EVOLUTION OF GROUNDWATER NITRATE CONCENTRATIONS UNDER VARIOUS CLIMATE CHANGE SCENARIOS FOR PRINCE EDWARD ISLAND, CANADA

Harold Vigneault, Jean-Marc Ballard and René Lefebvre
INRS-ETE, Institut National de la recherche scientifique, Québec, Canada
Daniel Paradis and Martine M. Savard
Natural Resources Canada, Geological Survey of Canada, Québec, Canada
Georges Somers
Prince Edward Island Department of Environment, Energy and Forestry, Charlottetown, Canada

ABSTRACT
Nitrate (N-NO₃) in groundwater, apparently related to agricultural practices, is of concern in Prince Edward Island. To evaluate how nitrate concentrations could evolve with climate change, a quasi 2-D infiltration model and a 3-D numerical model of groundwater flow and nitrate mass transport for the entire island were developed. After calibration, present-day recharge and nitrate loading suggest that, by 2050, nitrate concentrations in the aquifer would increase by 11%. When considering the effect of climate change, recharge is reduced, and concentration increases by a range of 11-17%, or by 25%-32% if adapted agricultural practices are also considered.

RÉSUMÉ
Les nitrates (N-NO₃) dans l’eau souterraine constituent un problème apparemment relié aux pratiques agricoles à l’Île-du-Prince-Édouard. Afin de prédire l’évolution des concentrations en nitrate induite par les changements climatiques, un modèle d’infiltration quasi 2-D et un modèle numérique d’écoulement et de transport des nitrates en 3-D pour l’île ont été développés. Après calage, les résultats montrent qu’en 2050 les concentrations augmentent de 11% lorsque la recharge diminue et les concentrations en nitrate augmentent de 11 à 17%, ou de 25 à 32% lorsqu’une adaptation dans les pratiques agricoles est considérée.

1 INTRODUCTION
Global average temperature is predicted to increase by 0.6 to 4.0 °C in years 2090-2100 relative to years 1980-1999 (IPCC, 2007). Since global warming is expected to change the hydrologic cycle (Gleick, 1986) as well as the agricultural practices, it could affect the future evolution of nitrate concentrations found in groundwater.

The objective of this project was to make an assessment of the potential impact of climate change as well as the resulting agricultural practice changes on nitrate concentrations in groundwater over Prince Edward Island (PEI). Such an assessment must consider the effect of climate change both on nitrate loading and groundwater recharge. Climate change is itself predicted on the basis of meteorological models that have a degree of uncertainty requiring that different climate scenarios be considered in order to represent the potential range of changes, especially regarding temperature and precipitation. The present day and future nitrate loading were estimated with the Soil Residual Nitrate (RSN) indicator (De Jong and Qian, 2007) and the recharge was estimated with the HELP model (Schroeder et al., 1994). This paper is a synthesis of chapter 8 (Vigneaut et al., 2007) presented in a Climate Change Action Funds report - CCAF (Savard et al., 2007). The study aimed at extending the hydrogeologic characterization and modelling carried out on the Wilmot River watershed by Paradis et al. (2006) to the entire Island, by developing and calibrating with present-day recharge and nitrate loadings a three-dimensional numerical model (FEFLOW) of groundwater flow and nitrate transport to simulate the potential evolution of nitrate concentrations under different climate change and agricultural practice changes scenarios.

2 STUDY AREA
Prince Edward Island covers approximately 5 660 km² and is 225 km long by 3 to 65 km wide (Fig. 1). Topographic elevation ranges from sea level to 140 m above sea level. PEI is predominantly rural, with 42% of its surface covered by agricultural lands and 45% by forests. Forests mostly cover the eastern and western portions of the Island, whereas agricultural activities are mostly concentrated in the central part. Residential, urban
and industrial activities use less than 6% of the territory (Fig. 1).

2.1 Climate and hydrology

The climate of PEI is humid-continental, with long fairly cold winters and warm summers. Data selected from four meteorological stations distributed (Fig. 1) across the Island show fairly similar conditions. As an example of the climate found on the Island, the mean annual precipitation at the Charlottetown weather station (8300300) is 1173 mm (1971-2000), most of which falls as rain (75%). The mean annual temperature is about 5.3 °C and means for monthly temperature range from -8°C in January to 18.5°C in July.

The Island can be divided into fifty watersheds overall including 241 sub-watersheds. River basins are typically small, and the main rivers are estuarial over a significant portion of their length (Fig. 1).

2.2 Hydrogeology

Prince Edward Island is a crescent-shaped cuesta of continental red beds, Upper Pennsylvanian to Middle Permian in age, dipping to the northeast at about 1 to 3 degrees (Van de Poll, 1983). The constituent mineral grains of these sedimentary rocks were carried by streams and rivers from highlands in present-day New Brunswick and Nova Scotia and deposited under oxidizing conditions in the low-lying area which is now PEI (Prest, 1973). Van de Poll (1983) mapped the red bed units as an upward-fining series of cyclic deposits containing four «megacycles». These sequences consist of conglomerate, sandstone and siltstone red beds. These units exhibit rapid lateral and vertical facies changes and strong cross-bedding features. The continuity of lithological units is difficult to establish, even over short distances.

The bedrock sequence of PEI is almost entirely covered by a layer of unconsolidated glacial material from a few centimetres to several meters in thickness Prest (1973). These deposits are generally derived from local sedimentary rock and include both unsorted tills and water-worked glacio-fluvial and glacio-marine deposits. With few exceptions, these surficial deposits are not saturated, and do not represent significant aquifers.

In most parts of the Island, the rock aquifer is unconfined. The potentiometric map representing the water levels in the upper most part of the aquifer (first 35 m) was interpolated using more than 17 243 wells. This map shows that the water table in the sandstone generally follows the topography (not shown). As the aquifer material is thought to be relatively homogeneous over the Island, the definition of the conceptual model for the Island is based on works of Francis (1989) in the Winter River watershed and on Paradis et al. (2006) in the Wilmot River watershed. The conceptual model of the island may be summarized by an active uppermost sandstone layer extending from the water table to 20-35 m underlain by a less active layer (see Table 1).
3 DESCRIPTION OF NUMERICAL MODEL

3.1 HELP model

Groundwater recharge simulations were carried out with the quasi-two-dimensional deterministic hydrologic model HELP (Schroeder, 1994). This model was initially developed to simulate water infiltration in landfills, but it has been extensively used to estimate groundwater recharge (Jyrkama et al., 2002; Allen et al., 2003; Croteau et al., 2005). The model simulates daily movement of water in the ground and accounts for the effects of surface storage, snowmelt, runoff, infiltration, evapotranspiration, vegetative growth, soil-moisture storage and lateral subsurface drainage.

The spatial estimation of groundwater recharge over PEI was obtained by dividing the Island in cells of 500 m for a total number of 21 168 cells. Surface information needed for the analysis was retrieved with a GIS.

HELP was first run with historical records of temperature and precipitation (1960-2001) and calibrated with the average seasonal distribution of recharge obtained from well hydrographs and the runoff estimated from stream hydrographs. Runoff was estimated by hydrograph separation using the Furey and Gupta (2001) filter. The calibration of the annual runoff was carried out using three gauged streamflow stations (Wilmot, Mill, and Morell). Results showed that the seasonal recharge and runoff calibrations are respectively within 4-17% and 5-12% of the previously estimated values.

The average recharge over the entire province was estimated at 369 mm/yr for the 1960-2001 period. Recharge values can vary from 0 mm/yr in wetland areas to 704 mm/yr in coarse sandy areas, based on HELP simulation for the indicated period.

3.2 FEFLOW model

To represent the groundwater flow system and to simulate nitrate transport under various scenarios of climate change and agricultural practice changes for the entire province, the three-dimensional finite element numerical simulator FEFLOW (Diersch, 2004) was used. The finite element grid design is based on the conceptual model referred to in section 2.2. Table 1 presents the properties of the model according to this conceptual model.

The boundary conditions are constant heads all around the Island in the first layer and no flow boundaries in the underlying layer to simulate the flow along the saline front. Moreover, since rivers are known to be connected to the aquifer (Francis, 1989; Paradis et al., 2006), constant heads were also applied on main rivers and streams.

The nitrate (N-NO₃) concentrations for the initial conditions applied to the model came from the RSN values. The RSN is an indicator that estimates, at the Soil Landscape of Canada polygon level, the quantity of inorganic soil nitrogen at the time of harvest as part of the CANB model (Yang et al., 2007). RSN includes inputs in the form of load of nitrogen fertilizer, manure and nitrogen fixation, and outputs in the form of nitrogen in harvested crops. There are 23 Soil Landscape of Canada polygons covering the entire PEI. The RSN values used in the model came from the 5 census years (1981, 1986, 1991, 1996, and 2001) made by Agriculture Canada. The total mass of these values, in kilogram per hectare of cultivated land, were transformed into concentrations in groundwater for each Soil Landscape of Canada polygon by considering the equivalent farm land area, prorated over the entire polygon, and the aquifer recharge for this polygon. Values obtained reflect the fact that highest concentrations of nitrate in groundwater are in the center of the Island, where the agricultural activities are most intense.

The FEFLOW model was calibrated with three types of data: (1) the potentiometric map base on measured heads in domestic wells; (2) the mean baseflow recession (MBR) curve for rivers and; (3) the groundwater nitrate concentration records in domestic wells over the entire island for 2000-2005. More details on the calibration process are found in Paradis et al. (2006).

<table>
<thead>
<tr>
<th>Layer # (Depth in m)</th>
<th>Field K (m/s)</th>
<th>Numerical model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>K (m/s)</td>
</tr>
<tr>
<td>1 (0-5)</td>
<td>4.5x10⁻⁴ to 1x10⁻³</td>
<td>1x10⁻⁴</td>
</tr>
<tr>
<td>2 (5-10)</td>
<td>8.1x10⁻⁵</td>
<td>5x10⁻⁵</td>
</tr>
<tr>
<td>3 (10-15)</td>
<td>1x10⁻⁵</td>
<td>1x10⁻⁵</td>
</tr>
<tr>
<td>4 (15-30)</td>
<td>1.7x10⁻⁴</td>
<td>1x10⁻⁴</td>
</tr>
<tr>
<td>5 (30-80)</td>
<td>1.7x10⁻⁴ to 8.4x10⁻⁷</td>
<td>1x10⁻⁴</td>
</tr>
<tr>
<td>6 (80-180)</td>
<td>n.d.</td>
<td>1x10⁻⁴</td>
</tr>
<tr>
<td>7 (180-380)</td>
<td>n.d.</td>
<td>1x10⁻⁴</td>
</tr>
<tr>
<td>8 (380-880)</td>
<td>n.d.</td>
<td>1x10⁻⁴</td>
</tr>
</tbody>
</table>

Results of the calibration for the nitrate concentrations are shown on Fig. 2, where average measured nitrate concentrations are compared to simulated concentrations per Soil Landscape of Canada polygon. The difference between mean measured and simulated concentrations is on average 0.5 mg/L, meaning that the...
mass of nitrate is slightly underestimated. However, it should be noted that nitrate concentrations are distributed randomly around the 1:1 line. This highlights the fact that the model represents well the average conditions found on the Island but does not closely represent the concentrations within each watershed. Hence, model predictions should be used only to discuss general trends and not to assess specific local conditions.

![Graph showing FEFLOW model calibration with average groundwater nitrate concentrations measured in domestic wells for 2002-2005. Each point represents the average nitrate concentration in a Soil Landscape of Canada polygon, whereas the bars span the concentration interval from the 25% to the 75% percentiles of observed concentration. More than 17,000 measurements in domestic wells were used. The 45° perfect-fit line is presented as a reference.](image)

Figure 2. FEFLOW model calibration with the average groundwater nitrate concentrations measured in domestic wells for 2002-2005. Each point represents the average nitrate concentration in a Soil Landscape of Canada polygon, whereas the bars span the concentration interval from the 25% to the 75% percentiles of observed concentration. More than 17,000 measurements in domestic wells were used. The 45° perfect-fit line is presented as a reference.

4 CLIMATE CHANGE SCENARIOS

4.1 Climatic scenarios and agricultural practice changes

Four future climatic scenarios were selected to run predictive modelling. These scenarios are based on the two times carbon dioxide (2xCO₂) assumption that is expected to be reached in 2050. The four climatic scenarios were provided by the Canadian Climate Center General Circulation Model. To summarize these scenarios, average temperature and precipitation for 2040-2069 and their percentage of change relative to the 2001 conditions are presented in Table 2. This table shows that, on average, and compared to the historical conditions, scenarios CGCM2 A1 and HadCM A2a predict the driest conditions, whereas scenario CGCM2 B1 predicts the wettest one and HadCM B2a provides intermediate conditions. Moreover, the mean temperature increases in all scenarios, implying an increase in evapotranspiration and a decrease in runoff. Estimated recharge is highest with scenario CGCM2 B1 (wettest conditions) with an increase of 7%, whereas the three other scenarios show a decrease of 2% to 12% as compared to historical values. These climatic scenarios were used as inputs for the HELP infiltration model to estimate the groundwater recharge. For a better spatial resolution of the weather data, the Island was divided into four zones corresponding to the weather stations: O’Leary, Summerside, Charlottetown and Monticello (Fig. 1).

The agricultural practice changes for the period of 2040-2069 show that the average RSN value is increased by 15% (5% to 30% depending on the Soil Landscape of Canada polygon - not shown) when considering an increase in nitrogen loads due to the predicted intensification of agricultural activities. These estimates are based on professional judgment (Bootsma et al., 2001).

4.2 Flow and transport scenarios

Nine groundwater flow and mass transport simulation scenarios were defined to estimate the potential impact of climate change and agricultural practice changes for the future:

Scenario #1: Maintain the current recharge conditions and the current agricultural practices until 2069. This scenario (baseline) is used to assess when aquifer concentrations are reaching steady-state conditions using present-day nitrate loadings (equilibrium between N input and N output from the aquifer).

Scenarios #2-5: Maintain the current agricultural practices in each Soil Landscape of Canada polygon, but change the groundwater recharge based on the values obtained from the four climate change scenarios. The mass of nitrate applied over the watershed is kept constant for the 23 SLC polygons until 2069. This mass represents the mean RSN value from the 5 last censuses (1981, 1986, 1991, 1996 and 2001). These scenarios compared to scenario #1, are used to assess the impact of climate change alone (i.e. without agricultural practice changes).
Scenarios #6-9: Use the RSN values modelled for the 2040-2069 period with the four climate change scenarios along with the groundwater recharge based on the values obtained from these climate change scenarios. These scenarios are used to assess the combined impact of climate change and agricultural practice changes.

Nitrate (N-NO\textsubscript{3}) concentrations in Fig. 3a, b, c, and d correspond to average concentrations for the first four layers of the numerical model (representing the aquifer zone exploited by most domestic wells). For comparison purpose, 4 classes of nitrate contamination were defined based on nitrate concentrations obtained from the numerical model: background (0-1 mg/L), low (1-3 mg/L), medium (3-5 mg/L) and high (greater than 5 mg/L). These ranges of nitrate concentrations are used instead of absolute concentrations to emphasize the fact that the model can indicate regional trends of nitrate concentrations but not an exact value for a given watershed.

4.3 Climate change impact assessment

For comparison purposes, Fig. 3a and b shows the spatial distribution of nitrate concentration classes for all watersheds and the histogram of nitrate concentration classes representing respectively present-day conditions and the baseline scenario (#1) for the year 2050. When compared to the present-day (2001) simulation, the average increase in nitrate concentrations on the Island is about 11% by 2050, even when maintaining present-day nitrate loading. This increase is due to the fact that present-day nitrate concentrations have not yet equilibrated with the nitrate loadings applied. No climate change or agricultural practice changes are taken into account at this stage.

Under the baseline scenario conditions, the 3 watersheds that were in the Background class have moved to the Low class by 2050. In 2001, 26 watersheds were in the Low class, 17 in the Medium and 4 in the High. In 2050, 25 watersheds are in the Low class, 17 in the Medium and 8 in the High. More watersheds have changed class in the western part than in the eastern part of the island. That can be due to a lower mean recharge in the western part, thus leading FEFLOW to calculate higher nitrate concentrations since the total mass of the RSN was applied on the water table.

Figure 3c shows the single spatial distribution of nitrate concentrations for the four climate change scenarios (scenario #2-5) for the year 2050. Indeed these scenarios resulted in very similar values. When compared to the present-day (2001) simulation (Fig. 3a), differences are apparent on the average nitrate concentrations for the 4 climate change scenarios that increase by 11% for CGCM2 B1, 15% for HadCM B2a, and 17% for CGCM2 A1 and HadCM A2a. The impact of climate change without the effect of equilibration is on the order of 0% for CGCM2 B1, 4% for HadCMB2a and 6% for CGCM2 A1 and HadCMA2a. On a class basis, there is no significant change of class between each climate change scenarios. Compared to the 2050 Baseline scenario, only 2 watersheds move from the Low to the Medium class for all climate change scenarios.

The impact of climate change in scenarios #2-5 does not seem to be very important compared to the effect of scenario #1.

4.4 Agricultural practice changes impact assessment

Figure 3d, e and f shows the spatial distribution of nitrate concentrations for the four climate change scenarios with agricultural practice changes (scenarios #6-9). When compared to the present-day (2001) simulation (Fig. 3a), average nitrate concentrations increase by 25% (CGCM2 B1), 29% (HadCM B2a), and 32% (CGCM2 A1 and HadCM A2a). The impact of agricultural practice changes without the effect of scenario #1 and climate change from scenarios #2-5 is in the order of 14% for CGCM2 B1, 18% for HadCM B2a and 21% for CGCM2 A1 and HadCM A2a.

In Fig. 3d, e and f the class distribution shows no significant change between CGCM2 A1 and HadCM A2a. These scenarios are the most impacted by the agricultural practice changes and the distribution of the watersheds in each class is 18 in the Low class, 21 in
the Medium class and 11 in the High class. Scenarios CGCM2 B1 and HadCM B2a are the least impacted and their class distribution is respectively 21 and 20 in the Low class, 19 and 21 in the Medium class and 10 and 9 for the High class. The center area of the Island appears to be the most affected by the agricultural practice changes because this is were intensive agriculture takes place.

Figure 3. Class distribution of simulated mean nitrate concentrations per watershed and histogram of the number of watersheds in each class: (a) for present day (2001); (b) for year 2050 with today’s nitrate loading; (c) the four climate change scenarios and (d, e and f) the four climate change (CC) scenarios involving agricultural practice changes (APC).
5 CONCLUSION

The potential impact of climate change and the resulting agricultural practice changes on future nitrate concentrations in groundwater over the entire PEI was estimated through the definition of nine different groundwater flow and mass transport simulation scenarios. Results from these scenarios show that 1) reaching steady-state conditions of aquifer concentrations under present-day nitrate loading accounts for 11% increase, 2) climate change alone accounts for an increase of 0 to 6% of the increase, and 3) the agricultural practice changes is responsible for a 14 to 21% of the increase. The combined effect of steady-state, climate change and agricultural practice changes would lead to a total increase in nitrate concentrations in the PEI aquifers between 25 to 32%, climate change contributing the least to this increase. Moreover, the general trend from 2001 to 2050 is that a significant number of watersheds are predicted to move to the highly impacted group having a nitrate concentration between 5 and 10 mg/L (10 mg/L corresponding to the Canadian drinking water guideline). In 2001, 4 watersheds were in this group compared to 8 predicted for 2050 after reaching steady-state conditions and climate change impact, and 9 to 11 after agricultural practice changes is also considered. It is noted that such results are obtained when assuming that agricultural practice changes would lead to higher nitrate loadings. This situation could be avoided if agricultural practices were managed to decrease nitrate loadings instead of progressively increasing them.

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