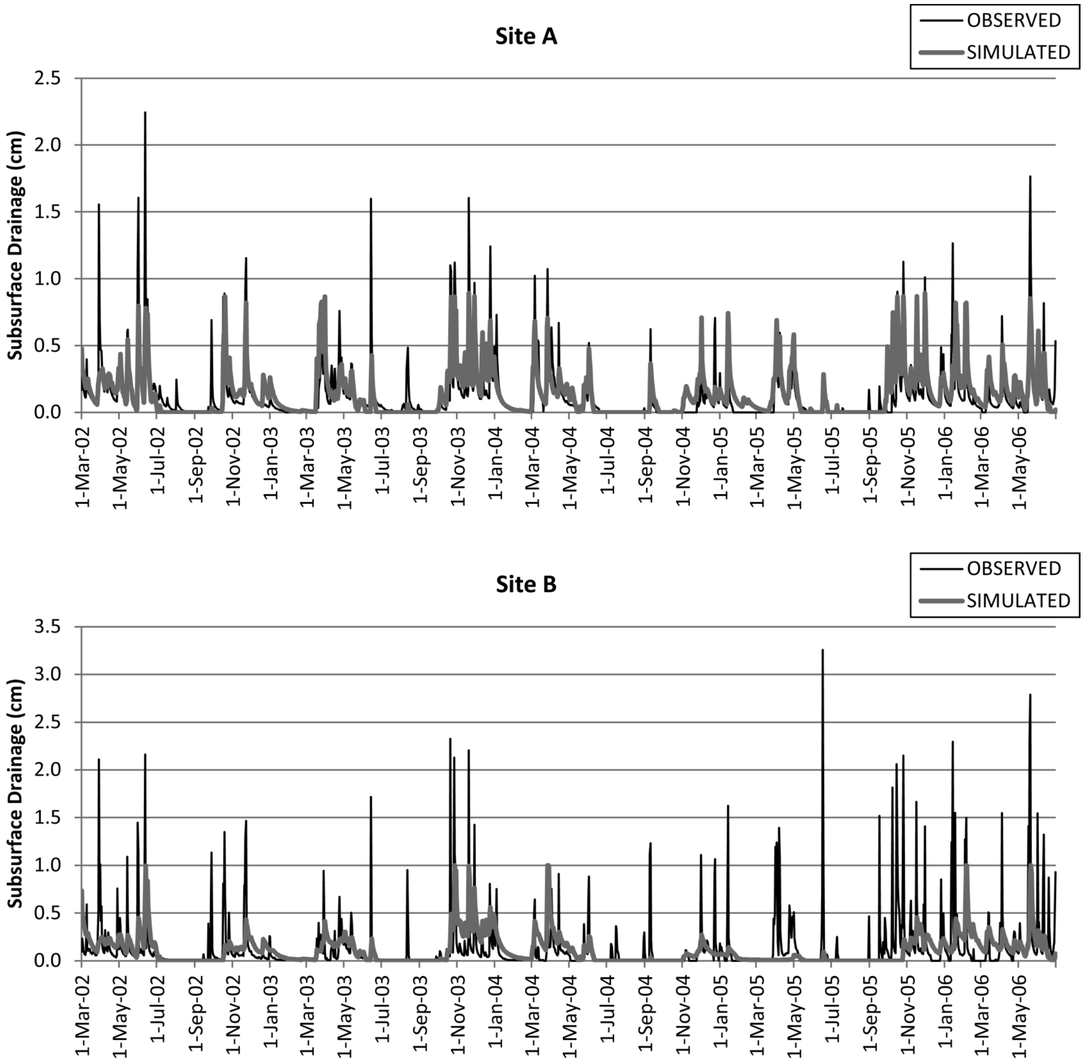
Nash–Sutcliffe efficiency was chosen due to its frequent use in hydrological modeling. A disadvantage of NSE is an overestimation of model performance for higher flow dynamics, and an underestimation for lower flow dynamics. This is due to the fact that the difference between observed and simulated values is squared, resulting in the neglect of lower values (Krause et al. 2005). Due to the variation of flows experienced at the experimental sites, in particular low surface runoff flows, a modified version of NSE was used to reduce its sensitivity to high flows, and increase its sensitivity to low flows. The need for squared differences was eliminated by introducing absolute value signs, as seen below (Krause et al. 2005):

$$(8) \qquad \mathrm{NSE}^* = 1 - \frac{\sum_{i=1}^{N} |P_i - O_i|}{\sum_{i=1}^{N} |O_i - O_{\mathrm{avg}}|}$$

where NSE* is the modified NSE, N is total number of months, i is month, P_i is the model predicted value in month i, O_i is the observed value in month i, and O_{avg} is the average of observed values.

Although DRAINMOD simulates output on a daily basis, model predictions and observed values were compared on a monthly basis. Table 3 lists the modified NSE values for subsurface drainage and surface runoff at both sites for the calibration period of March 2002 through December 2003. An NSE value of one indicates a perfect fit of observed versus simulated values, whereas values lower than zero would deem the model inadequate (Krause et al. 2005). For the calibration period, modified NSE values of 0.5 and 0.3 were achieved for subsurface drainage at Site A and Site B, respectively, and modified NSE values of 0.6 and 0.1 were obtained for surface runoff at Site A and Site B, respectively. All values are greater than zero, indicating adequate model calibration.

Fig. 2. Observed vs. simulated daily subsurface drainage.



Model validation

Model validation was carried out with an entirely separate dataset from January 2004 through June 2006. Model performance during validation was also assessed using the modified NSE. Table 3 lists the modified NSE values for subsurface drainage and surface runoff at both sites during the validation period; modified NSE values of 0.6 and 0.1 were achieved for subsurface drainage at Site A and Site B, respectively, and modified NSE values of –0.2 and 0.1 were obtained for surface runoff at Site A and Site B, respectively. Validation results were mostly good, with modified NSE values greater than zero in all cases except for surface runoff at Site A.

Subsurface drainage

At both sites, subsurface drainage was the primary source of water removal. Surface runoff was quite low.

Figure 2 shows a daily comparison of observed and simulated values for subsurface drainage at both sites, while Fig. 3 shows a monthly comparison. Based on these figures, DRAINMOD simulates the general trends of daily and monthly flow patterns well at both sites. The general pattern of daily drainage and peak flows was also well simulated by Dayyani (2010), Luo et al. (2001), and Sands et al. (2003). In the study presented in this paper, there is a general tendency for DRAINMOD to underestimate daily peak flows at both sites (Fig. 2). Conversely, Sands et al. (2003) reported that DRAINMOD overpredicted the peak values of larger drainage events.

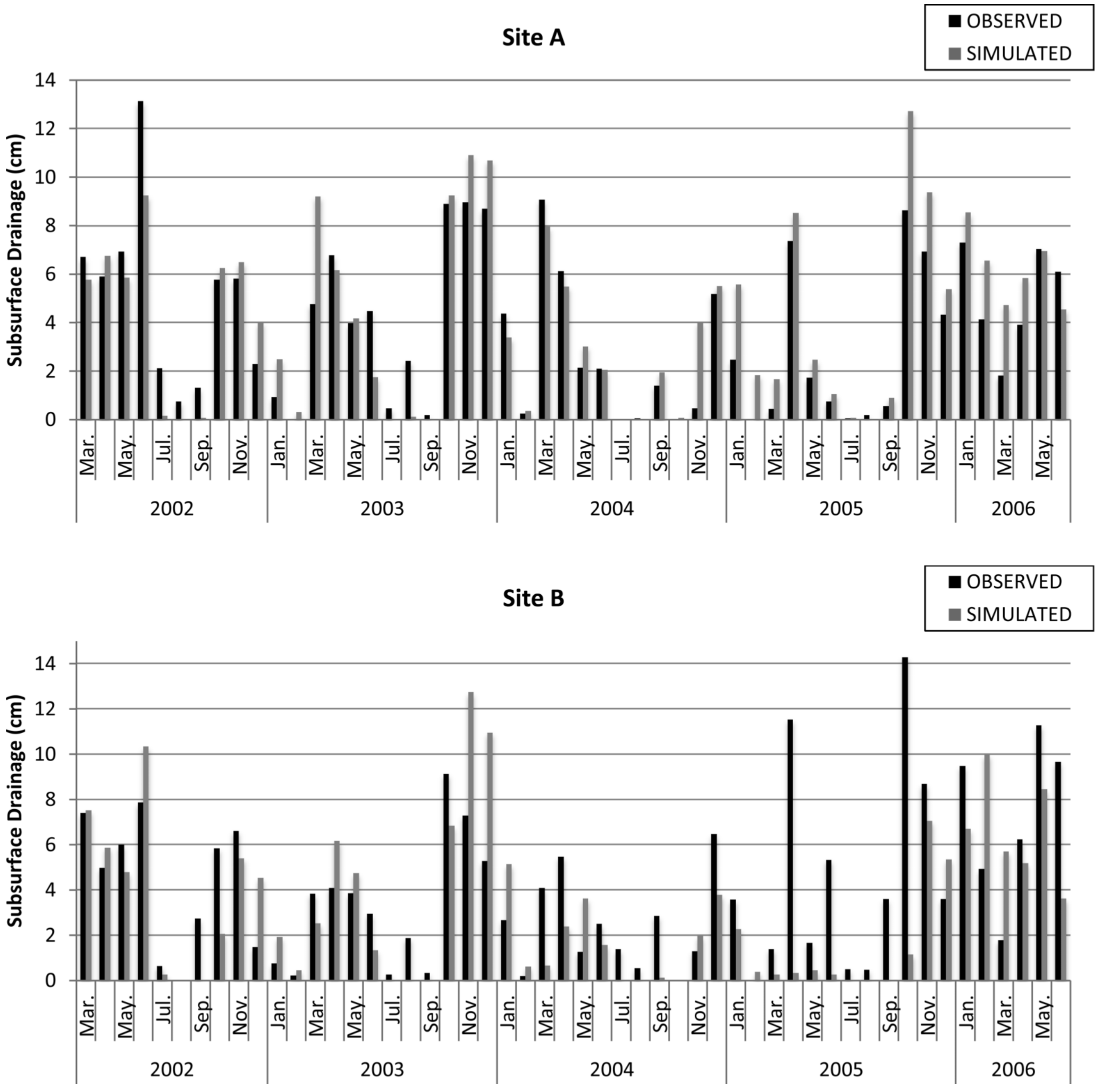
As seen in Fig. 4, DRAINMOD overestimated subsurface drainage in all years except 2002 at Site A, and underestimated subsurface drainage in all years except 2003 at Site B. Although cumulative yearly flows show rather large disparities, the model predicted subsurface drainage adequately at both sites when evaluated on a monthly basis, with Site A showing better results. Any overestimation of subsurface drainage could be explained by the lack of consideration for macropore flow in the model (Chikhaoui et al. 2008). Model predictions may have been improved if observed ET was used rather than predicted ET.

Particularly poor simulations were exhibited in 2005 at Site B. This could be attributed to exceptionally high flows observed in that year. This is the only year in which Site B was not tilled, which could help to explain the higher drainage flows observed. No-till farming conserves soil moisture and improves drainage because of reduced evaporation and improved soil permeability (Rice 1983).

Surface runoff

Figure 5 shows a monthly comparison of observed and simulated values for surface runoff at both sites. Surface runoff values were very low throughout the study period, and as a result, consistent flow patterns between observed and simulated data are

Fig. 3. Observed vs. simulated monthly subsurface drainage.



less clear than with subsurface drainage. In general, model performance declined when surface runoff values were below a threshold of 1 to 2 cm. At Site A, DRAINMOD underestimated surface runoff from 2002 to 2004, and overestimated surface runoff in 2005 to 2006. At Site B, surface runoff was underestimated in all years.

DRAINMOD was unable to adequately predict surface runoff during the validation period at Site A. This poor performance is evident by a number of poorly predicted events throughout validation years (January 2004 through June 2006). When analyzing the data it is clear that the modified NSE value of –0.2 is due to only a few outlier cases where the model failed to accurately predict larger flow events. Furthermore, the low runoff volumes that occurred during the calibration years may have been insufficient to accurately calibrate the model, explaining this poor performance. This is always a challenge with agricultural runoff models, where low flow events often occur.

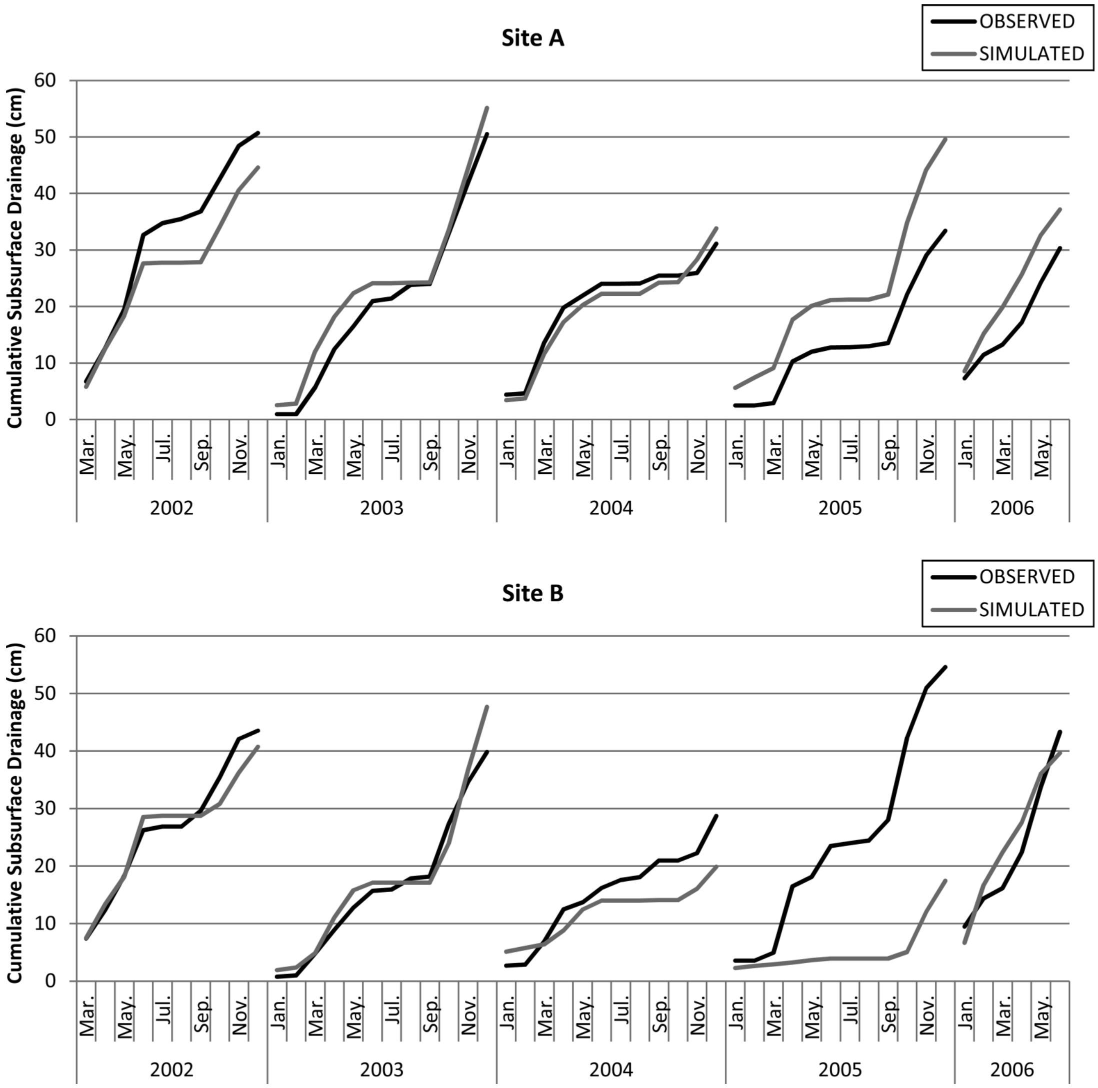
Furthermore, because of model limitations, DRAINMOD was run assuming that both sites were cultivated in corn for all years. Vegetation type has an impact on surface runoff volume because row crops (such as corn and soybeans) are not as efficient in terms of reducing surface runoff as grass and alfalfa. The latter are more dense, create a lower soil moisture content due to a higher level of transpiration in the root zone, and exhibit improved infiltration. In addition, leguminous grass crops and alfalfa usually promote improved soil structure, which facilitates infiltration thereby reducing runoff (Eastman 2008). Site B was cultivated in corn, barley, and soybeans (refer to Table 2) which are all row crops, and exhibit similar surface runoff patterns. On the other hand, Site A was cultivated in corn (a row crop) during calibration; and alfalfa, clover, and hay during validation. DRAINMOD's poor performance in predicting surface runoff at Site A during the validation period could also be a result of the variation in crop type between calibration and validation periods.

In general, surface runoff was predicted more poorly than subsurface drainage (refer to Table 3). Similar results have been found in past studies, and it is generally understood that DRAINMOD performs better at predicting subsurface drainage (Dayyani 2010). This is likely due to the lower volumes seen with surface runoff and poor model sensitivity to lower flows.

Spring snowmelt analysis

Sands et al. (2003) showed that DRAINMOD performed less satisfactorily for snowmelt periods, compared to the early season of January through June. In the study presented in this paper, model output was evaluated in two time frames: the entire year and spring snowmelt. Studies by Romero et al. (2002) and Jones and Pomeroy (2001) indicate that the Canadian snowmelt period generally occurs

Fig. 4. Observed vs. simulated cumulative subsurface drainage.



between mid-March and mid-May. A spring snowmelt period extending from 1 March to 31 May was utilized for this study to account for year to year variability in snowmelt occurrences. Figure 6 compares the observed and simulated total subsurface drainage flows during both the spring snowmelt period and annually. It can be seen that in all years model performance does not vary significantly between both periods; although poor predictions in 2005 seem to have been worst year-round than during the spring snowmelt period at Site A. Table 4 lists the modified NSE values for both time frames, for all years, for both subsurface drainage and surface runoff. For subsurface drainage, the modified NSE values at Site A were 0.6 for year-round predictions and 0.4 for spring snowmelt predictions, and at Site B they were 0.2 for year-round predictions and 0.0 for spring snowmelt predictions. At both sites, predictions were slightly poorer for the spring snowmelt period. For surface runoff, the modified NSE values at Site A were 0.2 for year-round predictions and 0.4 for spring snowmelt predictions, and at Site B they were 0.3 for year-round predictions and 0.4 for spring snowmelt predictions. At both sites, surface runoff predictions were slightly better for the spring snowmelt predictions.

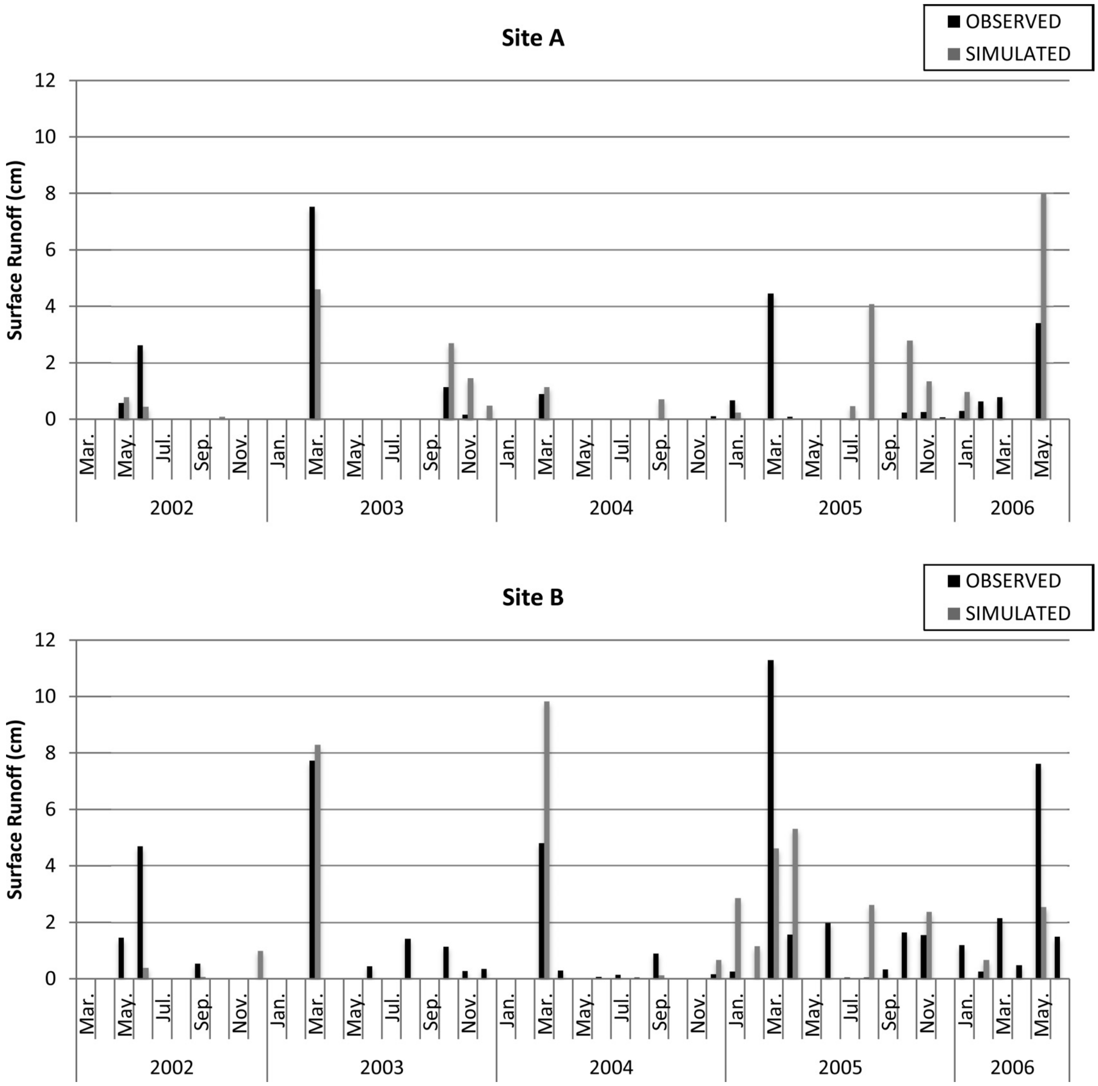
In general, DRAINMOD predicted subsurface drainage slightly less well during the spring snowmelt period, and predicted surface runoff slightly better. The improved surface runoff predictions during the spring snowmelt period are most likely a result of the higher flow volumes exhibited. DRAINMOD proved to be adequate in predicting spring snowmelt behaviour, having modified NSE values greater than zero, except for subsurface drainage at Site B. This poor performance at Site B is likely due to the soil's poor drainage characteristics.

As a result of climate change, more frequent freeze–thaw cycles are predicted (Henry 2008), which one might expect to alter subsurface drainage and surface runoff partitioning behaviour. Nevertheless, Xiuqing and Flerchinger (2001) found that during these freeze–thaw events the ground is likely to remain frozen or exhibit ice layering (caused by the freeze–thaw cycling), inhibiting water infiltration and percolation to tile drains. Therefore, future surface runoff volumes are predicted to remain relatively consistent despite climate change and an increased frequency of soil freeze–thaw cycles.

Site differences

Overall, DRAINMOD performed better at predicting drainage at Site A compared to Site B; except for surface runoff during validation (Table 3). This can be attributed to the more uniform soil conditions at Site A, while phenomena such as soil cracking and preferential flow were observed at Site B. This is attributed to the higher clay content at Site B.

Fig. 5. Observed vs. simulated monthly surface runoff.



The better simulation of surface runoff at Site B during validation could be due to the higher observed surface runoff (see Fig. 5). Lower flows, similar to those at Site A during validation, are more difficult to predict. The low surface runoff at Site A can be explained by the fact that its soil is coarse textured, where larger pore spaces allow for greater water retention, infiltration, and removal by the tile drains. Similarly, the greater volume of surface runoff at Site B can be attributed to its finer textured soil, where smaller pore spaces and non-connecting pores result in lower infiltration (Eastman 2008).

Conclusions

Artificial drainage is commonly used in temperate humid climates, such as eastern Canada, to manage excess soil water and improve the productivity of poorly drained agricultural soils. Computer modeling is a convenient tool for analyzing the hydrological and water quality processes of various drainage designs and management scenarios under a wide range of environmental conditions. In cold climate regions, very little work has been previously done to assess and validate agricultural drainage models during winter freeze–thaw conditions and spring snowmelt.

This study evaluated the performance of DRAINMOD for simulating surface runoff and subsurface drainage during the periods of spring freeze and thaw and snowmelt, by comparing simulations with measured data from two experimental field sites in Quebec. The model was first calibrated with data from March 2002 through December 2003 and then validated with an independent dataset from January 2004 through June 2006. Calibration provided a significant improvement in model performance as confirmed by good modified NSE monthly values at both sites, except for surface runoff at Site A. At both sites, subsurface drainage was the primary water removal process, and surface runoff was quite low. The poor prediction of surface runoff during validation at Site A can possibly be attributed to the low measured runoff volumes, which may have been insufficient to accurately calibrate the model. In addition, this could be due to the fact that DRAINMOD did not account for a variation in crop type between calibration and validation.

To assess the effectiveness of DRAINMOD in a cold climate, this study specifically examined its performance during spring snowmelt. DRAINMOD predicted subsurface drainage slightly less well during the spring snowmelt period of March through May, and predicted surface runoff slightly better. Although, model performance did not vary greatly between spring snowmelt and year-round time frames. DRAINMOD proved to be adequate in predicting spring snowmelt behaviour, except for subsurface drainage at Site B. The poor performance at Site B is likely due to phenomena such as soil cracking and preferential flow.

Fig. 6. Year-round and spring snowmelt predictions of subsurface drainage.

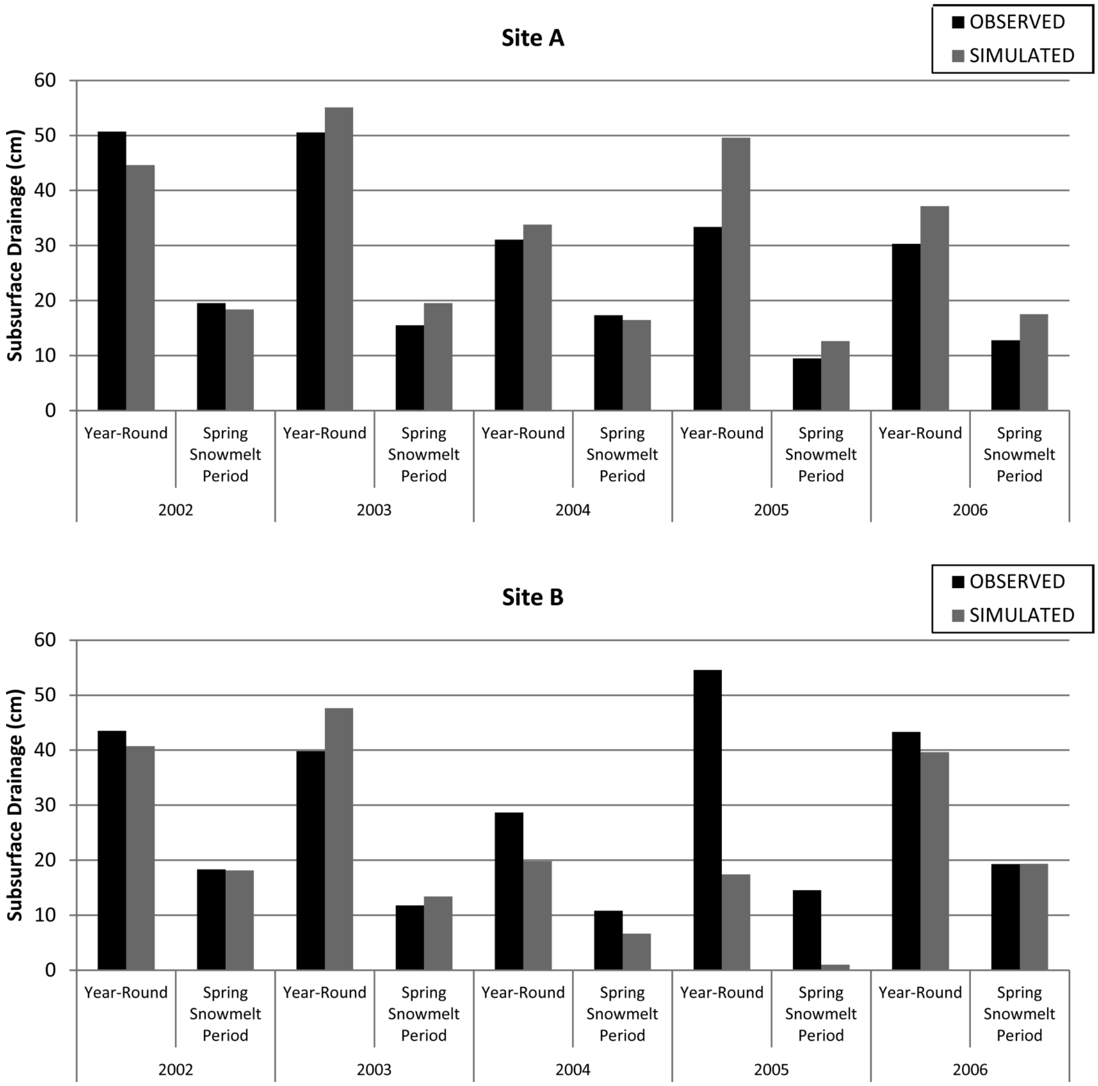


Table 4. Modified NSE values for various time frames.

Site	Time frame	Subsurface drainage	Surface runoff
A	Year-round	0.6	0.2
	Spring snowmelt period*	0.4	0.4
B	Year-round	0.2	0.3
	Spring snowmelt period*	0.0	0.4

*March through May.

These findings indicate that DRAINMOD predicts monthly subsurface tile drainage outflows well (year-round and during spring snowmelt) under the specific geographical and climatic conditions of this study area. DRAINMOD predicted surface runoff less well, and was unable to adequately predict runoff when flows were below a threshold of 1 to 2 cm. Although DRAINMOD has been greatly improved for use in cold climate regions, certain limitations still exist in its overall effectiveness. An improvement in surface runoff predictions could be achieved with a greater sensitivity to low flows. In addition, the capability to input yearly crop information could improve calibration and validation consistency. Furthermore, a method to better capture the behaviour of soils with poor drainage characteristics is needed; for example, by incorporating an algorithm for macropore flow.

Acknowledgements

This research was funded by the Fonds Québécois de la Recherche sur la Nature et les Technologies (FQRNT) and by the Max Bell Foundation. The authors thank those who have contributed to this study over the years: Mr. Apurva Gollamudi (McGill University), Mr. Peter Enright (McGill University), Mr. Richard Lauzier (Ministère de l'Agriculture, des Pêcheries et de l'Alimentation du Québec), and Mr. Martin Mimeault (Ministère du Développement Durable, de l'Environnement et des Parcs), as well as field assistants and technicians. Appreciation is expressed towards the Institut de Recherche et de Développement en Agroenvironnement for their technical assistance and involvement with the water sample analysis. Sincere gratitude is also directed to the two land owners who allowed the use of their fields for this study.

References

Abou Nohra, J. 2006. Modeling phosphorus transport in soil and water. Ph.D. thesis, Department of Bioresource Engineering, McGill University, Montreal, QC.

Arnold, J.G., Allen, P.M., and Bernhardt, G. 1993. A comprehensive surface groundwater flow model. Journal of Hydrology, **142**: 47–69. doi:10.1016/0022-1694(93)90004-S.

Chikhaoui, M., Madramootoo, C.A., and Stämpfli, N. 2006. Effect of tile drain spacing on phosphorus losses from agricultural fields. *In* Proceedings of the 22nd Eastern Canadian Symposium of the Canadian Association on Water Quality, Concordia University, Montreal, QC., 3 November 2006.

Chikhaoui, M., Madramootoo, C.A., Eastman, M., and Michaud, A. 2008. Estimating preferential flow to agricultural tile drains. *In* Proceedings of the ASABE Annual International Meeting, Providence, Rhode Island, 29 July 2008.

Dayyani, S. 2010. Modeling hydrology and nitrogen fate and transport in a tile-drained agricultural watershed in a cold region. Ph.D. thesis, Department of Bioresource Engineering, McGill University, Montreal, QC.

Eastman, M. 2008. Field-scale nutrient transport monitoring and modeling of subsurface and naturally drained agricultural lands. M.Sc. thesis, Department of Bioresource Engineering, McGill University, Montreal, QC.

Eastman, M., Gollamudi, A., Stämpfli, N., Madramootoo, C.A., and Sarangi, A. 2010. Comparative evaluation of phosphorus losses from subsurface and naturally drained agricultural fields in the Pike River watershed of Quebec, Canada. Agricultural Water Management, **97**: 596–604. doi:10.1016/j.agwat.2009.11.010.

Enright, P., and Madramootoo, C.A. 2004. Phosphorus losses in surface runoff and subsurface drainage waters on two agricultural fields in Quebec. *In* Proceedings of the 8th International Drainage Symposium, Sacramento, California, 21 March 2004. American Society of Agricultural Engineers, St. Joseph, Michigan.

Fausey, N.R., Doering, E.J., and Palmer, M.L. 1987. Purposes and benefits of drainage. *In* Farm drainage in the United States: history, status and prospects. *Edited by* G.A. Pavelis. United States Department of Agriculture, Economic Research Service, Washington, D.C. pp. 4851.

Gollamudi, A. 2006. Hydrological and water quality modeling of agricultural fields in Quebec. M.Sc. thesis, Department of Bioresource Engineering, McGill University, Montreal, QC.

Gollamudi, A., Madramootoo, C.A., and Enright, P. 2007. Water quality modeling of two agricultural fields in southern Quebec using SWAT. Transactions of the ASAE, **50**(6): 1973–1980. doi:10.13031/2013.24100.

Helwig, T.G., Madramootoo, C.A., and Dodds, G.T. 2002. Modeling nitrate losses in drainage water using DRAINMOD 5.0. Agricultural Water Management, **56**: 153–168. doi:10.1016/S0378-3774(02)00005-7.

Henry, H. 2008. Climate change and soil freezing dynamics: historical trends and projected changes. Climate Change, **87**: 421–434. doi:10.1007/s10584-007-9322-8.

Jamieson, A. 2001. Evaluating phosphorus losses in surface and subsurface runoff from two agricultural fields in Quebec. M.Sc. thesis, Department of Agricultural and Biosystems Engineering, McGill University, Montreal, QC.

Jamieson, A., Madramootoo, C.A., and Enright, P. 2003. Phosphorus losses in surface and subsurface runoff from a snowmelt event on an agricultural field in Quebec. Canadian Biosystems Engineering, **45**: 1.1–1.7.

Jones, H.G., and Pomeroy, J.W. 2001. Early spring snowmelt in a small boreal forest watershed: influence of concrete frost on the hydrology and chemical composition of streamwaters during rain-on-snow event. *In* Proceedings of the 58th Eastern Snow Conference, Ottawa, Ont., 14–17 May 2001.

Kirkham, D. 1957. Theory of seepage of ponded water into drainage facilities. *In* Drainage of agricultural lands. *Edited by* J.N. Luthin. Agronomy Monograph 7, American Society of Agronomy and Soil Science Society of America, Madison, WI. pp. 139–181.

Krause, P., Boyle, D.P., and Bäse, F. 2005. Comparison of different efficiency criteria for hydrological model assessment. Advances in Geosciences, **5**: 89–97. doi:10.5194/adgeo-5-89-2005.

Leonard, R.A., Knisel, W.G., and Still, D.A. 1987. GLEAMS: Groundwater loading effects on agricultural management systems. Transactions of the ASAE, **30**(5): 1403–1428. doi:10.13031/2013.30578.

Luo, W., Skaggs, R.W., and Chescheir, G.M. 2000. DRAINMOD modifications for cold conditions. Transactions of the ASAE, **43**(6): 1569–1582. doi:10.13031/2013.3057.

Luo, W., Skaggs, R.W., Madani, A., Cizikci, S., and Mavi, A. 2001. Predicting field hydrology in cold conditions with DRAINMOD. Transactions of the ASAE, **44**(4): 825–834.

Ministère de l'Agriculture, des Pêcheries et de l'Alimentation du Québec (MAPAQ). 1990. Inventaire des problèmes de dégradation des sols agricoles du Québec, région agricole 6 Richelieu Saint-Hyacinthe, Gouvernement du Québec, Bibliothéque Nationale du Québec, pp. 119.

Nearing, M.A., Foster, G.R., Lane, L.J., and Finkner, S.C. 1989. A process-based soil erosion model for USDA water erosion prediction project technology. Transactions of the ASAE, **32**(5): 587–1593.

Rawls, W.J., Brakensiek, D.L., and Miller, N. 1983. Green-Ampt infiltration parameters from soils data. Journal of Hydraulic Engineering, **109**(1): 62–70. doi:10.1061/(ASCE)0733-9429(1983)109:1(62).

Rice, R.W. 1983. Fundamentals of no-till farming. American Association for Vocational Instructional Materials, Athens, Georgia.

Romero, D., Madramootoo, C.A., and Enright, P. 2002. Modelling the hydrology of an agricultural watershed in Quebec using SLURP. Canadian Biosystems Engineering, **44**: 1.11–1.20.

Sands, G.R., Jin, C.X., Mendez, A., Basin, B., Wotzka, P., and Gowda, P. 2003. Comparing the subsurface drainage flow prediction of the DRAINMOD and ADAPT models for a cold climate. Transactions of the ASAE, **46**: 645–656.

Singh, R., Helmers, M.J., and Qi, Z. 2006. Calibration and validation of DRAINMOD to design subsurface drainage systems for Iowa's tile landscapes. Agricultural Water Management, **85**: 221–232. doi:10.1016/j.agwat.2006.05.013.

Skaggs, R.W. 1976. Determination of the hydraulic conductivity-drainable porosity ratio from water table measurements. Transactions of the ASAE, **19**(1): 73–80. doi:10.13031/2013.35970.

Skaggs, R.W. 1978. A water management model for shallow water table soils. Water Resources Research Institute of the University of North Carolina Report 134, North Carolina State University, Raleigh, N.C.

Skaggs, R.W., and Van Schilfgaarde, J. 1999. Agricultural drainage. Agronomy Monograph 38, American Society of Agronomy, Madison, WI.

Skaggs, R.W., Brevé, M.A., Mohammad, A.T., Parsons, J.E., and Gilliam, J.W. 1995. Simulation of drainage water quality with DRAINMOD. Irrigation and Drainage Systems, **9**: 259–277. doi:10.1007/BF00880867.

Smith, M. 1992. CROPWAT: A computer program for irrigation planning and management. Issue 46 of FAO Irrigation and Drainage Paper, Food and Agriculture Organization of the United Nations, Rome, Italy.

Thornthwaite, C.W. 1948. An approach toward a rational classification of climate. Geological Review, **38**: 55–94.

Turcotte, R., Favre, A.-C., Lacombe, P., Poirier, C., and Villeneuve, J.-P. 2005. Estimation des débits sous glace dans le sud du Québec : comparaison de modèles neuronal et déterministe. Revue canadienne de génie civil, **32**(6): 1039–1050. doi:10.1139/l05-084.

Van Schilfgaarde, J. 1974. Nonsteady flow to drains. *In* Drainage for agriculture. *Edited by* J. Van Schilfgaarde. American Society of Agronomy, Madison, WI. pp. 245–307.

Wang, S., Prasher, S.O., Patel, R.M., Yang, C.-C., Kimc, S.-H., Madani, A., Macdonald, P.M., and Robertson, S.D. 2006. Fate and transport of nitrogen compounds in a cold soil using DRAINMOD. Journal of Computers and Electronics in Agriculture, **53**: 113–121. doi:10.1016/j.compag.2006.04.005.

Warld, A.D., Alexander, C.A., Fausey, N.R., and Dorsey, J.D. 1988. The ADAPT drainage and pesticide transport model. *In* Proceedings of Modeling Agricultural, Forest and Rangeland Hydrology, Chicago, Illinois, 12–13 December 1988. ASAE, St. Joseph, Michigan, pp. 129–141.

Williams, J.R., Jones, C.A., and Dyke, P.T. 1984. A modeling approach to determining the relationship between erosion and soil productivity. Transactions of the ASAE, **27**: 129–144. doi:10.13031/2013.32748.

Xiuqing, Z., and Flerchinger, G.N. 2001. Infiltration into freezing and thawing soils under differing field treatments. Journal of Irrigation and Drainage Engineering, **127**: 176–182. doi:10.1061/(ASCE)0733-9437(2001)127:3(176).

Xu, C.-Y., and Singh, V.P. 2001. Evaluation and generalization of temperature-based methods for calculating evaporation. Hydrological Processes, **15**: 305–319. doi:10.1002/hyp.119.