Modeling the influence of tile drainage flow and tile spacing on phosphorus losses from two agricultural fields in southern Québec

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

ABSTRACT

Tile drainage is a widely adopted water management practice in the eastern Canadian provinces of Québec and Ontario. It aims to improve the productivity of poorly drained agricultural fields. Nevertheless, studies have also shown that subsurface drainage is a significant pollution pathway to surface water. This study was undertaken to evaluate the effect of tile drain spacing on surface runoff, subsurface drainage flows, and phosphorus (P) loss from two tile-drained agricultural fields located near Bedford, Québec. Field data were used with the DRAINMOD model, and in developed regression models in order to perform the analysis. Both DRAINMOD and the regression models showed good performance. Simulation results indicated that when lateral tile drain spacing is increased, the volume of subsurface drain flow decreases, and the volume of surface runoff increases, at sites with sandy and clay loam soils. For every 5 m increase in drain spacing, total phosphorus (TP) loads in subsurface drainage decreased by 6% at a site with sandy loam soil, and increased by 20% at a site with clay loam soil. TP loads in surface runoff increased as a result of increased drain spacing.

Key words | DRAINMOD, hydrologic modeling, phosphorus management, runoff, tile drainage, water quality

ABBREVIATIONS

EF efficiency  
ET evapotranspiration  
MAE mean absolute error  
N nitrogen  
P phosphorus  
PET potential evapotranspiration  
RMSE root mean square error  
TDP total dissolved phosphorus  
TP total phosphorus  
TPP total particulate phosphorus

INTRODUCTION

Tile drainage improves crop yields and reduces surface runoff and soil erosion, but contributes to the loss of nutrients from agricultural fields (Skaggs & Van Schilfgaarde 1999). As a result, increased levels of nutrients are transported to downstream freshwater reaches leading to eutrophication (Smith et al. 2006). During eutrophication, excess nutrients (such as nitrogen (N) and phosphorus (P)) cause increased aquatic flora biomass production, creating anoxic conditions and increased turbidity. As a result, surface waters experience decreased biodiversity, and poor recreational conditions (Ansari et al. 2011). P usually shows limited mobility in soils and its contribution to accelerated water eutrophication is mainly attributed to surface rather than subsurface flow (Sharpley et al. 1993). However, in Québec as well as in other Canadian provinces, research investigations have identified subsurface drainage as a significant pollution pathway of P to surface water bodies (Jamieson et al. 2003; Eastman et al. 2006; Kinely et al. 2007).

The partitioning of drainage water between surface and subsurface pathways, and the subsequent potential for surface...
runoff have been shown to greatly affect P losses (Enright & Madramootoo 2004). Other studies have clearly shown that the movement of P by subsurface transport depends on the characteristics of the soil profile; P losses through subsurface flow have been shown to depend on the P sorption capacity of soils (Sharpley & Halvorson 1994) as well as the presence or absence of preferential pathways in the soil (Enright & Madramootoo 2004). On the other hand, Enright & Madramootoo (2004) found that there is no relationship between either soil test P, or percent P saturation and P losses in an agricultural field. It is well understood that soil texture largely impacts P losses. Research findings from Chikhaoui et al. (2008) found that with a clay loam soil, particulate P is the dominant form of P loss through the subsurface drainage system. In addition, it was found that fine textured soil experiences mostly preferential flow, while coarse textured soil exhibits mostly matrix flow.

The quantity and quality of water discharged from tile drainage systems are very much dependent on drainage density (Skaggs et al. 1995; Chikhaoui et al. 2006). Drainage density, defined as the rate of water removed per day, is a function of drain spacing; drainage density is typically high when there is narrow drain spacing. Many studies have quantitatively evaluated the loss of N from subsurface drainage systems using simulation models (Helwig et al. 2002; Kladivko et al. 2004), indicating that N losses are strongly correlated with drain spacing. Kladivko et al. (1999) found that narrow drain spacing had a negative impact on drainage water quality. However, few investigations have evaluated the effect of drain spacing on P losses. In fact, P is now regarded as the limiting nutrient in the development of nutrient management plans in Quebec, given the oversaturation of soils by P in Quebec.

Simulation models can be a time- and cost-efficient method of developing predictive scenarios by extending existing knowledge. Once validated using field data, a model has the potential to predict outcomes and evaluate scenarios for best management practices under a wide range of conditions (Gollamudi 2006). Several models have been developed to predict subsurface drainage flows and facilitate the design of agricultural drainage systems. DRAINMOD (Skaggs 1978) is widely used in North America to simulate outflows from subsurface tile drainage systems. This process-based model has been successfully used for different soil types and crop conditions (Helwig et al. 2002; Sands et al. 2003; Wang et al. 2006). However, DRAINMOD does not simulate P loads. To evaluate the effect of drain spacing on P losses, DRAINMOD must be coupled with another model that links subsurface drainage outflows and P loads. Several other models have been developed to simulate P loads, as well as general surface and subsurface agricultural water quality in different regions around the world. Some of these models are: EPIC (Erosion Productivity Impact Calculator; Williams et al. 1984), GLEAMS (Groundwater Loading Effects of Agricultural Management Systems model; Leonard et al. 1987), WEPP (Water Erosion Prediction Project model; Nearing et al. 1989), ADAPT (Agricultural Drainage and Pesticide Transport model; Warld et al. 1988), SWAT (Soil and Water Assessment Tool; Arnold et al. 1998) and AnnAGNPS (Annualized Agricultural Nonpoint Source model; Sarangi et al. 2007). Every model is unique and requires extensive input data for successful calibration and subsequent use. Some of these models do not account for existing tile drainage systems or snowmelt events that generally occur in cold regions. In order to take these factors into consideration, simple empirical models of P losses through tile drainage can be developed, calibrated with local data, and coupled with hydrological models for use as an alternate predictive tool (Beauchemin et al. 2005).

The main objectives of this study were: (1) to calibrate and validate DRAINMOD using observed drainage data from two experimental sites in southern Quebec over a period ranging from 2002 to 2004; (2) to establish a relationship between subsurface drain flows and P loads, and to link this empirical model with DRAINMOD outputs; and (3) to investigate the effects of drain spacing on surface runoff, subsurface drainage, and P losses in two selected agricultural tile-drained fields.

This study is based on field measurements at two drain spacings (10 and 13 m), and simulation models were used to extrapolate the results to a range of other drain spacings normally encountered in Quebec. The results from this study are limited to the geographic location studied, and similar results may not be attained in an alternate location, or at a different scale.
MATERIALS AND METHODS

Site description

The data used in this study were collected from two experimental agricultural fields located in the Pike River watershed (Québec) about 70 km southeast of Montréal (Figure 1). These two fields are situated on privately owned land and are located approximately 3 km apart. Site A is on a dairy farm with a surface and subsurface drainage area of 6 ha. Site B belongs to a swine and cash crop producer, and has a surface drainage area of 7 ha and a subsurface drainage area of 7.8 ha.

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 predominant soil type at Site B is a Sainte Rosalie clay loam. The internal drainage of this soil is imperfect; it contains 22% sand and 40% clay. At Site B, deep vertical cracks are common during the summer months when the soil is exposed to periods of extreme wetting and drying. Both soils are characterized by a granular soil structure. Soil test P concentrations and P saturation levels were calculated based on samples collected in 2001 using the Mehlich-III procedure as described by Tran & Simard (1995). A complete list of the soil characteristics is available in Table 1.

These two sites were underlain with a conventional parallel tile drainage system. The subsurface drainage system consists of plastic corrugated lateral pipes of

Table 1 | Soil phosphorus, tillage, crop rotation, and fertilization in the experimental fields

<table>
<thead>
<tr>
<th>Site</th>
<th>Soil test P</th>
<th>P saturation</th>
<th>Tillage</th>
<th>Crop rotation</th>
<th>Fertilization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site A</td>
<td>373 kg ha⁻¹</td>
<td>22%</td>
<td>Mouldboard plough in the fall (except in 2004)</td>
<td>Corn (Zea mays L.)</td>
<td>56 kg ha⁻¹ in May</td>
</tr>
</tbody>
</table>
| Site B | 114 kg ha⁻¹ | 5.3%         | Mouldboard plough in the fall | Soybean (Glycine max L.) | –             

These two sites were underlain with a conventional parallel tile drainage system. The subsurface drainage system consists of plastic corrugated lateral pipes of.
11 cm diameter and 21 cm diameter outlets. The system was installed with a trenchless plow in a systematic pattern. The outlets were made of corrugated plastic pipe for Site A and clay pipe for Site B. Lateral spacing was 13 m at Site A and 10 m at Site B. The drains were installed at an average depth of 1 m below the soil surface.

Site A was cultivated in corn and alfalfa during the period of study. Site B was cultivated mainly in cash crops such as corn and barley. The cropping sequence for the region is 600 mm yr\(^{-1}\). The estimated total annual potential evapotranspiration (PET) for the region is 600 mm yr\(^{-1}\). 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 (2002–2004), except Site A in 2004. The fields were not irrigated. The timing and magnitude of fertilization varied across years of simulation and depended on the crop being cultivated; the quantities of phosphorus fertilizer applied and frequency of application are presented in Table 1. Although the sites were instrumented in October 2000, data from 2001 were unusable as a result of equipment malfunction and were excluded from this study.

**Data collection**

The 30-year climatic normal precipitation recorded at Environment Canada’s Philipsburg weather station located approximately 9 km from the sites is 1,096 mm yr\(^{-1}\), with an annual snowfall equivalent of 204 mm yr\(^{-1}\). 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 (PET) for the region is 600 mm yr\(^{-1}\) (Gollamudi et al. 2007). This region has an average annual temperature of 6.8 °C and a frost-free period of 155 days (Jamieson et al. 2003).

Since 2001, these two experimental fields have been monitored for surface runoff and tile drainage outflows, as well as for various water quality parameters. The instrumentation, data collection, and sampling methodology used during the study period are identical for both sites.

Surface runoff from the fields was measured using H flumes with two water level sensors. The primary sensor was an SR50 ultrasonic depth sensor (Campbell Scientific Inc., Logan, Utah, USA) and the secondary sensor was a Keller-173 pressure transducer (Campbell Scientific Inc.). Surface runoff volumes were calculated based on a rating curve, specific to the flume specifications, at each site. Flow-proportional composite water samples were collected automatically by American Sigma 900-series water samplers (Hach, Loveland, Colorado, USA).

The subsurface drainage systems were modified to record drain discharge. 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 sensor was an IF-200 fixed insertion flow meter (Global Water Instrumentation Inc., Gold River, California, USA). Similar to the surface runoff water sampling strategy, flow-proportional water samples were collected automatically by a WS700 composite sampler (Global Water Instrumentation Inc.) from the tile drainage outlet, which is located 1 m below the soil surface. The sampler was activated for every 1 mm of drainage water depth discharged from the tile outlet.

Periodically, grab samples were collected from both surface runoff and subsurface drainage outlets and compared to the other collected composite samples for quality control purposes. Additionally, a hidden duplicate sample was included in each batch for quality control at the lab. Samples were analysed for total phosphorus (TP), total dissolved phosphorus (TDP), and total particulate phosphorus (TPP), as described by Murphy & Riley (1962). The sites were also equipped with soil temperature thermocouples and barometric pressure data loggers, for year-round monitoring. All data collected in the field were checked rigorously for gaps and errors; a complete dataset was available for the two study years.

**Model description**

DRAINMOD (version 5.1) is a deterministic hydrologic field scale model developed by Skaggs (1978) to assess the performance of surface and subsurface drainage systems. The model predicts surface runoff, subsurface drainage, evapotranspiration (ET), infiltration, and water table variations. It is conceptualized using a water budgeting protocol for the soil profile section located midway between adjacent drains, and from the impermeable layer up to the soil surface. The model uses Hooghoudt’s equation to calculate
subsidence 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). ET is estimated from the PET value, using the Thornthwaite (1948) method. In addition, infiltration is estimated using the Green–Ampt equation and deep seepage is estimated using Darcy’s law. A detailed description of DRAINMOD can be found in Skaggs (1978).

Input data required for DRAINMOD are grouped into subcategories: weather data, drainage design parameters, soil properties, crop information, and trafficability parameters. Additionally, the DRAINMOD 5.1 package includes soil thermal conductivity parameters for simulating field hydrology processes which take place in cold conditions, such as soil freezing, thawing, and snowmelt (Luo et al. 2000). Table 2 provides a summary of the hydrologic components and input data used to operate DRAINMOD for the purpose of this study.

It is necessary to calibrate the model with field measurements and to validate it with an independent dataset. After calibrating and validating DRAINMOD, simulations were performed for both sites, analysing different drain spacings ranging from 5 to 70 m, at 5 m increments. This range was chosen to encompass drain spacing values observed in Quebec, as well as to provide extreme values for trend analysis.

### Development of an empirical model for P loss prediction

All statistical analyses were performed using IBM SPSS software, version 11 (2002). A threshold level of significance of 0.05 (95% probability level) was used to establish the significance of the different parameters.

The relationships between tile drain outflow and different forms of P loads were estimated using a simple regression analysis. Drain outflow depth obtained as an output of DRAINMOD was used as an input for the regression model. Two regression models were developed for each site describing the relationships between tile drainage flow and TP and TPP. TDP was estimated to be the difference between TP and TPP. The regression models were developed using drainage water samples collected during the year 2002. The dataset was subdivided into two sets for model development and subsequent validation; out of the total number of samples (47), 75% were used to develop the model and the other 25% were used for evaluating the model’s performance.

Evaluation of the regression models for their accuracy in predicting P loads was carried out using mean absolute error (MAE), and the root mean square error (RMSE). The MAE

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**Table 2 | Field parameters and DRAINMOD inputs**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Site A</th>
<th>Site B</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Drainage system</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Field area (ha)</td>
<td>6</td>
<td>7.8</td>
</tr>
<tr>
<td>Drain spacing (m)</td>
<td>13</td>
<td>10</td>
</tr>
<tr>
<td>Drain depth (m)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Effective radius of drains (cm)</td>
<td>0.35</td>
<td>0.35</td>
</tr>
<tr>
<td>Drainage coefficient (cm day⁻¹)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td><strong>Soil temperature</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil thermal conductivity function (coefficients) (W/m°C)</td>
<td>a = 0.39</td>
<td>a = 0.39</td>
</tr>
<tr>
<td>Diurnal phase lag of air temperature (hr)</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Base temperature as the lower boundary (°C)</td>
<td>7.2</td>
<td>7.2</td>
</tr>
<tr>
<td>Rain/snow dividing temperature (°C)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Snowmelt base temperature (°C)</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Degree day coefficient (mm day⁻¹)</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Critical ice content (cm³ cm⁻³)</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td><strong>Soil properties</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bulk density (g cm⁻³)</td>
<td>1.40</td>
<td>1.06</td>
</tr>
<tr>
<td>Organic matter (mean %)</td>
<td>6.81</td>
<td>3.94</td>
</tr>
<tr>
<td>Number of soil horizons in soil profile</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Soil horizon</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Soil horizon thickness (cm)</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Ksat (cm hr⁻¹)</td>
<td>3.56</td>
<td>1.3</td>
</tr>
</tbody>
</table>

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and the RMSE were estimated using equations presented by Mayer & Butler (1993):

\[
\text{MAE} = \frac{\sum_{i=1}^{n} |O_i - P_i|}{n} \tag{1}
\]

\[
\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} (O_i - P_i)^2}{n}} \tag{2}
\]

where \(O_i\) is the observed value, \(P_i\) is the predicted value, and \(n\) is the number of values.

The MAE indicates the average absolute difference between predicted and observed values. The RMSE quantifies the relative degree of difference between the model’s predicted and observed values. The RMSE also indicates any bias compared to the random variation that may occur (Willmott 1984). If predicted values are exactly equal to observed values, MAE and RMSE are equal to zero.

**Model calibration and evaluation criteria**

DRAINMOD was operated using observed data from 2002 to 2004; 2003 and 2004 data were used to calibrate the model, whereas 2002 data were used to validate the model. Observed ET data were not available for the study area; ET values were therefore predicted using the Thornthwaite equation. Throughout the calibration process predicted ET values were optimized by modifying the monthly ET adjustment factors, which were all initially 1.0.

Model-predicted and observed values were compared on a monthly basis. The model performance was evaluated by calculating modeling efficiency, EF (James & Burges 1982):

\[
EF = \frac{\sum_{i=1}^{n} (O_i - O)^2 - \sum_{i=1}^{n} (P_i - O)^2}{\sum_{i=1}^{n} (O_i - O)^2} \tag{3}
\]

where \(O_i\) is the observed value, \(P_i\) is the predicted value, \(n\) is the number of values, and \(O\) is the mean observed value over the time period (1 to \(n\)).

EF is an overall indication of goodness of fit which directly relates model predictions to observed data. EF evaluates the error relative to the variance of the observed values. Good model performance is indicated by an EF value close to one (Mayer & Butler 1993).

**RESULTS AND DISCUSSION**

**Predictions of tile drain outflow**

**Model calibration**

Table 3 shows the observed and predicted total yearly subsurface tile drainage volumes based on cumulative monthly data. Figure 2 shows that DRAINMOD accurately predicted tile drainage flows at both sites during the first year of calibration. During the second year of calibration DRAINMOD slightly underestimated drain outflow in the winter and spring, and slightly overestimated drain outflow in the fall at Site A. DRAINMOD slightly overestimated drain outflow during the entire second year of calibration at Site B. The cumulative subsurface drainage outflow depths predicted during the calibration period were 5% higher than the observed values for Site A, and 3% lower

<table>
<thead>
<tr>
<th>Site</th>
<th>Year</th>
<th>Yearly precipitation (mm)</th>
<th>Yearly drainage (mm)</th>
<th>Yearly drainage (% of yearly precipitation)</th>
<th>Average EF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Observed</td>
<td>Predicted</td>
<td>Observed</td>
</tr>
<tr>
<td>A</td>
<td>2003/4 (Calibration)</td>
<td>1,654.6</td>
<td>892.8</td>
<td>946.0</td>
<td>54%</td>
</tr>
<tr>
<td></td>
<td>2002 (Validation)</td>
<td>912.1</td>
<td>507.0</td>
<td>540.0</td>
<td>56%</td>
</tr>
<tr>
<td>B</td>
<td>2003/4 (Calibration)</td>
<td>1,463.4</td>
<td>721.4</td>
<td>697.2</td>
<td>49%</td>
</tr>
<tr>
<td></td>
<td>2002 (Validation)</td>
<td>854.8</td>
<td>435.4</td>
<td>401.6</td>
<td>51%</td>
</tr>
</tbody>
</table>

Note: results are based on cumulative monthly data; EF (efficiency) was calculated using monthly subsurface tile drainage data.
for Site B. DRAINMOD was very sensitive to adjustments in bulk density and vertical saturated hydraulic conductivity. The variation between the results from Site A and Site B can be attributed to the variability in soil properties, such as texture, bulk density, and saturated hydraulic conductivity at these sites (Table 2). In addition, the overestimation for Site A may be partly due to higher rainfall at this site (Table 3).

Overall, the slight underestimation or overestimation of monthly subsurface flows can be explained by two factors: first, potential for macropore flow was excluded from the model (Chikhaoui et al. 2008) and second, ET was based on adjustment factors in the absence of observed data. Improved ET estimation could improve the performance of the model. It is clear that several other methods would give more accurate ET estimates, such as the Penman equation or the Combination Method, but these would require input data that are difficult to acquire in many scenarios, especially for the long recording periods which are needed to run DRAINMOD. Nevertheless, the Thornthwaite method is deemed to be sufficiently accurate and appropriate for drainage modeling in humid regions (Skaggs 1980). For these reasons, the Thornthwaite equation was used for ET estimation.

Comparison of these observed and predicted values during the calibration period (2003–2004) at both sites revealed good results. At both sites, yearly average EF values were calculated to be 0.69 or more (Table 3), indicating a satisfactory calibration of DRAINMOD.

Model validation

Figure 3 illustrates the relationship between monthly observed and predicted values of drain outflow for the validation datasets. At Site A, when approximately 110 mm of tile drainage was predicted, 130 mm was observed. Based on the linear trend, this point appears as though it could be an outlier. However, similar results have been obtained

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**Figure 2** Observed and predicted cumulative tile drainage during the calibration period (2003/04) for Site A and Site B.

**Figure 3** Comparison between observed and predicted monthly tile drainage during the validation period (2002) for Site A and Site B.
from past research at these two sites (Gollamudi 2006), which confirm that this point should not be considered as an outlier. The regression equation can therefore be used with confidence.

A comparison of observed and predicted values of monthly subsurface tile drainage for the validation period (2002) at both sites revealed satisfactory results with yearly average EF values close to 1 (EF = 0.83 at Site A and EF = 0.70 at Site B) (Table 3). These findings indicate that DRAINMOD performs well in predicting monthly subsurface tile drainage outflows for both soil types for these specific geographical and climatic conditions.

DRAINMOD performed better during validation than during calibration. This can be explained by the fact that validation was carried out during a year in which conditions were ideal for the model performance, i.e., warmer weather with high rainfall. Many large rainfall events occurred during the validation period (2002) and the temperature during that winter was somewhat warmer than during the calibration period (2003 and 2004).

Regression models for P predictions

The regression models developed for TP and TPP loads in both tile drainage and surface runoff were found to be linear when expressed logarithmically and are expressed in Table 4. The linear relationship between tile drainage depth and TP and TPP loads is graphically displayed for Sites A and B in Figures 4 and 5, respectively. Table 4 also provides the upper and lower limits of the boundary in which predicted values are found at a 95% confidence level. An analysis of variance test based on simple

<table>
<thead>
<tr>
<th>Site A</th>
<th>Tile drainage</th>
<th>Intercept (log(g/ha))</th>
<th>95% confidence level</th>
<th>Upper limit</th>
<th>Lower limit</th>
<th>Slope (log(g/ha)/log(mm))</th>
<th>95% confidence level</th>
<th>Upper limit</th>
<th>Lower limit</th>
<th>R²</th>
<th>Calculated P</th>
</tr>
</thead>
<tbody>
<tr>
<td>TP</td>
<td>−0.43</td>
<td>−0.08</td>
<td>−0.78</td>
<td>1.15</td>
<td>1.48</td>
<td>0.82</td>
<td>0.65</td>
<td>51.50</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TPP</td>
<td>−0.26</td>
<td>−0.07</td>
<td>−0.59</td>
<td>0.77</td>
<td>1.08</td>
<td>0.45</td>
<td>0.47</td>
<td>24.60</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface runoff</td>
<td>TP</td>
<td>0.16</td>
<td>0.42</td>
<td>1.74</td>
<td>2.22</td>
<td>1.24</td>
<td>0.65</td>
<td>52.53</td>
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</tr>
<tr>
<td>TPP</td>
<td>0.06</td>
<td>0.29</td>
<td>−0.22</td>
<td>1.66</td>
<td>2.18</td>
<td>1.20</td>
<td>0.62</td>
<td>49.93</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Site B</th>
<th>Tile drainage</th>
<th>Intercept (log(g/ha))</th>
<th>95% confidence level</th>
<th>Upper limit</th>
<th>Lower limit</th>
<th>Slope (log(g/ha)/log(mm))</th>
<th>95% confidence level</th>
<th>Upper limit</th>
<th>Lower limit</th>
<th>R²</th>
<th>Calculated P</th>
</tr>
</thead>
<tbody>
<tr>
<td>TP</td>
<td>−0.24</td>
<td>0.03</td>
<td>−0.51</td>
<td>1.52</td>
<td>1.80</td>
<td>1.23</td>
<td>0.78</td>
<td>120.17</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TPP</td>
<td>−0.29</td>
<td>−0.01</td>
<td>−0.57</td>
<td>1.48</td>
<td>1.77</td>
<td>1.18</td>
<td>0.76</td>
<td>105.16</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface runoff</td>
<td>TP</td>
<td>0.28</td>
<td>0.50</td>
<td>1.87</td>
<td>2.33</td>
<td>1.40</td>
<td>0.77</td>
<td>69.68</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TPP</td>
<td>0.24</td>
<td>0.05</td>
<td>−0.03</td>
<td>1.73</td>
<td>2.27</td>
<td>1.17</td>
<td>0.67</td>
<td>42.70</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

*Significant at α = 0.01.
regression was performed. It was observed that the calculated P values were larger than the critical P values, meaning that the null hypothesis (slope equal to zero) could be rejected (Table 4). This shows that these values are not significant, and the regression models can be used with 95% confidence.

All P regression models for Site B have greater slopes than for Site A. This indicates increased overall P losses from Site B compared to Site A. Possible reasons for this differentiation are discussed in the subsequent section.

Regression model performance was evaluated by comparing predicted values with observed data. The validation of the regression models was carried out with an independent dataset, i.e., data that were not used to develop the model. For Site A, predicted TP and TPP loads had an MAE of 1.45 or less, and an RMSE of 1.92 or less. For Site B, predicted TP and TPP had MAE values ranging from 2.44 to 6.31 and RMSE values ranging from 2.74 to 9.75 (Table 5). Ideally, MAE and RMSE values would be equal to zero. In general, MAE and RMSE values were lower for Site A than for Site B. Predictions at Site B were inferior due its problematic soil properties (i.e., soil cracking, preferential flow, high P levels, etc.), whereas Site A exhibited more uniform soil conditions. Nevertheless, predicted values were in sufficiently good agreement with observed values. The developed models are therefore considered appropriate for use in predicting the TP and TPP loads in tile and surface drainage for this experiment.

It is likely that the performance of the regression models would improve if additional variables, like P saturation, soil test P, and other source factors, as well as fertilization rates were included in the model (Gburek et al. 2000; Sharpley et al. 2001; Beauchemin et al. 2005; Chikhaoui et al. 2007).

Effect of drain spacing

Drainage volumes

The effect of drain spacing on subsurface and surface drainage volumes is shown in Figure 6 for the year 2002. As lateral drain spacing was increased from 5 to 70 m, the depth of subsurface drain flow decreased from 575 to 225 mm at Site A, and from 500 to 60 mm at Site B. Similarly, the depth of surface runoff increased from 0 to 75 mm at Site A, and from 0 to 200 mm at Site B. Thus, subsurface drain outflow decreased and surface runoff increased as drain spacing was increased.

When drain spacing is narrow there is more storage for infiltrating water, thus explaining the reduced surface runoff (Skaggs et al. 1982). In most cases, the relationship between drain spacing, surface runoff, and subsurface

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**Table 5** | Prediction error statistics of the developed regression models

<table>
<thead>
<tr>
<th></th>
<th>Site A</th>
<th></th>
<th></th>
<th>Site B</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tile drainage</td>
<td>Surface drainage</td>
<td>Tile drainage</td>
<td>Surface drainage</td>
<td>Tile drainage</td>
<td>Surface drainage</td>
</tr>
<tr>
<td>TP MAE</td>
<td>1.45</td>
<td>0.85</td>
<td>0.78</td>
<td>0.87</td>
<td>2.44</td>
<td>2.51</td>
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<tr>
<td>TP RMSE</td>
<td>1.92</td>
<td>0.97</td>
<td>0.85</td>
<td>0.96</td>
<td>2.74</td>
<td>3.41</td>
</tr>
<tr>
<td>TPP MAE</td>
<td>0.85</td>
<td>0.97</td>
<td>0.85</td>
<td>0.96</td>
<td>2.74</td>
<td>3.41</td>
</tr>
<tr>
<td>TPP RMSE</td>
<td>0.85</td>
<td>0.97</td>
<td>0.85</td>
<td>0.96</td>
<td>2.74</td>
<td>3.41</td>
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<tr>
<td></td>
<td>5.92</td>
<td>9.75</td>
<td>9.00</td>
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</tr>
</tbody>
</table>

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Figure 5 | Relationship between the TP and TPP loads in tile drainage and tile drainage depth for Site B.
drainage flows depends on the soil type, or more specifically, soil hydraulic properties such as hydraulic conductivity (Wang et al. 2006). The effects of drain spacing on drainage properties were more pronounced for Site B than for Site A. The overall higher subsurface drain flow and lower surface runoff at Site A can be explained by the fact that its soil has a coarse texture, where large pore spaces allow for higher infiltration and therefore larger water removal by the tile drains. Similarly, the greater volume of surface runoff and lower subsurface flow at Site B can be attributed to its finer textured soil, where smaller pore space and non-connecting pores result in lower infiltration (Eastman 2008).

**P losses in tile drainage**

The effect of drain spacing on P losses through tile drainage was simulated with a regression model. The simulated results are shown in Figure 7. An increase in drain spacing resulted in a reduction in P loads in drain outflow. For Site A, when drain spacing was increased from 5 to 70 m, TP loads decreased from 0.5 to 0.2 kg ha\(^{-1}\) yr\(^{-1}\). An analysis of the overall results at Site A showed that an incremental increase in drain spacing of 5 m resulted in 6% decrease in TP loads in subsurface drainage. The impact of increasing drain spacing at Site B was more pronounced; when drain spacing was increased from 5 to 70 m, TP loads decreased from 2.3 to 0.1 kg ha\(^{-1}\) yr\(^{-1}\). In this case, an increase of 5 m in drain spacing could result in a 20% decrease in TP loads in subsurface drainage. Overall, in these scenarios drain spacing significantly affected P loads in tile drainage.

The more significant decrease in TP loads in tile drainage witnessed at Site B is likely due to the fact that at
this site, TPP was dominant in tile drainage, whereas at Site A, TDP was dominant. At Site B, TPP accounted for 84% of TP loads. This predominance may be linked to the mechanisms of P transport which occur under the specific conditions prevalent in the soil profile of a fine textured soil. During dry periods, clay soils tend to shrink, forming deep cracks which serve as conduits for drainage water, thus causing preferential flow (Eastman 2008). This connection between preferential flow and soil cracks was observed at Site B in previous studies (Enright & Madramootoo 2004; Chikhaoui et al. 2008). Studies have also concluded that, in clay loam soils, preferential flow is the dominant transport mechanism of soil particulates (Cynor & Findlay 1995): soil macropores can provide a direct route for eroded sediment to subsurface drains. This is corroborated in similar investigations which explore the relationship between sediment load and TPP (Chikhaoui et al. 2006). On the other hand, at Site A, TDP accounted for 65% of TP loads. The relatively low TPP loading from Site A can be explained by its coarse soil texture which has the capacity to absorb and store large volumes of water, and which discharges water more gradually (Gollamudi et al. 2007). Bypass flow clearly did not occur to the same extent at Site A as it did at Site B. Rather, it is likely that the relatively high rate of TDP in tile drainage at Site A was due to the predominance of matrix flow caused by the soil and water flux interactions, as demonstrated by Chikhaoui et al. (2008).

**P losses in surface runoff**

The effect of drain spacing on P losses through surface runoff was also simulated with a regression model. The simulated results are shown in Figure 8. An increase in drain spacing resulted in an increase in P loads in surface outflow; when drain spacing was increased from 5 to 70 m, TP loads increased from 0 to 0.4 kg ha⁻¹ yr⁻¹ for Site A, and from 0 to 4.5 kg ha⁻¹ yr⁻¹ for Site B. As discussed above, when drain spacing is increased, surface runoff also increases. Higher surface runoff results in increased erosion, sediment flow, and thus explains the simulated increase in P losses.

TP loads increased more dramatically for Site B than for Site A. As discussed above, this difference is likely attributed to the finer soil texture at Site B, and dominance of TPP.

**Optimizing drain spacing**

The results from this study clearly demonstrate that drain spacing has a significant effect on P losses through tile drainage and surface runoff. Cumulative TP losses (through both surface runoff and subsurface drainage) from tile-drained fields can be used to evaluate the possibility of reducing total P loadings by optimizing drain spacing at a given site. In order to determine the optimal drain spacing in terms of P loading for a given soil texture and climatic region, other factors such as the impact on crop yield and cost benefits should also be considered. If drains are too close, water is removed from the plant root zone more rapidly, limiting moisture availability and potentially decreasing crop yield. However, drain spacings greater than 40 m would have a negative effect on the agricultural productivity of most soils, since waterlogging of the crops is likely to occur during very high rainfalls (Zhao et al. 2000).
Additional factors influencing drainage and P losses

Crop rotations

Type of vegetation has an impact on P losses by determining the susceptibility of a field to erosion, as well as the volume of surface runoff. Row crops (such as corn, barley, and soybeans) are not as efficient in terms of reducing surface runoff as hay crops (such as grasses and alfalfa), which are more dense, have a lower soil moisture content due to a higher level of transpiration in the root zone, and have improved infiltration. Furthermore, hay crops have improved soil structure which also facilitate infiltration (Eastman 2008). Site A was planted with corn from 2001 to 2003, while Site B was planted with soybeans, barley, or corn in all years (Table 1). As such, the volume of surface runoff, and P losses at both sites were influenced similarly by the type of crop from 2001 to 2003. In 2004, Site A was under alfalfa while Site B was under corn. Based on this, the infiltration at Site A may have been higher than Site B in 2004, resulting in a lower volume of surface runoff and less erosion at Site A. Therefore, in this year, the influence of the type of crop reinforces the effect that the soil texture at Site A had in decreasing the amount of surface runoff and erosion, and further explaining the overall higher P loads witnessed from Site B.

Tillage

Tillage practices have an effect on drainage, as well as P losses from agricultural fields. No-till farming conserves soil moisture and improves drainage because of reduced evaporation, increased organic matter, improved soil permeability, and decreased runoff and erosion (Rice 1985). As a result, reduced leaching and runoff of agricultural chemicals (i.e., phosphorus) may occur (Uri 1999). Furthermore, machinery used for tillage could result in soil compaction, leading to poor drainage and increased surface runoff (Eastman 2008). Both sites were consistently tilled with a mouldboard plough in the fall, except for Site A in 2004. The fact that Site A was not tilled in 2004 would imply the possibility for higher subsurface drain flows and decreased P losses in that year. This effect could help to explain the higher drainage flows observed at Site A in 2004. In general, P losses were greater at Site B. The effect of the tillage regime in 2004, in addition to the soil texture properties at Site B explain this observation.

Organic matter content

Site A has a higher organic matter content than Site B (Table 2). Organic matter content influences the processes governing nutrient movement in soil and water. When a soil’s organic matter content is higher, soil particles are better aggregated into larger units, and there is less soil loss potential (Gollamudi et al. 2007). Therefore, Site A would presumably experience less sediment and TPP losses than Site B. This, in combination with all other factors, may help to explain why TDP was dominant in tile drainage at Site A, whereas TPP was dominant in tile drainage at Site B.

Fertilizer application

Regular fertilizer doses in combination with high rainfall intensity would normally result in high P loading (Eastman et al. 2010). On average, Site A received higher fertilization loads than Site B (Table 1). Nevertheless, measured TP losses through tile drainage at Site B were higher than at Site A. Apparently, fertilizer loads at Site A were not so much greater than Site B as to offset the effects of soil texture, and possibly crop type.

Rain storm and snowmelt events

Rain storm and large snowmelt events increase the possibility for surface runoff. TP concentrations were shown to rise and fall with surface flow rates at both sites. This clearly shows that rain storm and snowmelt events increase TP losses. Similarly, Jamieson et al. (2003) found that tile drains are a significant pathway for phosphorus movement during snowmelt events. Large, intense rainfall events which occurred at the sites throughout the spring and summer (May through August) produced high TP losses. The high percentage of TPP in the subsurface drainage water of Site B during this time period illustrates that even during periods when soil is highly saturated, high levels of TPP losses through the
subsurface drainage system as a result of bypass flow conditions in clay rich soils may still exist (Eastman 2008).

CONCLUSIONS

Artificial subsurface drainage is commonly used to improve the productivity of poorly drained agricultural soils. However, drainage can have significant impacts on the water quality of downstream rivers and lakes. This study has identified the effects of tile drain spacing on phosphorus losses for two selected tile-drained agricultural fields in Québec. DRAINMOD was linked with two regression models in order to assess P losses in surface runoff and subsurface drainage for different tile drain spacings. DRAINMOD proved to be capable of predicting monthly subsurface drainage outflow satisfactorily. Regression models were developed in order to predict TP, TDP, and TPP loads. This approach, involving a minimal number of parameters, predicted P loads with acceptable accuracy. Simulated results showed that, when climate, geography, and field management practices are kept constant, an incremental increase of 5 m in tile drain spacing could result in a 20% decrease in TP loads in subsurface drainage for a fine textured soil. A lesser impact was observed for a coarse textured soil; where an incremental increase of 5 m in drain spacing resulted in a 6% decrease in TP loads in subsurface drainage. Generally, the simulated results indicated that a significant reduction of P loads in drainage systems occurs when tile drain spacing is increased. Soil texture and structure are extremely important considerations when assessing the risk of P loss from an agricultural field. Determining optimal tile drain spacing is complex because agronomic benefits, environmental impacts, and cost benefits must be balanced. Additional field research is needed to evaluate the effects of drainage system parameters on surface runoff, subsurface drainage, and P losses, with a focus on possible field management interventions.

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 the many people 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). We also express our sincere appreciation to the Institut de Recherche et de Développement en Agroenvironnement for their technical assistance and involvement with the water sample analysis. We thank the two land owners who allowed us to use their fields for this study.

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First received 28 September 2012; accepted in revised form 23 April 2013