Evaluation of WARMF model for flow and nitrogen transport in an agricultural watershed under a cold climate
Shadi Dayyani, Shiv O. Prasher, Ali Madani, Chandra A. Madramootoo and Peter Enright

ABSTRACT
The Watershed Analysis Risk Management Framework (WARMF) model is adapted to simulate flow and nitrate-N transport in an agricultural watershed in Quebec, Canada. The model was evaluated for the St. Esprit Watershed (24.3 km²), which is a part of the 210 km² St. Esprit river basin, a tributary of the L’Assomption Watershed (4,220 km²). WARMF’s hydrologic calibration and validation was performed using data from the gauge station located at the outlet of the watershed. Water-quality data collected were used to guide water quality calibration/validation. Simulations were carried out from 1994 to 1996; data from 1994 and 1995 were used for model calibration and data from 1996 were used for model validation. The model performed reasonably well in simulating the hydrologic response and nitrate losses at the outlet of the watershed. The $R^2$ between the observed and simulated monthly stream flow for calibration was 0.92, and that for validation was 0.94. The corresponding coefficients of efficiency ($E$) were 0.89 and 0.91. The $R^2$ and $E$ values for calibration/validation of NO3-N loads simulation were 0.89/0.84 and 0.86/0.75, respectively. Thus, the model simulated monthly flow and nitrogen losses with a good degree of accuracy over the entire year. Key words | cold climate, hydrology, modeling, WARMF, water quality, watershed scale

INTRODUCTION
The agricultural sector in Canada in general and Quebec in particular has witnessed substantial growth over the past two decades. The increase in agricultural production can be attributed to several factors, such as mechanization of farm operations, soil and water management, use of chemical fertilizers, and improved crop varieties (Gollamudi 2006). At the same time, this has placed the region’s water bodies under severe environmental stress. In Quebec, agriculture is responsible for over 70% of the total non-point source pollution (Enright & Madramootoo 2004). Increased levels of phosphorus and nitrogen in lakes and rivers promote eutrophication, a phenomenon that may result in excessive growth of algae and poisonous cyanobacteria that deplete dissolved oxygen and render it hazardous for aquatic as well as human life. In Quebec, nitrogen and phosphorus contamination of watercourses and lakes is largely attributed to non-point source pollution from agricultural fields (Gollamudi 2006).

While long-term field-scale monitoring is necessary to establish a theoretical understanding of nutrient dynamics, only a limited number of studies are available due to the high cost of instrumentation and operation (Gollamudi 2006). Additionally, collecting long-term data for a range of climatic, hydrologic, and topographic conditions is a time-consuming and difficult process. Thus, complementing real-time field data with a validated hydrological and water quality simulation model is both cost-effective and time-efficient.

Hydrological and water quality simulation models have developed from elementary to complex algorithms in the
past three decades (Gollamudi 2006). A common starting point for all of these models is the necessity to accurately simulate the movement of water through different pathways of the hydrologic cycle – precipitation, overland flow, infiltration, subsurface flow, deep seepage, evapotranspiration (ET), and stream flow. The ability of a model to accurately simulate hydrological processes, such as surface runoff and subsurface drain flow, is important for reliable predictions of nutrient losses. The key criteria in choosing a model include the availability of reliable input data for the model parameters, spatial/temporal scale of use, and nature of output.

In this study, we used the Watershed Analysis Risk Management Framework (WARMF) model (Chen et al. 1998), to predict water quality and quantity in an agricultural watershed in Quebec, Canada. WARMF is a user-friendly tool, organized into five linked modules under one geographic information system (GIS)-based graphical user interface (GUI). It was developed under the sponsorship of the Electric Power Research Institute (EPRI) as a decision support system for watershed management. The scientific basis of the model has undergone several peer reviews by independent experts under US EPA guidelines (EPRI 2000). WARMF has been applied to over 15 watersheds in the United States and internationally (Chen et al. 2001a; Weintraub et al. 2001b, 2004; Herr et al. 2002; Keller et al. 2004; Geza & McCray 2007; Rambow et al. 2008). The focus of these studies has varied from total mass daily loading (TMDL) calculation (nutrients, sediment, fecal coliform, metals) to more research-oriented applications, such as modeling the fate and transport of mercury in a watershed and the impact of onsite wastewater systems on a watershed model. The algorithms of WARMF were derived from many well-established codes (Chen et al. 2001b). Algorithms for snow hydrology, groundwater hydrology, river hydrology, lake hydrodynamics, and mass balance for acid-base chemistry were based on the Integrated Lake-Watershed Acidification Study model (Chen et al. 1983). Algorithms for erosion, deposition, resuspension, and transport of sediment were adapted and modified from ANSWERS (Beasley et al. 1999). WARMF (Chen et al. 1998) is classified as a watershed decision support system (DSS), sponsored by EPRI. A DSS provides information and tools that help collaborative decision-making among interested parties (Chen et al. 2001b). WARMF was designed to assist in watershed management and TMDL development, and is publicly available. WARMF intended users are technical and non-technical stakeholders making watershed decisions. WARMF is organized into five linked modules (Engineering, Data, Consensus, TMDL, and Knowledge) under one, GIS-based GUI. The Engineering module is the dynamic, simulation model that drives WARMF. The Data module provides time series input data (meteorological, point source) and calibration data. The Knowledge module is a utility to store important documents for the watershed. At the center of WARMF are the two watershed approach modules for Consensus building and TMDL calculations, which provide road maps for the step-by-step decision-making process (Weintraub et al. 2001a). The model can be used to run simulations for certain management goals and objectives within a watershed that enables the user to see and compare the outcomes of alternative management plans. Output from the model can be shown in GIS-based maps, graphs, and tables.

The main objective of this study was to evaluate the WARMF model to: (1) estimate flow; and (2) estimate nitrate-nitrogen losses in an agricultural watershed in a cold region using three-site years of data. The evaluated model is a decision support system for watershed managers to perform TMDL analysis or to evaluate the impacts of different management practices to improve the quality of water. WARMF can be used to simulate the nitrogen load leaving a watershed, enabling managers to determine how load reductions can be most effectively allocated.

**MATERIALS AND METHODS**

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The pollutant accumulation and wash-off from urban areas was adapted from the Storm Water Management Model (Chen & Shubinski 1971; USEPA 1992). The sediment sorption-desorption of pesticides and phosphorus and the kinetics of nutrients and algal dynamics were adapted from WASP5 (Ambrose et al. 1991). A complete description of the WARMF formulations can be found in Chen et al. (1998).

**Engineering module**

The Engineering module is a GIS-based watershed model that calculates daily runoff, subsurface flow, stream flow, and water quality of river segments and reservoirs. The model divides the watershed into various components, including sub-watersheds, stream segments, and lake layers. Figure 1 shows the network of sub-watersheds and rivers for the St. Esprit Watershed. Sub-watersheds are further divided into canopy and soil layers. Land surface is described by land use. In order to run water quality simulations, these components are connected into an integrated network allowing for the flow of pollutants between them.

A hydrologic model within WARMF simulates canopy interception, snow pack accumulation and melt, infiltration through soil layers, ET from soil, exfiltration of groundwater to stream segments, and kinematic wave routing of stream flows. Figure 2 shows the conceptual model of hydrology for WARMF. A sub-watershed can have various land uses on the land surface. Below ground, the soils can have up to five layers (only two layers are shown in Figure 2). The groundwater table can rise or fall depending on the balance between vertical percolation from above and lateral outflow to the river segment (Chen et al. 2001b). The potential ET for each month is calculated as a function of latitude using Hargreaves’ equation (Hargreaves 1974).

In general, the hydrologic simulation is performed as follows (Chen et al. 2005). The rate of infiltration into the soil is limited by the vertical hydraulic conductivity of the top soil layer. If the soil is frozen (which occurs at the St. Esprit Watershed) or the groundwater table rises to the ground level, the water from precipitation and snowmelt is backed up to the ground surface. The water retained on the ground surface fills surface depression storage. When surface depression storage is filled, the excess water flows to a river segment by sheet flow, which is calculated by Manning’s equation. For each soil layer, percolation is calculated from the layer above and to the layer below. The soil layer has an allocation of evaporation according to the root distribution of plants. The model performs a flow balance in each time step (daily) to update soil moisture.

![Figure 1](image1.png) | Network of land catchments and rivers for the St. Esprit Watershed.

![Figure 2](image2.png) | Definition sketch for the compartments of a watershed (Chen et al. 2001b).
by accounting for the evaporation and the difference in percolation to and from the soil layer. The hydraulic conductivity of soil layers is a function of soil moisture. The available void space in the soil is filled with the water, which percolates downward. When the percolation reaches the groundwater table, it raises the groundwater level. Groundwater can flow out to the river segment by lateral flow, which is calculated with Darcy’s equation using horizontal hydraulic conductivity and slope. The unconfined aquifer is assumed to be watertight. Any known loss of groundwater to the deep confined aquifer must be specified as groundwater pumping for WARMF to extract water from the unconfined aquifer. Stream flow is routed by the kinematic wave method, and Manning’s equation is used to calculate the outflow rate. Water depth is determined by performing a flow balance by accounting for inflow from the upstream river segment, inflow from land catchments on both sides of the river segment, outflow to the downstream river segment, and the change of storage. Such simulations track the flow paths of precipitation from land into different water bodies (Chen et al. 2005).

The Chemistry module performs various mass balance and chemical equilibrium calculations along each flow path (Weintraub et al. 2001b; Eisen-Hecht & Kramer 2002). A complete mass balance is performed, starting with atmospheric deposition and land application as boundary conditions. Pollutants are routed with water in throughfall, infiltration, soil adsorption, exfiltration, and overland flow. The sources of point and non-point loads are routed through the system with the mass so that the source of non-point loading can be tracked back to land use and location (Chen et al. 1998).

Data and Knowledge modules

The Data module contains meteorology, air quality, and point source data used to run the model. It also contains observed flow and water quality data used for model calibration purposes. The data are accessed using a map-based interface and can be viewed and edited in both graphical and tabular format. Supplemental watershed data, documents, case studies, or reports of past modeling activities are stored in the Knowledge module for easy access by model users (Chen et al. 1998).

Consensus and TMDL modules

The last two watershed approach modules are roadmaps providing guidance for stakeholders during the decision-making process. The Consensus module provides information in a series of steps for stakeholders to learn about the issues, formulate and evaluate alternatives, and negotiate a consensus. It provides a simple menu for scenario generation that allows stakeholders, without extensive WARMF knowledge, to simulate reductions of loads from point/non-point sources of pollution, atmospheric deposition, or diversion quantities by a percentage (Chen et al. 2002b). Users require knowledge of the models and interfaces to run more detailed scenarios (e.g., changes in land use distribution, changes in fertilizer application rates, etc.). Through the TMDL module, calculations are made for a series of control points from upstream to downstream within the watershed. Iterative sets of simulations can be performed to calculate various combinations of point and non-point loads that the water body can accept and meet water quality criteria for the designated uses at these control points (Chen et al. 1998).

Site description

The WARMF model was applied to the St. Esprit Watershed, located approximately 50 km north of Montreal between 45°55′0″ and 46°0′0″ N, and 73°41′32″ and 73°36′0″ W (Figure 3) in south-western Quebec, Canada. It is a part of the 210 km² St. Esprit River basin, a tributary of the L’Assomption Watershed (4,220 km²). The land in the watershed is predominantly used for agriculture. The human population of the watershed is about 700; however, there are no villages or towns within the watershed.

The St. Esprit Watershed comprises a net drainage area of 24.3 km². During the study period (1994–1996), approximately 64% of the total area was under crop production with the majority of land use under corn crop, followed by cereals, soybeans, vegetables, hay, and pastures. The remaining 36% of the area was occupied by forested, bare, and residential lands (Table 1). Over 50% of the agricultural land has subsurface drainage. The difference in elevation from the outlet to the highest point of the watershed is
44 m and the principal watercourse is 8.5 km long. Topography can be described as flat to rolling, with most of the cultivated land having slopes of less than 3%. The elevation data were obtained from GeoBase (GeoBase 2007), Canadian Digital Elevation Data; the watershed boundary was created using GIS tools and digital elevation map (DEM) (Figure 4). The streams map was taken from previous studies on St. Esprit Watershed and also created using DEM and GIS tools (Enright et al. 1995; Mousavizadeh et al. 1995; Sarangi et al. 2005a, b).

These maps, along with 1:63,360 soil maps (Lajoie 1965), 1:15,000 field-level aerial photography, and information provided by Enright et al. (1995) identified approximately 16 soil types, and 10 different land use categories (Figure 5). Soil textures in the watershed are variable; in general, the largest proportion of the watershed is occupied by coarse-textured

<table>
<thead>
<tr>
<th>Land use</th>
<th>Area (m²)</th>
<th>Area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn</td>
<td>6,272,063</td>
<td>26</td>
</tr>
<tr>
<td>Cereal</td>
<td>2,073,508</td>
<td>8.5</td>
</tr>
<tr>
<td>Soya</td>
<td>1,565,615</td>
<td>6.4</td>
</tr>
<tr>
<td>Vegetable</td>
<td>1,966,098</td>
<td>8.1</td>
</tr>
<tr>
<td>Hay</td>
<td>2,919,677</td>
<td>12</td>
</tr>
<tr>
<td>Forest</td>
<td>6,345,533</td>
<td>26</td>
</tr>
<tr>
<td>Pasture</td>
<td>703,183</td>
<td>2.9</td>
</tr>
<tr>
<td>Irrigation-pond</td>
<td>165,435</td>
<td>0.68</td>
</tr>
<tr>
<td>Residential</td>
<td>1,241,621</td>
<td>5.1</td>
</tr>
<tr>
<td>Unused</td>
<td>1,107,939</td>
<td>4.5</td>
</tr>
<tr>
<td>Total</td>
<td>24,360,673</td>
<td>100</td>
</tr>
</tbody>
</table>
soils (sand and sandy loam 44%), followed by fine-textured soils (clay and clay loam 39%). The distribution of soil textural classes in the watershed is shown in Figure 6. The lower portion of the watershed is mostly composed of clays and clay loams, including the Ste. Rosaile and St. Laurent Series (Lapp et al. 1998). Most of the annual crop production takes place on the heavier soils. The upper regions of the watershed are composed of loamy and sandy soils. Natural drainage on these soils is poor and tile drainage systems have been installed to lower the water table to enhance crop production (Enright et al. 1995).

In the watershed, the period of frost varies from 122 to 138 days. Average annual precipitation varies between 860 and 1,050 mm, with approximately 20 to 25% as snow (Sarangi et al. 2005a, b). Average annual potential ET is between 400 and 560 mm. The mean temperature in the month of July, the warmest month of the year, varies between 18 and 21 °C (MAPAQ 1985).

**Instrumentation and monitoring**

In the winter of 1993–1994, a stream gauging station was established at the watershed outlet, and a meteorological station was installed in the watershed (Figure 3). The equipment installed at the watershed outlet included a water level sensor (Druck 950 submersible pressure transducer) installed on the stream bed bottom, a UDG01 ultrasonic level sensor mounted over the outlet culvert, and a data logger (Campbell Scientific CR10) located in the gauging station building to record and store the data. A backup system that independently measures water level and flow velocity and sends these data to the primary data logger was also installed. Water samples were collected on a flow-weighted basis. An automated water sampler was installed at the gauging station. A sampler intake line was suspended over the control section to be monitored. An automated sampling strategy was based on the flow volume calculation; the automated sampler was programmed for activation at a variable but predetermined threshold value of accumulated flow. The collected samples consisted of the automated type and the in-stream grab samples collected on the weekly or bi-weekly site visits. Details of the water sampling protocol are given in Enright et al. (1995).

The meteorological station was equipped with sensors for air and soil temperature, solar radiation, wind speed and direction, snow accumulation, as well as a tipping bucket rain gauge and a Campbell Scientific data logger (Perrone & Madramootoo 1998). Table 2 shows monthly precipitation for 1994–1996 measured at the site and
average 30-year monthly precipitation measured at the St. Jacque weather station, located about 6 km from the experimental site. The annual precipitations of 1994 and 1995 were 14 and 49 mm below the 30-year average (1997–2007), respectively; while, the annual precipitation in 1995 was 71 mm above the 30-year average range of monthly average precipitation for 30 years (37 to 103.2 mm (Table 2).

Land use and land management information were collected on St. Esprit as part of an integrated watershed monitoring and management project (Enright et al. 1995; Papineau & Enright 1997). There were 25 farms, of which information from 18 of the farms was available. The participating producers account for approximately 67% of the agricultural land use of the watershed (Sarangi et al. 2005a, b).

Model inputs

WARMF inputs include meteorology data (daily precipitation and min/max temperature, cloud cover, dew point temperature, air pressure, and wind speed), soil properties (field and saturated moistures of soil, vertical and horizontal hydraulic conductivities, and bulk density), land use data, DEM, sub-watershed boundaries, ground slope and aspect, and fertilizer application data. WARMF’s water quality-related parameters comprise initial soil concentration of ammonia, soil nitrification rate, litter fall rate, productivity of land uses, and air quality data.

The climatic data were obtained from the meteorological station installed in the watershed. The DEM (Figure 4) was developed using topographic data (contour lines and elevation point data). The natural drainage network was generated from the DEM of the watershed, using the Arc-Hydro tools of GIS. The sub-watershed boundary map (watershed delineation) was developed using DEM and by knowing where the watershed outlet is located. Using GIS tools, the watershed was discretized into 18 sub-watersheds ranging from several hundred m² to a few km² in size (Figure 1). The slope and aspect maps were developed using DEM in GIS. The county-level soil maps were digitized and a soil database (Figure 6) was developed and used to identify the different soil types across the watershed. Crop-related data were taken from land use maps imported into GIS (Figure 5). Fertilizer data were obtained from the GIS shape files developed for the watershed (Papineau & Enright 1997; Mousavizadeh 1998). WARMF overlays the polygons of land uses to the polygons of sub-watersheds to calculate the percentages of land use categories (e.g., urban, agriculture, deciduous forest, coniferous forest, open, etc.). The van Genuchten equation (Van Genuchten 1980) was used to determine the soil parameters (retention curve and hydraulic conductivity). The van Genuchten parameters were obtained from previous research performed in Quebec (Mousavizadeh 1992, 1998; Perrone 1997; Dayyani et al. 2009, 2010) and also using the Rosetta model (Schaap et al. 2001). Air and rain chemistry data were obtained from the National Atmospheric Deposition Program (NADP) website (NADP 2009). The closest station to the watershed was HWF187, located approximately 220 km south of the watershed. Other parameters were set to the default values recommended in the model manual.

Methods of evaluation

Three years of data (1994–1996) were available for the study area. This data set was divided into two parts: 1994–1995 for calibration and 1996 for validation. Statistical tools such as average deviation (AD), root mean square error (RMSE), coefficient of determination ($R^2$), and Nash–Sutcliffe ($E$) coefficient (Nash & Sutcliffe 1970), were used to evaluate
Model performance for both calibration and validation periods. The coefficient of determination is a measure of accuracy or the degree to which the measured and predicted values agree. The average deviation is used to determine whether the model made over- or underpredictions. The RMSE measures the difference between predicted and observed values. It is sensitive to the extreme values and deals with both systematic and random errors. The Nash and Sutcliffe coefficient measures the goodness-of-fit between observed and simulated values. A value of 1 represents a perfect match, while a value of zero (0) shows a prediction no better than using the mean of the data. The negative efficiency indicates that the prediction is worse than simply taking the mean of the measured values.

Moriasi et al. (2007) reviewed performance statistics reported by different researchers for many watershed models and summarized model evaluation criteria. The model performance ratings vary from ‘unsatisfactory’ to ‘very good’ for Nash–Sutcliffe efficiency (E) (very good: 0.75–1; good: 0.65–0.75; satisfactory: 0.5–0.65; unsatisfactory: ≤0.5), RMSE observations, standard deviation ratio (RSR), and percent bias (PBIAS). Coefficient of determination (R²) and E are the most widely used statistics for hydrological modeling performance evaluation (Gasman et al. 2007) and typically R² values greater than 0.5 are considered acceptable (Santhi et al. 2001).

The model performance was first qualitatively assessed with graphical displays of the results and then statistical measures were used for quantitative evaluation. The graphical comparison is made easily using the scenario manager of the WARMF model. For example, Scenario 1 may be used to represent a set of numerical values of model coefficients used in the simulation. Scenario 2 may be used to represent a second set of modified model coefficients used in the simulation. Once the simulations are performed, WARMF can plot the observed data as well as the model predictions for both scenarios on the same graph. By visual inspection, it is relatively easy to see whether the changes to model coefficients improve the match.

**Model calibration and validation**

Model calibration is the procedure in which model parameters are adjusted to improve the match between the simulated and observed values. Only a few parameters are adjusted for each calibration. In this study, the model was calibrated by adjusting the evaporation coefficients (magnitudes, skewness), snow/ice-related parameters (melting rates, snow formation, and melting temperature), field and saturated soil moisture, vertical/horizontal hydraulic conductivities, detention storage, initial soil concentration of nitrate, surface roughness (Manning’s n), litter fall rate, and soil nitrification and denitrification rates. These parameters were selected for calibration based on the literature (Weintraub et al. 2001b; Geza & McCray 2007; Herr 2008, personal communication). The initial values of the calibration parameters were taken from studies conducted at the St. Esprit Watershed (Mousavizadeh et al. 1995; Perrone 1997; Mousavizadeh 1998; Sarangi et al. 2005a, b) or studies performed in regions with the same soil and climatic conditions (Dayyani et al. 2009, 2010).

Measured flow, nitrate–nitrogen (NO₃–N), and climatic data are available from 1994 to 1996 for the gauging and weather stations installed in the watershed. Model initialization is important as WARMF assumes zero initial snowpack so it is recommended to start simulation before January 1. Thus, the calibration started on May 1, 1993 in order to initialize the model; the first 8 months of simulation (before January 1, 1994) were not considered in the evaluations of the calibration process. The meteorological data for these extra 8 months were obtained from St. Jacque weather station, since it was not recorded at the weather station installed in the watershed. Ideally, one may want to collect field data in a variety of wet and dry years. However, the field investigators have no control over the natural meteorologic and hydrologic variability. Model calibration/validation must be performed for the period that the field data were collected.

**RESULTS AND DISCUSSION**

**Hydrologic simulations**

WARMF calculates daily flow and pollutant concentrations for all river segments. As in this study the data were measured only at the outlet of the watershed, the simulated
flow and NO$_3$–N concentrations were compared with the observed values at the outlet of the watershed.

Figure 7 compares simulated and observed daily hydrographs at the outlet of the watershed for the entire simulation period of 1994–1996. Figure 7(a) is for the calibration period of 1994–1995, in which the simulated and observed daily values showed an $R^2$ value of 0.53 and E value of 0.45 (Table 3); Figure 7(b) shows results for the validation period with the $R^2$ of 0.58 and E of 0.5. The model seems to have performed reasonably well at simulating the timing of runoff events. WARMF underestimated several peaks during the snowmelt for both calibration and validation periods. The statistical indices calculated from the predicted and observed daily drainage outflows are given in Table 3. The positive mean deviation during the calibration and validation period between observed and simulated daily values indicates that the model slightly underpredicted flow. Mean deviation values of daily drain flow, 0.50 and 0.29 mm, indicate that daily underestimations were small.

In certain cases during the winter/spring period, the model simulated greater flow than was observed which could be due to the fact that the model does not consider frozen water on the ground surface, eventually simulating greater runoff. For most of the events during the winter/spring period, simulated and observed timing of runoff peaks was found to differ by 1 day. This difference is thought to arise due to the quantity of accumulated snow on the soil surface resulting in differences in the roughness of bare and snow-covered land surfaces. The model considers the same surface roughness coefficient irrespective of the day of the year or the soil surface conditions. In reality, flow velocity is higher on snow-covered surfaces due to lower friction (in a cold climate the surface of snow-pack is usually frozen); thus, the time for the flow to reach the watershed outlet is faster.

Figure 8 presents WARMF’s simulated monthly results and observed data. The WARMF calibration results showed a high correlation between simulated and observed monthly flows ($R^2 = 0.92$ and $E = 0.89$), although the model seemed to slightly overestimate flow during a few months (AD > 0; Table 3). During the validation period, the $R^2$ and $E$ were 0.94 and 0.91, respectively, showing good correspondence between the simulated and observed monthly values. The modeling errors (RMSE) during calibration and validation years were low, 17.1 and 17.6 mm, further indicating that the model performed well in predicting monthly flow at the outlet of the watershed.

As mentioned earlier, overall the model seems to underestimate the flow during the winter and snowmelt period.

| Table 3 | Model performance during calibration and validation |
|-----------------|-----------------|-----------------|-----------------|
| Daily drain flow | | | | |
| AD (mm) | 0.50 | 0.29 | 0.50 | 0.29 |
| RMSE (mm) | 2.37 | 3.26 | 2.37 | 3.26 |
| $R^2$ | 0.53 | 0.58 | 0.53 | 0.58 |
| $E$ | 0.45 | 0.50 | 0.45 | 0.50 |
| Monthly drain flow | | | | |
| AD (mm) | 7.27 | 4.16 | 7.27 | 4.16 |
| RMSE (mm) | 17.06 | 17.62 | 17.06 | 17.62 |
| $R^2$ | 0.92 | 0.94 | 0.92 | 0.94 |
| $E$ | 0.89 | 0.91 | 0.89 | 0.91 |
| Monthly nitrogen losses | | | | |
| AD (kg.ha$^{-1}$) | 0.18 | 0.41 | 0.18 | 0.41 |
| RMSE (kg.ha$^{-1}$) | 0.48 | 0.86 | 0.48 | 0.86 |
| $R^2$ | 0.89 | 0.84 | 0.89 | 0.84 |
| $E$ | 0.86 | 0.75 | 0.86 | 0.75 |
Other researchers in the Quebec region have reported that there is considerable amount of flow coming out of the tile drainage system during the winter and spring (Gollamudi 2006; Dayyani et al. 2009, 2010). As WARMF does not take into account the tile drainage system, and almost half of the St. Esprit Watershed is subsurface drained, it does not simulate the base flow properly especially during the winter and snowmelt period, leading to underestimating the total flow during those months.

The model validation results are slightly better than the model calibration results (Table 2; higher $R^2$ and $E$ values). This is contrary to what is normally observed in model simulations; calibration results are usually better than validation results. While it may indicate that the model has not been overly calibrated, it is also likely that the WARMF model may be simulating a wetter year better. From Table 2, one can see that not only 1996, the validation year, was wetter than both 1994 and 1995, the two calibration years, it was also wetter as compared to the 30-year average precipitation for the watershed. However, this observation needs to be checked further in future modeling studies with this model.

### Nitrogen simulations

Once the hydrology component of the model was calibrated and validated, nitrogen simulations were conducted to calibrate the nitrogen component of the model. Water-quality data collected during the flow calibration period, 1994–1995, were used to guide the nitrogen calibration. Using parameters fine-tuned in the calibration process, the model was validated using 1996 data.

The fertilizer application rate and timing of data were taken from the GIS shape files and St. Esprit Watershed reports (Papineau & Enright 1997; Mousavizadeh 1998). The adjusted parameters used during calibration were soil nitrification and denitrification rates, litter fall rate, and initial NO$_3$–N concentrations in the soil. Initial runs of the model to simulate NO$_3$–N concentrations were conducted using the nitrogen input values, taken from Dayyani et al. (2010), Elmi et al. (2000), and Lapp (1996). Figure 9 compares the simulated and observed monthly NO$_3$–N losses at the outlet of St. Esprit Watershed. The movement of NO$_3$–N has been closely associated with the movement of water in agricultural soils (Armstrong & Burt 1993). In this study, the NO$_3$–N losses were also dependent...
The comparison between the observed and simulated monthly NO₃⁻N and cumulative losses (Figures 9 and 10) shows that the model performed quite well with the R² values of 0.89 and 0.84 and E values of 0.86 and 0.75 for calibration (Figure 9(a)) and validation (Figure 9(b)) periods, respectively (Table 3).

About 67% of the overall NO₃⁻N losses was recorded in April, May, and June 1994; this is correlated to the intensive flow rates (72% of the annual flow) measured during this period (Figure 9(a)). In 1994, heavy rainfall events occurred soon after the second surface fertilizer application (early June). June had 187 mm of rainfall, 1.8 times the 30-year average rainfall (Table 2). Although the flow was being underestimated over the snowmelt period in all three years, the NO₃⁻N losses were overestimated (Figures 9(a) and 9(b)), which might be because of the timing of first and second fertilizer application, in May and June. Overall, the comparison between the observed and simulated monthly and cumulative NO₃⁻N losses (Figure 10) shows that the model performed quite well, although tended to slightly underestimate the total annual losses by 9% and 8% during calibration (Figure 10(a)) and validation (Figure 10(b)) periods, respectively. This could be due to the flow underestimation by the model.

The statistical comparison (Table 3) showed good agreement between simulated and measured monthly NO₃⁻N losses during the study period. The overall positive mean deviation (AD) value (0.18 and 0.41 kg ha⁻¹) indicates that the monthly N losses are slightly underestimated (Table 3). The coefficient of determination was more than 0.84, indicating a good correspondence between simulated and observed NO₃⁻N losses. Overall, the model performance was slightly better during the calibration period, with the modeling efficiency (E) being 0.86 as compared to 0.75 for validation.

The comparison between the observed and simulated annual nitrate–nitrogen losses (Table 4) shows that the model performed quite well, although tended to slightly underpredict cumulative losses, which could be due to underestimation of flow.

The WARMF performed reasonably well in simulating the seasonal variation of flow (Figure 11), although the

<table>
<thead>
<tr>
<th>Observed and simulated cumulative flow and NO₃⁻N losses for calibration and validation periods</th>
<th>Observed</th>
<th>Simulated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow (mm)</td>
<td>N (kg ha⁻¹)</td>
<td>Flow (mm)</td>
</tr>
<tr>
<td>1994</td>
<td>563.8</td>
<td>14.6</td>
</tr>
<tr>
<td>1995</td>
<td>488.5</td>
<td>12.7</td>
</tr>
<tr>
<td>1996</td>
<td>742.4</td>
<td>20.1</td>
</tr>
</tbody>
</table>

The comparison between the observed and simulated annual nitrate–nitrogen losses (Table 4) shows that the model performed quite well, although tended to slightly underpredict cumulative losses, which could be due to underestimation of flow.

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Figure 10 | Simulated versus observed cumulative NO₃⁻N losses at the watershed outlet for calibration (a) and validation (b) periods.

Figure 11 | Simulated versus observed seasonal flow and NO₃⁻N losses at the watershed outlet for calibration (1994–1995) and validation (1996) periods.
spring flow is underestimated in all years. The dynamics of nutrient transport are different in the three seasons which experienced high flows (winter, spring, and fall), due to the changing hydrologic conditions among these seasons. WARMF was able to reproduce the conditions of all seasons satisfactorily for both the calibration and validation years, although the spring nitrate–nitrogen loads are overestimated (Figure 11).

Mousavizadeh (1998) applied ANSWERS2000 to the St. Esprit Watershed. The model seemed to underestimate the flow; total simulated cumulative runoff values were 66.6, 54.9, and 71.7% of measured cumulative runoff values, for 1994, 1995, and 1996, respectively. Romero (2006) evaluated the performance of the SLURP hydrological model at St. Esprit Watershed and reported $R^2$ values of 0.522 and 0.66 for calibration and validation periods, respectively. Geza & McCray (2007) applied the WARMF model to a watershed in Colorado and reported $R^2$ values of 0.58 and $R^2 = 0.68$ for simulation of monthly stream flow. SWAT model has been applied to different watersheds around the world; the range of reported $R^2$ and $E$ values are for daily flow $R^2 = 0.37–0.78$ (Spruill et al. 2000; Wang & Melesse 2005, 2008) and $E = -0.04$ to 0.19 (Spruill et al. 2000); for monthly flow $R^2 = 0.67–0.92$ (Santhi et al. 2001; Jha et al. 2007; Wang et al. 2008) and $E = 0.54–0.94$ (Peterson & Hamlett 1998; Saleh et al. 2000; Di Luzio et al. 2002; Jha et al. 2007); for monthly simulation of nitrate-nitrogen $R^2 = 0.72–0.89$ (Santhi et al. 2001; Jha et al. 2007) and $E = 0.27–0.75$ (Saleh et al. 2000; Di Luzio et al. 2002; Jha et al. 2007). Comparing the results of this study (Table 3) with the above-mentioned applications of different watershed models indicates that the WARMF model performed well in simulating flow and N loads at the outlet of the watershed.

**CONCLUSIONS**

The WARMF model was applied to a watershed in southwestern Quebec, Canada, and adequately predicted the daily flow and nitrate-nitrogen losses at the outlet of the watershed. The simulations were performed for a 3-year period from 1994 to 1996. The model simulated the pattern of monthly flow with a good degree of accuracy: the $R^2$ for calibration was 0.92, and that for validation was 0.94. The corresponding coefficients of efficiency ($E$) were 0.89 and 0.91. The model also performed well in simulating the flow during the snowmelt period with the error of 26%, 33%, and 11% in 1994, 1995, and 1996, respectively. The model also performed well in simulating nitrate loads at the outlet of watershed (Nash and Sutcliffe coefficient $\geq 0.75$). We are satisfied with the performance of the WARMF model in a small agricultural watershed in a cold climate.

**REFERENCES**


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