Evaluation of the Root Zone Water Quality Model (RZWQM) for Southern Ontario: Part I. Sensitivity Analysis, Calibration, and Validation

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This study focuses on the performance of the Root Zone Water Quality Model (RZWQM) for corn production in southern Ontario. The model was used to simulate the amount of subsurface tile drainage, residual soil nitrate-nitrogen (NO₃-N), NO₃-N in subsurface drainage water, and crop yield. A precalibration sensitivity analysis of the model was conducted for several key parameters using field data collected at the study site. The RZWQM’s hydrology component was most sensitive to the Brooks and Corey fitting parameters and saturated hydraulic conductivity (Ks), while the tile drain flow and the water table depth were sensitive to the Brooks and Corey fitting parameters of bubbling pressure (ψ bp) and pore-size-distribution index (λ). The fraction of dead-end pores had relatively little effect on tile drain N loss. The crop yield is most affected by N uptake, age, and evapotranspiration rate. RZWQM simulated evapotranspiration was within the range (568 ± 55 mm) of the observed evapotranspiration. The model simulated corn yield very well (-0.1% difference) at the calibration site; however, it underestimated yield (-14.1%) at the validation site. Overall, the RZWQM simulated tile drain flow, NO₃-N loss to tile drainage water, and crop yield with reasonable accuracy, but tended to underestimate the amount of soil NO₃-N (mean deviation, -0.971). The inability of the model to handle the spatial and temporal variability of the soil may have affected its prediction accuracy. The model also needs improvement in simulating early spring snowmelt hydrology.

Key words: subsurface tile drainage, computer simulation, nitrate losses, corn production

Introduction

Best management practices (BMPs) can be evaluated by field experimental research or by computer simulation modelling. Field research in agriculture has been largely empirical, site specific, and conducted without active help of agricultural system models (Ma et al. 2000a). Numerous agricultural system models can be used for evaluating the effectiveness of agricultural BMPs. Each model has its own assumptions, strengths, and weaknesses. Model users need to recognize that models are more valuable as a heuristic tool than as a full surrogate for reality because many gaps still exist in our understanding of the functioning of natural systems (Sinclair and Seligman 1996).

Many studies are examples of applying computer simulation models to predict the effect of various soil and weather scenarios on agricultural production, and to estimate the need for nitrogen (N) fertilizer BMPs. McLaughlin (2001) used the EPIC (erosion/productivity impact calculator) model (Williams et al. 1990) to develop predictive equations for N loss for predicting nitrate-nitrogen (NO₃-N) leaching risk for selected soil and climate scenarios. Sogbedji et al. (2001) used the LEACHM (Leaching and Estimation and Chemistry Model) (Wagenet and Hutson 1989) to evaluate the effects of early season weather conditions on N application rate and availability. Azevedo et al. (1997) used the Root Zone Water Quality Model (RZWQM) to simulate the long-term impact of nitrogen management practices on crop yield NO₃-N losses in tile water.

The first version of the RZWQM was completed by a group of United States Department of Agriculture - Agricultural Research Service scientists (RZWQM Team 1992). McLaughlin (2001) identified nine agricultural nonpoint source pollution models, and ranked the RZWQM at the top for simulating hydrologic and nutrient processes in the soil/plant/air system. Recently, Chinkuyu et al. (2004) concluded that the RZWQM is better than the GLEAMS (Ground Water Loading Effects of Agricultural Management Systems) (Knisel, 1993) for simulating hydrological processes. A number of studies have examined the performance of the RZWQM; however, to date, no known study has undertaken an evaluation of the RZWQM for spring hydrology and snowmelt under Ontario conditions.

Nitrate leaching losses, including NO₃-N loss through tile drains, have been reported by many researchers (Hanson 2000; Bakhsh et al. 2001). Jaynes and Miller (1999) observed that the RZWQM simulated NO₃-N loads in the tile drain were within 10 kg per hectare per year of observed values. The RZWQM over-predicted N losses during wet years, and under-predicted N losses...
during dry years. Bakhsh et al. (2001) indicated that the RZWQM performed better in simulating the NO$_3$-N loads in tile drains for corn production systems than those for soybean production systems.

Martin and Watts (1999) observed that, to improve the performance of the RZWQM, adjustments are needed for a number of default crop growth input variables suggested by Hanson et al. (1999). Jaynes and Miller (1999) found that there was less year-to-year variation in the RZWQM modelled corn and soybean yields than the observed yields. They found that this was due to the lack of recognition of some processes such as pest damage and weather damage. Also, Bakhsh et al. (2001) observed only a 4% difference between the RZWQM simulated and the observed crop yield.

Evaluating the sensitivity of the model outputs to a change in input parameters is an integral part of modelling. The range of variation of input variables may be determined from experimental measurements (Fontaine et al. 1992) or as a specific percentage of an expected value (Barnes and Young 1994). A number of studies have investigated the sensitivity of the RZWQM (Ahuja et al. 1993; Singh et al. 1996; Ma et al. 2000b). Walker et al. (2000) identified saturated hydraulic conductivity ($K_s$), Brooks and Corey fitting parameters, soil macroporosity, and drain spacing as the key input factors affecting tile flow and surface runoff. They also observed that macropore size is not critical in determining the distribution of pesticides and nutrients in the soil matrix. Singh et al. (1996) showed how improper values for the Brooks and Corey fitting parameters dramatically affect the shape of the tile outflow hydrograph. However, none of these studies were conducted for Ontario conditions.

This field/computer-simulation study focuses on sensitivity analysis, calibration, validation, and application of the RZWQM under Ontario conditions. The details of the study are divided into two parts. This paper (Part I) presents the sensitivity analysis, calibration, and validation results. The specific objectives are to conduct a precalibration sensitivity analysis for key parameters of the model, and to calibrate and validate the RZWQM for residual soil NO$_3$-N, tile flow, NO$_3$-N concentration in tile flow, and crop yields in separate watersheds. The second paper (Part II) presents the results of the use of the model for the evaluation of BMPs in an Ontario context.

**Methodology**

The RZWQM version 1.0.2000.1129 was selected in this study, and the processes modelled in the RZWQM included soil physical processes, soil chemical processes, nutrient processes, pesticide processes, plant growth processes, and management processes. The model uses the Green-Ampt equation for infiltration into the soil, Richard's equation for soil matrix flow, Poisuelle's law for macropore flow, the extended Shuttle-Wallace equation (Farahani and DeCoursey 2000) for evapotranspiration (ET). A detailed description of processes modeled in the RZWQM has been outlined by Ahuja et al. (2000).

**Description of Study Area**

The data from two sites, the “NBS” site (no-till) and the “TGW” site (conventional), monitored during the Ontario’s Green Plan Systems Comparison Project (1993-1998), were used for evaluation of the RZWQM under Ontario conditions. The data from the NBS site were used to calibrate, and data from TGW site were used to validate, the RZWQM. The NBS site is located near Blyth, about 80 km north of London, Ontario.

The soil type on the NBS site is classified as an imperfectly drained Listowel silt loam. The average slope of the site is 1.4%. The site was under a no-till practice for seven years and received no manure prior to the study period (Sadler-Richards 1998). The tile drainage area of the site is 0.77 ha. Figure 1 shows the locations of tile drains, soil sampling, and groundwater monitoring locations. The data to define the soil water characteristic curves were also collected on three slope positions (high, mid, and low) at the site. The soil profile descriptions and textural data collected by VandenBygaart et al. (1999) were reviewed, analyzed, and transformed to match the RZWQM’s requirements for characterizing soil macroporosity (Table 1). A macropore was assumed to be any pore space larger than 1 mm in diameter (Goss et al. 2002).

The TGW site (Fig. 2), under conventional tillage, is approximately 80 km from the London weather station and about 22 km from the Stratford weather station. Both of these stations were parameterized for weather generation. The soil on the TGW site is an imperfectly drained Listowel silt loam. The area of the field at the validation site was 2.92 ha with an average slope of 1.6%. The drain system collects drainage water from the entire field with a drain spacing of 15.2 m. Table 1 shows the summary of the soil profile and soil textural data obtained from VandenBygaart et al. (1999) for this site. The site did not receive any application of manure prior to and during the study period (1994 to 1996). The site was planted to corn in 1994, soybeans in 1995, and winter wheat in 1995/1996.

The nitrogen data available for these sites include composite soil nitrogen in the early spring before fertilizer application, after the first rain event following the fertilizer application, one month after the fertilizer application, and after crop harvest. The other data available include microbial biomass, soil temperature, and soil moisture at the sites during the growing season. A specially designed monitoring catchbasin and associated propeller-type flow meter were used to measure and sample the surface flow and tile drain flow during a flow event. Groundwater was also monitored, sampled, and analyzed for nutrients.
Fig. 1. Field description of the NBS (no-till) calibration site.

### TABLE 1. Description of soil horizons used for calibration and validation of RZWQM

<table>
<thead>
<tr>
<th>Horizon number</th>
<th>Horizon depth interval (cm)</th>
<th>Texture (%)</th>
<th>Organic matter (%)</th>
<th>Bulk density (Mg/m³)</th>
<th>Brooks and Corey coefficients(^a)</th>
<th>(\psi_{fb})</th>
<th>(\lambda)</th>
<th>(\theta_r)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Sand</td>
<td>Silt</td>
<td>Clay</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td><strong>Calibration Site</strong></td>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
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<tr>
<td>1</td>
<td>0-10</td>
<td>21.7</td>
<td>57.9</td>
<td>20.4</td>
<td>3.9</td>
<td>1.30</td>
<td>29.176</td>
<td>0.207</td>
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<tr>
<td>2</td>
<td>10-22</td>
<td>20.5</td>
<td>58.2</td>
<td>21.3</td>
<td>3.4</td>
<td>1.45</td>
<td>12.633</td>
<td>0.105</td>
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<tr>
<td>3</td>
<td>22-30</td>
<td>16.1</td>
<td>57.7</td>
<td>26.2</td>
<td>2.5</td>
<td>1.44</td>
<td>14.767</td>
<td>0.107</td>
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<td>4</td>
<td>30-45</td>
<td>19.2</td>
<td>52.4</td>
<td>28.4</td>
<td>1.4</td>
<td>1.55</td>
<td>12.071</td>
<td>0.112</td>
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<tr>
<td>5</td>
<td>45-60</td>
<td>26.1</td>
<td>52.2</td>
<td>21.7</td>
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<td>1.60</td>
<td>12.075</td>
<td>0.113</td>
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<td>17.4</td>
<td>54.1</td>
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<td>12.138</td>
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<td>55.0</td>
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<td>12.128</td>
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<td>12.138</td>
<td>0.075</td>
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<td>9</td>
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<td>55.0</td>
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<td>12.138</td>
<td>0.075</td>
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<td>7</td>
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<td>44.0</td>
<td>41.0</td>
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<td>1.51</td>
<td>12.146</td>
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<tr>
<td>6</td>
<td>100-120</td>
<td>15.0</td>
<td>44.0</td>
<td>41.0</td>
<td>0.3</td>
<td>1.51</td>
<td>12.145</td>
<td>0.075</td>
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<tr>
<td>7</td>
<td>120-225</td>
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<td>44.0</td>
<td>41.0</td>
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<tr>
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<td>225-500</td>
<td>15.0</td>
<td>44.0</td>
<td>41.0</td>
<td>0.2</td>
<td>1.60</td>
<td>4.680</td>
<td>0.035</td>
</tr>
</tbody>
</table>

\(^a\) Brooks and Corey fitting coefficients estimated using soil profile data combined with the McBride (2001) 1983 water retention model.

\(^b\) Bubbling pressure (cm H₂O).

\(^c\) Pore size distribution index.

\(^d\) Residual water content.

\(^e\) Soil profile and textural data from VandenBygaart et al. (1999).
Input Data for the RZWQM

Breakpoint rainfall data were prepared by formatting the tipping bucket rain gauge data from the London station. Gaps in these data were filled by using the data from the Stratford station (22 km away). The Stratford weather station provided only data on rainfall amount. Therefore, rainfall intensity data needed for the RZWQM were generated by ClimGen, a weather generation tool (Nelson, 2002). No winter data were collected on the test sites, and therefore, the data required for application of the RZWQM (such as snow pack density) were adopted from Gray and Male (1981).

The soil profile data were combined with the McBride (1983) water retention model to estimate the Brooks and Corey fitting coefficients for each soil horizon for the calibration and validation sites (Table 1). The $K_s$ was calculated based on the extensive field data by using the Guelph pressure infiltrometer and taken as $\frac{1}{2}$ of the geometric mean. These values were collected by Gupta et al. (2006). The value of $K_s$ used in this study was comparable to the values calculated by other researchers for similar soil in the area. Also, there was only one $K_s$ used for the whole soil profile. Other literature describing RZWQM investigations found that a single $K_s$ for a whole profile was appropriate.

Initial soil water content was based on field measurements, and the observed water table was matched with the day the run was initiated. Data on soil NO$_3$-N and NH$_4$-N (ammonium nitrate) were available up to a 30-cm depth in 15-cm increments. The assumption of exponential reductions in mineral N concentrations with depth (Stevenson 1965; Millman 1999) was used to extrapolate values for NO$_3$-N and NH$_4$-N beyond the 30-cm depth. The residue and microbial pools were initialized by consecutively running the model five times through the site's three-year crop rotation cycle. The other field-measured data included organic matter content, water content, depth of tile drains, and macropore characterization for each defined soil layer. With these data, the modeling exercise was completed for approximately one crop rotation cycle, from the spring of 1994 to the fall of 1996.

Calibration of the RZWQM

Prior to calibration of the RZWQM, a sensitivity analysis was performed to identify key calibration input variables. The procedure involved varying a parameter individually by a fixed percentage while all other parameters were kept constant. Table 2 summarizes the hydrology input variables considered in the sensitivity analysis and the ranges over which they were tested. These input variables were selected based on findings of Ahuja et al. (1993), Singh et al. (1996), and Walker et al. (2000), and on the weaknesses of the measured dataset available for the site. Macroporosity-related input variables were adjusted to better match observed with simulated tile water NO$_3$-N levels.
The version of the RZWQM used in this study has simplified snowmelt routines patterned after the Precipitation Runoff Modeling System (PRSM) (Leavesley et al. 1983). Little information is available to assist model users in identifying appropriate values for snow covered soils in the field. Also, no winter data were available for the sites; however, sensitivity analysis of the snowmelt algorithm for snowpack dynamics showed that most of the input was insensitive to the output other than average maximum snowpack density.

The input variables considered in the sensitivity analysis for plant growth were maximum nitrogen uptake rate ($N_{\text{max}}$), photosynthate to respiration ratio ($R_1$), biomass needed for leaf area index (SLW), age effect for plants in propagule development stage ($A_p$), and age effect for plants in the seed development stage ($A_s$).

**Hydrology component.** In calibrating the model, an iterative approach suggested by Hanson (2000) was followed. In this approach the hydrology component was calibrated first, and followed by the nutrient and crop growth components, respectively. Given that tile flow simulated by the RZWQM was highly sensitive to the Brooks and Corey fitting parameters, a detailed approach was developed for calibrating these parameters from field-measured data. The first approach was to use McBride’s (1983) laboratory measures data to determine the bubbling pressure ($\psi_{bp}$) and pore-size-distribution index ($\lambda$) for the Brooks and Corey function for each silt loam soil sample in the dataset. The value of third fitting parameter, the residual water content parameter ($\theta_r$), required to fit the Brooks and Corey relationship was assumed to be equal to 0.015, typical for a silt loam soil. The results helped to narrow down the range of possible values for these parameters, but the standard deviation showed a relatively wide range in which the values might fall. Therefore, a second approach was used to calibrate these parameters for the study sites by applying the McBride (1983) water retention model. This model has been a very good estimator of water release characteristics for southern Ontario soils (McBride, 2001). The McBride water retention model requires information on a soil horizon’s soil texture, bulk density, and organic matter for each soil layer. All the information used for this analysis is shown in Table 1. Once the retention curve was generated by using McBride’s model, it was then fitted to the Brooks and Corey function in order to arrive at values for the Brooks and Corey fitting parameters. The fitting parameters were optimized by selecting the combination of parameter values to obtain the lowest sum of squared difference ($\varepsilon$) between the generated data and the Brooks and Corey model using equation 1 given by James and Burges (1982):

$$
\varepsilon = \sum_{i=1}^{n} (M_i - P_i)^2
$$

where:
- $M$ = the McBride model estimated value at time $i$,
- $P$ = the Brooks and Corey predicted value at time $i$,
- $n$ = the number of values.

Using the Brooks and Corey parameters fitted to the McBride model significantly shifted the water retention curve relative to the curve developed using the RZWQM’s default Brooks and Corey approach. A summary of the optimized values of the Brooks and Corey parameters for each soil layer is given in Table 1.

Preliminary investigative runs indicated that the hydrology output was less sensitive to changes in $K_s$ for the individual horizon compared with a changing $K_s$ for the entire soil profile, a result also reported by Ma et al. (2000b). Ultimately, an iterative approach involving calibration of the nutrient and plant growth components yielded a $K_s$ value of 5.87 cm·hr$^{-1}$. This value is similar to the expected values reported by Gupta et al. (2006) for the soil used in this study.

**Nutrient component.** Initial estimates of microbial and humus pools were established based on field-measured values of crop residue, soil organic matter content, and microbial biomass carbon. The model was then run for three full three-year crop rotation cycles (1 May 1984 to 30 April 1993) using the data for the same period from 2.1 km away at the Blyth, Ontario weather station. After each three-year run, the nutrient pool balances were saved and used as the initial conditions for subsequent runs. This procedure was repeated four additional times to stabilize the microbial and residue pools. To check the calibration of the nutrient pools further, RZWQM-simulated

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**TABLE 2.** Input variables and test ranges considered in the sensitivity analysis of RZWQM’s hydrology component

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Base Value</th>
<th>Range Tested</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_s$ (cm·hr$^{-1}$)</td>
<td>11.74</td>
<td>0.05 - 200</td>
</tr>
<tr>
<td>Tile drain depth (m)</td>
<td>0.9</td>
<td>0.7 - 1.10</td>
</tr>
<tr>
<td>Drainable porosity (cm·cm$^{-1}$)</td>
<td>0.18</td>
<td>0.02 - 0.35</td>
</tr>
<tr>
<td>Brooks and Corey coefficients</td>
<td>25.7</td>
<td>0.1 - 100</td>
</tr>
<tr>
<td>$\psi_{bp}$ (cm)</td>
<td>0.21</td>
<td>0.05 - 0.5</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>0.000001</td>
<td>0.001 - 0.000001</td>
</tr>
</tbody>
</table>

*a* Saturated hydraulic conductivity.

*b* Bubbling pressure (cm H2O).

*c* Pore size distribution index.
Crop growth component. Crop data including crop growth stage, plant height, and flowering/silking dates were available at the site (McKague et al. 2002). Values for crop N uptake and the distribution of N between the harvested seed and the stover/straw were estimated based on data available from Ontario’s nutrient management software packages, NMAN2001 (Nutrient Management Planning Software. Ontario Ministry of Agriculture, Food and Rural Affairs, Canada) and MCLONE4 (Manure Costs Labor, Odours, Nutrients and Environment. Canadian Farm Business Management Council, Ottawa, Ontario).

Within the program, the total N in the seed and total amount of N in the above ground biomass for corn and soybean are given by the following relationships:

For corn:

\[ N_{c_{\text{seed}}} = 0.01685 \times Y_c \]  
\[ N_{c_{\text{up}}} = 0.02372 \times Y_c \]

For soybean:

\[ N_{s_{\text{seed}}} = 0.0743 \times Y_b \]  
\[ N_{s_{\text{up}}} = 0.0996 \times Y_b \]

where:

- \( N_{c_{\text{seed}}} \) is the total amount of N in the seed portion of corn (kg·ha\(^{-1}\)).
- \( N_{c_{\text{up}}} \) is the total amount of N in the seed portion of soybean (kg·ha\(^{-1}\)).
- \( N_{s_{\text{seed}}} \) is the total amount of N in the seed portion of soybean (kg·ha\(^{-1}\)).
- \( N_{s_{\text{up}}} \) is the total amount of N in the total above-ground biomass of soybean (kg·ha\(^{-1}\)).
- \( Y_c \) is the observed or expected yield of corn grain seed by a producer after applying N, respectively (kg·ha\(^{-1}\) at 0% moisture content).
- \( Y_b \) is the observed or expected yield of soybean seed, respectively (kg·ha\(^{-1}\) at 0% moisture content).

A set of field data from Partners in Nitrogen Use Efficiency (PINUE) study (1998-2000) (Burr et al. 2002) in southwestern Ontario was used to confirm the relationships in NMAN2001 and MCLONE4 (McKague et al. 2002). The PINUE data were used to test the linearity between crop yield and N uptake. The slopes of the regression lines obtained from the regression analysis were found to be very similar to their respective coefficients used in equations 2 to 5. The PINUE data were also used to assess a value for the grain to total above-ground biomass ratio. The average computed ratio for corn was 0.542 with a standard deviation of 0.068, and for soybean was 0.376 with a standard deviation of 0.152. These values compare well with literature values (Olsen and Kurtz 1982). The RZWQM does not include a crop growth model for winter wheat. Based on field measured N uptake data for winter wheat from the PINUE study, it was determined that the 1995 wheat yield being modelled removed 100 kg of N per hectare, and this value was used as an input to the RZWQM. To partition corn and soybean N uptake for model calibration purposes, corn and soybean input variables were adjusted in a manner that brought the simulated yield and plant N uptake as close as possible to field-measured values. The final calibrated values for the crop input data obtained through an iterative procedure are given in Table 3. These values are also similar to the values reported by Hanson et al. (1999) for the MSEA (Management Systems Evaluation Areas) sites in Iowa and Minnesota.

Results and Discussion

Sensitivity Analysis of the RZWQM

The sensitivity analysis for the hydrology component of the RZWQM showed that the Brooks and Corey fitting parameters (\( \psi_{bp} \) and \( \lambda \)) and \( K_s \) are the most sensitive parameters for tile drain flow (Fig. 3a). In addition, tile drain flow was also sensitive to lateral \( K_s \) and drainable porosity, and less sensitive to tile drain depth (Fig. 3b). The water table depth is moderately sensitive to the \( \psi_{bp} \), \( \lambda \), lateral \( K_s \), and the depth of tile drains (Fig. 3c and d). These results are similar to the findings in other RZWQM studies reported in the literature. The sensitivity of the Brooks and Corey fitting parameters and \( K_s \) to the amount and shape of the hydrograph of tile drain flow were also reported by Singh et al. (1996), Bakhsh et al. (1999), Walker et al. (2000), and Chinkuyu et al. (2004). Also, Singh et al. (1996) found that lateral \( K_s \) has a significant effect on the peak rate of the subsurface drain flow.

The sensitivity analysis of the nutrient component of the RZWQM largely focused on the variables characterizing soil macroporosity (Fig. 3e). The fraction of dead end pores had relatively little influence on tile drain N loss, while total macroporosity and macropore radius had a significant effect (Fig. 3e). However, Ahuja et al. (1993) found that distribution of chemicals and nutrients in the soil profile was not particularly sensitive.
Fig. 3. Sensitivity analysis of hydrological inputs to tile drain flow (a and b), water table depth (c and d), and tile nitrate loss (e). S1 = bubbling pressure, A2 = Pore size distribution index.
to macropore size, while Walker et al. (2000) found tile flow to be rather insensitive to changes in inputs defining soil macroporosity. Model documentation does not recommend adjustment of rate coefficients in the nutrient component unless there is strong evidence for such adjustments; therefore, after preliminary sensitivity analysis on some variables, it was decided to use the default values provided by the model developers.

The input variables used in the crop growth component were adjusted in an iterative manner in combination with the other model component inputs to arrive at a calibrated data set for the calibration site. The input variables such as Leaf Area Index, above ground biomass production, seed yield, and soil NO$_3$-N concentrations in the top 30 cm of soil influenced the model’s output of corn yield, N uptake, and ET rate. Age effect variables ($A_p$ and $A_s$) were found to be more responsive to change when modelling soybean growth than simulating corn growth. Similarly, corn yield was potentially affected by SLW and $R_s$, however, SLW and $R_t$ did not affect soybean yield dramatically. The sensitivity analysis of the potential leaf stomatal resistance showed some effect on grain and biomass yields and on the ET rate, and was included in the calibration procedure for each crop. The general effects observed in the sensitivity analysis of these crop input variables are consistent with those reported by Ma et al. (2000b) and Walker et al. (2000).

**Calibration of RZWQM**

**Hydrology component.** Figure 4a presents the comparison of simulated daily tile flow hydrographs with observed tile flows for the study site. The data in Fig. 4a show that the majority of the flow events occurred outside the period of observation because no equipment was in place to monitor the event at these times. The propeller flow meter used to detect flow had a detection range of 0.1 to 8 m·s$^{-1}$ (Global Water 1994). Due to these detection limitations, the minimum detection limits were 0.45 L·s$^{-1}$ and 0.3 L·s$^{-1}$ for the rising limb and receding limb of the observed hydrograph, respectively. Figure 4b presents this revised set of data points and highlights the zone within which lower flows were unlikely to be detected by the flow monitoring system on this site. Comparison of data in Fig. 4a and 4b shows few instances (e.g., mid-June 1994) when flow was detected in the field at rates below those suggested by the model. Such discrepancies between observed and simulated values are quite possible due to detection limits of the monitoring equipment, as in this case where the flow meter needed a flow rate of 0.45 L·s$^{-1}$ for activation.

Within the period of observation and known limits of the flow detection equipment, the calibrated RZWQM seems to do a reasonably good job of predicting tile flow. Over the three-year period, for which measured tile flow data were available, the total simulated tile flow was within 5% of the measured total flow. The timings of the simulated events in most cases matched reasonably well with the observed events; however, there were some inconsistencies during the late fall period. For example, in October of 1995, following the wheat crop, the model simulated a significant flow event that was not observed in the field. This could be due to a localized storm, which may have occurred at the weather monitoring site but not at the experimental site. Such a localized rainfall pattern is fairly common in southern Ontario during summer and early fall. Also, evaluation of observed data from the area shows a pattern of localized precipitation, particularly during summer times, with higher intensity as observed by other researchers (Clodman and Chisholm 1994; King et al. 1996; Burrows et al. 2002, Bao et al. 2005).

Figure 4c shows the variations in observed and simulated water table depth with time over the study period. These data show that the model simulated water table depth reasonably well. However, it underestimated the water table depth in early fall 1995 and 1996, and in early spring 1996. Figure 4c also provides an indication that the model underestimated tile flow during early fall 1996 (Fig. 4b) because of lower simulated water table depth; however, the underestimation improved a few days after the first observed tile flow event. Figures 5a and 5b show the comparison of available measured soil

<table>
<thead>
<tr>
<th>Crop</th>
<th>$N_{max}^a$ (g/plant/day)</th>
<th>$R_1^b$ (fraction/day)</th>
<th>$SLW^c$ (g/unit leaf area)</th>
<th>$A_p^d$</th>
<th>$A_s^e$</th>
<th>$L_w^f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn</td>
<td>1.7</td>
<td>0.28</td>
<td>10.4</td>
<td>0.95</td>
<td>0.95</td>
<td>140</td>
</tr>
<tr>
<td>Soybean</td>
<td>2</td>
<td>0.44</td>
<td>0.94</td>
<td>n/a</td>
<td>n/a</td>
<td>120</td>
</tr>
<tr>
<td>Wheat</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>235</td>
</tr>
</tbody>
</table>

*a Maximum nitrogen uptake rate.

*b Photosynthetic to respiration ratio.

*c Biomass needed for leaf area index.

$d$ Age effect for plants in propagule development stage.

*e Age effect for plants in the seed development stage.

*f Leaf stomatal resistance.

n/a = not applicable.
Fig. 4. Comparison of daily simulated with observed tile drain flow (a), zone of nondetection of flow (b), and comparison of daily simulated with observed water table depth (c) for the NBS (no-till) calibration site. The date ranges of the observation periods are delimited by a thick line at the top (a,b) or bottom (c) of the chart, with the actual observation date range specified on top of the line.
Fig. 5. Comparison of observed and simulated soil moisture contents in the top 0 to 15 cm (a) and 15 to 30 cm (b) soil profile; comparison of simulated and observed soil NO$_3$-N concentrations in the top 0 to 15 cm (c) and 15 to 30 cm (d) soil profile; and comparison of simulated and observed soil NH$_4$-N concentrations in the top 0 to 15 cm (e) and 15 to 30 cm (f) soil profile for the NBS (no-till) calibration site.
moisture content data with calibrated estimates of soil moisture in the top 30 cm of soil. It shows that while estimates of soil moisture were close to measured values, the model typically overestimated soil moisture. The small change in water table depth (Fig. 4c, 5a, and 5b) or in soil moisture content of the soil profile could have a major influence on water balance.

A comparison was made of ET simulated by the RZWQM (468 ± 55 mm) with data available in the literature for the western region in Ontario. Dickinson and Diwu (2000) used long-term regional precipitation and stream flow data and water balance approach to estimate ET (500 to 550 mm). The estimates of ET (567 mm) reported by Rudra et al. (2000) were based on data collected from an annual crop at one site in southern Ontario. McLaughlin (2001) and Fallow et al. [1999] estimates, 550 ± 36 mm and 675 ± 68 mm, respectively, are simulated results obtained from application of the EPIC (Williams et al. 1990) and SHAW (simultaneous heat and water) (Flrichinger 1987) models, respectively. This comparison suggests that the calibrated RZWQM slightly underestimated actual ET. This weakness of the RZWQM was also observed by Farahani and Ahuja [1996] and Jaynes and Miller (1999). The average calibrated actual ET rate (532 mm·yr⁻¹), however, was well within the range of the results from other studies conducted in the area, particularly given that the test site is in the border zone between the southwest and central regions of Ontario.

**Nutrient component.** Figures 5c to 5f show the comparison of the simulated and observed NO₃-N and NH₄-N levels in the 0 to 15 cm and 15 to 30 cm soil zones, respectively. For most observations, NO₃-N in the soil profile was underestimated by this model. In addition, NH₄-N levels in the soil were also underestimated, suggesting a need to revise the numerous ammonification and decomposition rate input variables in the OMNI (Organic Matter and Nitrogen Cycling) model, a submodel in the RZWQM for nitrogen and carbon simulation. The model was particularly poor at estimating mineral N levels in the early spring. This was due to simplification of winter dynamics used in the RZWQM. Interestingly, the model simulations of soil NO₃-N levels during the year winter wheat was planted were more consistent with measured values than they were for years with corn or soybean. This could be due to the simulation of wheat growth using the “quickplant” routine, which contains information such as crop yield, nitrogen uptake, and planting and harvest dates of the modelled crop. For this study, much of this information for winter wheat was available. However, for corn and soybean, the OMNI module was used instead. A number of decomposition and nitrification rate constants were used in the OMNI module because of insufficient field data. These coefficients could ultimately affect the levels of nitrate in the profile. Therefore, simulating nutrient loss using the “quickplant” module for all crop types, including soybean and corn, may be just as effective. Also, building the input data set would certainly be much easier.

In general, the model estimates for soil microbial biomass, mineral N in the top 30 cm, and NO₃-N concentrations in tile flow did not fluctuate as much as the observed values (results not shown). It was observed that the RZWQM is not as reliable in predicting microbial levels in the early months following winter as it is in later times of the growing season. The top layer of the soil profile is likely to be the most difficult zone for predicting microbial population due to the variability in environmental conditions such as soil temperature and moisture. However, the model reasonably represented the soil temperature for the field conditions.

Due to the fact that few tile flow events were observed, very few tile nitrate samples were collected during the course of the field study. The collected samples had NO₃-N levels typically much higher than those estimated by the model. The exception again was in May 1996 following the fertilizer application when the model results were quite close to the observed value. Here, the fact that the RZWQM accounts for macropore flow may have been the reason for the improved estimate. A run using similar input values, but not simulating the macropore flow component, estimated only 0.35 ppm NO₃-N in the tile outflow for the April 25, 1996 event. The measured value was 9 ppm, whereas the model, when simulating macropore flow component, estimated 8.2 ppm NO₃-N.

**Crop yields.** The modelled and observed crop yield and N uptake values for the corn and soybean crops, and the percentage differences are shown in Table 4. The calibrated crop yields came very close to the measured yields. The simulated yields were within 1% of the observed yields. While N uptake for corn was also close (+1.3%) to the observed amount, the organic C to total aboveground biomass ratio of seed to total aboveground biomass for corn and soybean was 0.52 and 0.35, respectively. These values gave further confidence in the model’s ability to predict yields on the test site.

**Validation of the RZWQM**

The typical approach followed in the evaluation of the RZWQM included calibration using a data set from a field plot on one site, and validation using another set of data at the same site. The validation approach followed in this study is unique. In this study the model was calibrated at a site with given soil series and management practices, and validated at a different site with different soil series and management practices.

The calibration results for the hydrology, nutrient, and crop growth components of the RZWQM for the NBS (no-till) site were used for a second nearby field (the TGW site, Fig. 2) for validation. The TGW site is similar to
the calibration site but was managed using conventional tillage practices. Also, the model used different weather data inputs at a different point within the crop rotation in any particular year (i.e., cycle shift) and different long-term tillage practices (no-till versus conventional). This approach was used to take the typical validation step up a level, and to test the model performance under varying soil management conditions across southern Ontario.

The Brooks and Corey fitting coefficients for each of the soil horizons were calculated for the validation site. Also, soil hydraulic conductivity was taken from the field-measured values. The residue and microbial pools were initialized by consecutively running the model five times through the site's three-year crop rotation. Also, weather data for the nine years prior to the field study were used in the initialization process. Although the calibrated crop input values were used to characterize the corn and soybean crops, the growing years for these crops were different from the calibration site.

The comparison of the simulated and observed tile outflows is shown in Fig. 6a. These data show that the model had difficulty simulating a number of significant tile flow events during June and July, 1994 and 1995. Even in 1996, while it did predict a flow event in late June, the period of flow was shorter than observed. As well, in September 1996, the model did not predict the tile flow observed in the field. Given that the validation site had a larger tile drainage area than that of the calibration site, valid daily flow observations were not limited nearly as much by the lower sensitivity of detection of the tile monitoring flow meter. Only those events that gave flows of less than 0.1 cm·day⁻¹ could have potentially been undetectable by the monitoring equipment. Daily tile flows collected were paired with observed daily flows for the same day. The mean of the observed set of daily flows was 41% higher than the simulated flows for the same days.

The model overestimated water table depth in both 1994 and 1995, but produced simulation results closer to the observed conditions in 1996 (Fig. 6b). The model's estimate of actual ET was high for all years (664, 711, and 606 mm for 1994, 1995, and 1996, respectively). The annual actual ET for southern Ontario conditions ranges between 500-550 mm (Dickinson and Diiwu 2000). This suggests an error in estimating soil water content or an error in the calibrated value for leaf stomatal resistance, a crop input variable.

Figures 7a and b show the observed and simulated soil moisture contents at the validation site, indicating an overestimation of simulated soil moisture contents compared with the observed for the 0 to 15 and 15 to 30 cm soil zones. The tendency for the model to overestimate soil moisture content was noticed with the calibration results as well. The error in ET estimation may be a function of the soil horizon data that was input to describe the soil because soil textures below 70 cm were not well characterized on the site. The high estimate of soil moisture also suggests a weakness in the Shuttleworth-Wallace model used in the RZWQM to simulate ET under partial canopy and residue cover conditions. Also, the model's underestimation of the soil temperature was due to the predictions of higher than observed soil moisture content because the model adjusts soil temperature depending on moisture content. In addition, as discussed earlier, the RZWQM estimation of residue and canopy cover using the OMNI module was a factor.

Overall, these data (Fig. 6a and b, 7a and b) show similar trends for observed and simulated tile outflow, water table depth, and soil moisture content. However, tile outflow was under-predicted, and ET and soil moisture content were overpredicted for these years. Some improvement in some key variables in the hydrology component, as mentioned in sensitivity analysis, and the availability of observed data will be helpful to improve the simulated results of the RZWQM. It is also important to mention that some generated inputs were used in the hydrological component of the model due to the unavailability of weather data for the sites. Therefore, data sets from nearby stations (London and Stratford) and from the weather generator, ClimGen (Nelson, 2002), were used to estimate various inputs. As summer precipitation in Ontario is localized, there may be a possibility that there was less or no rainfall at the experimental sites. This could significantly affect the simulated results for that day. Also, some data such as rainfall intensity data for the nongrowing season, solar radiation, and relative humidity were generated using

<table>
<thead>
<tr>
<th>Year</th>
<th>Crop</th>
<th>Observed</th>
<th>Simulated</th>
<th>% Difference</th>
<th>Observed</th>
<th>Simulated</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1994</td>
<td>Soybean</td>
<td>2,219</td>
<td>2,244</td>
<td>+1.1</td>
<td>195</td>
<td>172</td>
<td>-11.8</td>
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<tr>
<td>1996</td>
<td>Corn</td>
<td>6,360</td>
<td>6,355</td>
<td>-0.1</td>
<td>147</td>
<td>149</td>
<td>+1.3</td>
</tr>
<tr>
<td>Validation site</td>
<td>1994</td>
<td>Corn</td>
<td>8,322</td>
<td>7,142</td>
<td>-14.1</td>
<td>197</td>
<td>206</td>
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<tr>
<td>1995</td>
<td>Soybean</td>
<td>2,923</td>
<td>2,184</td>
<td>-25.3</td>
<td>287</td>
<td>168</td>
<td>-41.5</td>
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</tbody>
</table>

* Crop yield at 0% moisture.
Fig. 6. Comparison of daily simulated and observed tile drainage flows (a) and water table depth (b) for the TGW (conventional) validation site. The date ranges of the observation periods are delimited by a thick line at the top (a) or bottom (b) of the chart, with the actual observation date range specified on top of the line. Zone of nondetection for flow monitoring equipment on TGW side is 0 to 0.1 cm/day.

ClimGen. In addition, the effect of different management practices and soil series for the validation site as compared with the calibration site could also affect the validation results.

Figures 7c and d show the simulated and observed soil NO$_3$-N concentrations in the top 30 cm for the validation site. Soil NO$_3$-N in the top 30 cm was usually underestimated until a fertilization event occurred, after which the soil NO$_3$-N concentrations were overestimated. This is similar to the pattern observed at the calibration site. The model's inability to fully predict site hydrology may be one reason. Again, high ET rates would affect the amount of water available for leaching, thereby reducing leaching losses of NO$_3$-N and leaving higher amounts of NO$_3$-N in the soil profile. If soil NO$_3$-N was not being removed by the crop—as simulated yield output suggests it was not removed in the year soybean was grown—then higher levels would have been simulated as being present in the soil. The simulated fall and winter season soil drainage would move the excess NO$_3$-N through the profile, leaving lower NO$_3$-N levels again for the start of a new growing season.

Very few tile flow events were observed in the field and, in some cases, the model did not simulate an observed tile flow event (Fig. 7e). For situations where a simulated tile flow event coincided with a field event, the predicted tile NO$_3$-N concentrations were often fairly close to the observed values. The overestimation of tile NO$_3$-N in April 1995 was due to the model's estimation of N build-up in the soil profile during the previous growing season, and to the accuracy of the hydrological component (simulation of tile flow events) of the model.
which may have led to the higher NO$_3$-N estimated than observed.

Table 4 shows a comparison of observed and simulated crop yields, and N uptake for the validation site. Generally, the yields of corn and soybean were underestimated by the RZWQM on the validation site. For corn, the estimate was 14.1% lower than the measured yield, just barely meeting the allowable 15% difference criterion. The simulated soybean yield was 25.3% less than the observed yield. However, total N uptake simulated for the corn crop and estimated from the observed yield were quite similar, while simulated N uptake for the soybean crop was far below the estimate based on the observed soybean yield.

Table 5 summarizes the statistical analysis of the observed and simulated data for tile drain flow, tile flow NO$_3$-N concentration levels, and soil NO$_3$-N. The parameters used in the analysis were mean deviation, a paired t-test, a correlation coefficient ($R^2$), and the sorted and unsorted efficiency values as described by Loague and Green (1991). The analysis showed a significant difference between the daily observed and simulated tile drain flow. Also, the determination coefficient and unsorted efficiency value were both low. Moreover, the high sorted efficiency suggests that the model was simulating values that had a similar range in magnitude to the measured values. The model did a better job in estimating the soil NO$_3$-N concentrations in the top 15 cm than in the 15 to 30 cm depth zone. The statistics showed that the model underestimated the NO$_3$-N levels in the soil profile.
Conclusions and Recommendations

Conclusions from the sensitivity analysis, calibration, and validation of the model are as follows:

- The most sensitive inputs for the hydrology component were the Brooks and Corey fitting parameters of $\psi_{bp}$ (bubbling pressure), $\lambda$ (pore-size-distribution index), and saturated hydraulic conductivity ($K_s$). Tile drain flow was highly sensitive to $\psi_{bp}$, $\lambda$, $K_s$, lateral $K_s$, and moderately sensitive to drainable porosity. The groundwater table depth was quite sensitive to the $\psi_{bp}$, $K_s$, lateral $K_s$, and the depth of tile drains. Also, the wide range of the measured and calculated values of $K_s$ emphasized the need to include it as a variable in the calibration process.

- The RZWQM allows only one set of data to represent soil characteristics over the entire year. It has been shown that various soil characteristics, especially $K_s$, can change seasonally within a year (Asare et al. 1990). While the RZWQM provides some allowance for soil factors like bulk density to change following tillage, these changes are not being adequately represented by the single set of Brooks and Corey fitting parameters. Adjustments to these fitting parameters within the ranges were found suitable for a silt loam soil. In addition, the approach developed by McBride (1983) could possibly improve tile flow simulations for Ontario conditions.

- The sensitivity/calibration analysis of the nutrient component of the model focused largely on the simulating effect of macropores in N losses to tile drains. It showed that the fraction of dead end pores had relatively little effect on tile drain N loss, and total macroporosity and macropore radius had counteracting effects. Also, the model tended to underestimate the amount of soil nitrate on the calibration and validation sites. The inability of the model to handle the spatial and temporal variability of the field and over-winter simulation approach affected its prediction accuracy.

- Input variables such as the age effect variables ($A_p$ and $A_s$), leaf stomatal resistance, biomass for leaf area index (SLW), and photosynthate to respiration ratio ($R_1$) in the crop component affected the simulated crop yield, N uptake, and ET rate. The various crop inputs affected the crop yield very differently between the two crops. For example, the response of a percentage change in $A_p$ and $A_s$ was more when modelling soybean growth than it was in simulating corn growth. In addition, corn yield was significantly affected by values given to SLW and $R_1$.

- Overall, the RZWQM did a reasonable job of simulating tile drain flow; however, it underestimated crop yield, N uptake, and NO3-N concentrations on the validation site. The results also show the importance of measuring precipitation on study sites; this will help improve the simulated results of tile flow and soil moisture content in the soil profile.

- The yields of corn were underestimated (-14.1%) by the RZWQM, just barely meeting the allowable 15% difference criterion on the validation site. However, total N uptake simulated for the corn was quite similar to observed values. The simulated soybean yield was 25.3% less than the observed yield, while simulated N uptake for the soybean crop was far below than the estimate based on the observed soybean yield.

- The current version of the RZWQM does not handle frozen soil conditions. Improvement of the RZWQM’s snow algorithm may provide better simulated results for Ontario. The water retention model developed by McBride (1983) is recommended to be incorporated into the RZWQM to better estimate water retention characteristics of soils in Ontario. In addition, more field work is needed to assist with identifying suitable values for a number of coefficients used in the RZWQM’s nutrient component. Also, the ET and plant water uptake components need further testing to understand the reasons for the high variability of the model’s predictions of actual ET or high ET periods.

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