Potential ecological impact of climate change on the water quality of an intensively managed agricultural watershed in Quebec, Canada

Beáta Novotná, Eric van Bochove and Georges Thériault

ABSTRACT

This study investigated the effects of climate change (CC) on water redistribution in a micro-watershed of a lowland agricultural area of the Bras d’Henri River in the temperate cold climate of Quebec, Canada. A Water Flow and Balance Simulation Model (WaSiM-ETH) was used to simulate the hydrology using current climatic conditions and land use characteristics, applying Richards’ equation. A one-day temporal resolution was used with a spatial resolution of $2 \times 2$ m. The CC scenarios Coupled Global Climate Model, version 1 (CGCM1) and Hadley Centre Coupled Model, version 3.1 (HadCM3.1) were downscaled to the regional level and integrated into WaSiM-ETH and evaluated for both current and modified climatic conditions. Mean annual precipitation values ($P$) increased from 15–33%, evapotranspiration from 7–26%, and discharge ($Q$) from 16–45%. The identification of the significant water quality problem represented by average value of total suspended solids (TSS) 265.29 (kg ha$^{-1}$), nutrients: nitrogen (NO$_3$-N) 16.83 (kg ha$^{-1}$) and total phosphorus (TP) 0.59 (kg ha$^{-1}$) for the whole evaluated period; and (TSS) 148.09 (kg ha$^{-1}$), (NO$_3$-N) 5.65 (kg ha$^{-1}$) and (TP) 0.31 (kg ha$^{-1}$) during the days with surface runoff, in relation to water quantity and CC creates the basis for erosion risk assessment.

Key words | agriculture, climate change, ecological impact, hydrologic model, watershed

ABBREVIATIONS

- AOGCM: Atmosphere-Ocean General Circulation Model
- BMP: best management practices
- CC: climate change
- CGCM1 and CX1: Coupled Global Climate Model, version 1
- CM: regional climate change scenario models
- ET: evapotranspiration
- GCM: General Circulation Models
- GHG: greenhouse gas
- HadCM3.1 and HAD: Hadley Centre Coupled Model, version 3.1
- IPCC: Intergovernmental Panel on Climate Change
- P: precipitation
- Q: discharge
- SWE: snow water equivalent
- TH: time horizon
- TP: total phosphorus
- TSS: total suspended solids
- WaSiM-ETH: Water Flow and Balance Simulation Model

INTRODUCTION

Agriculture is essentially an adjunct to natural ecosystems and depends on weather and climate (Wreford et al. 2010). As such, it is extremely vulnerable to climate change (CC) (Intergovernmental Panel on Climate Change (IPCC) 2009). Long-term changes in daily temperature extremes...
have been recently estimated for many regions of the world. Especially since the 1950s, these records reveal a decrease in the number of very cold days and nights and an increase in the number of extremely hot days and warm nights (IPCC 2007a). For the Northern Hemisphere, the IPCC predicts a mean temperature increase of between 1.1 and 6.4 °C during the 21st century. Over the last century, mean annual global surface temperature has already increased by approximately 0.4 to 0.8 °C (Climate Change 2001), while mean temperature over southern Canada rose an average of 0.9 °C between 1900 and 1998 (Zhang et al. 2000; Pohl et al. 2007). In Quebec, seasonal temperature trends between 1948 and 2005 differed by season, with an increase of about 0.9 °C for winter, 1.0 °C for spring, 0.5 °C for summer, and 0.2 °C for autumn, i.e., 0.6 °C for annual temperature (Osborn et al. 2004). Rising temperature will diminish the snowpack and increase evaporation, thereby affecting the seasonal availability of water (IPCC 2007b).

Globally averaged annual precipitation has also increased over the last century, especially in upper-latitude regions of Canada (IPCC 2007a). According to the Soil and Water Conservation Society (2003), Canada showed statistically significant positive trends in the average number of days with heavy rain. Global trends for 1-day and multi-day heavy precipitation show a tendency toward more days with heavy precipitation (Easterling et al. 2000; Christensen et al. 2007; IPCC 2007a). A thousand-year climatic simulation using the Atmosphere-Ocean General Circulation Model (AOGCM) shows an increase in mean winter precipitation of 20 to 30%. Since the 1970s, the frequency of heavy snowfall has decreased in the south and increased in the north of Canada (Zhang et al. 2001).

Several reports refer to a broad reduction in insolation on the Earth’s surface since 1990 (Wild et al. 2005). This decrease of available solar radiation for actual and potential evapotranspiration (ET) may be related to increasing cloud cover and precipitation, but also to soil moisture which increases actual ET closer to the potential ET (IPCC 2007a). These considerable changes, including changes in average air temperature and total precipitation courses, will have a significant impact on watershed hydrology, including snowmelt (Pike et al. 2008).

While potential CC has been studied to some extent in recent times, hydrological responses to these changes are still poorly documented (Menzel et al. 2002). Regardless of CC scenario, a two-fold increase in CO2 concentration leads to increased runoff mainly in winter and spring, with spring runoff occurring up to one month earlier (Arora 2001; Cunderlik & Burn 2004; Pike et al. 2008). A fifty-year trend analysis reports that annual mean discharge will decline across Canadian watersheds (Zhang et al. 2001), with monthly increases in March and April, and decreases in summer and fall. Quilbé et al. (2008a) report a slight but statistically significant decrease in annual discharge with increased winter discharge and decreased spring peak flow in the Chaudière watershed, Quebec. There was no apparent effect of CC on summer low flows. The magnitude and direction of shifts in hydrological regimes varies across Canada and among studies (Rodenhuis et al. 2007). In order to predict regional hydrological consequences of CC, it is necessary to document local and watershed-specific changes. This approach will provide more precise estimates than those from General Circulation Models (GCM).

The outcomes resulting from precipitation regime changes are useful, applying much more complex methods because of interactions between precipitation and land management.

Extrapolated relationships from changes in precipitation over the past century suggest increases in soil erosion from 4 to 95% with increases in runoff from 6 to 100%, which may already be evident on some croplands (Wreford et al. 2010). Assessing the current and future environmental risks and opportunities in Canada, CC will increase the potential for soil erosion due to surface runoff. The potential for large increases in magnitude and extent of soil erosion and runoff is considerable under simulated conditions for future precipitation. Different landscapes vary greatly in their vulnerability to soil erosion and runoff. Several studies, i.e., Bouraoui et al. (2003) and Ekstrand & Wallenberg (2010), report that CC is responsible for decreased snow cover, increased winter runoff, and also for increased diffuse nutrient losses. Intensive agricultural practices release significant amounts of nutrients, especially nitrogen and phosphorus, faecal bacteria, and sediment into receiving water bodies (Monaghan et al. 2005). To understand the adaptation process in a wider context, an analysis of the vulnerability of specific regions to CC is required.
This study provides a thorough analysis of how CC affects a small agricultural sub-watershed of the Chaudière River basin, Quebec, according to temporal trends for the long-term annual discharge and its seasonal variations. A micro-watershed, part of the Bras d’Henri Watershed Evaluation of Beneficial Management Practices project (van Bochove 2008), was selected for this study. The inclusion of upper and lower limits of a hydrologic response to CC could be applied to other Canadian watersheds with similar climatic conditions. The results can help to develop strategies for water resource decision-makers and for farmers to adapt their best management practices (BMP) to unpredictable and extreme weather events, longer and more frequent droughts, and pest infestations in order to improve water quality, reduce greenhouse gas (GHG) emissions and production costs, and improve rural economic development. This study provides bases for policy, operational, and management changes for specific regions affected by changing climatic conditions.

Study area

The study site (Figures 1(a) and 1(b)) is an intensively-managed agricultural second order catchment (2.36 km²) located in the Bras d’Henri sub-watershed (158 km²), south of the St. Lawrence River and Quebec City, Quebec, Canada. This region has a cold temperate climate (Environment Canada 1986). The Bras d’Henri belongs to the Beauvirage basin (709 km²) which is one of the main tributaries of the Chaudière River (6,682 km²). The Bras d’Henri micro-watershed is circular, with a valley length of 2.55 km, and is drained by two stream branches. The altitude above sea level ranges from 152 to 178 m with an average slope of 1.75%.

This watershed is located in the agroclimatic zone 3 (Environment Canada 1985) of the Appalachian region. According to this classification, the sum of the daily temperature with an average above 5 °C is 1,530 °C, for duration of 126 days. The average precipitation is 519 mm from May to September which is well-suited for oat, wheat, and barley crops (Dubé 2006). Meteorological and water quality data were monitored at the micro-watershed outlet from April 2004, and hydrometric measurements were taken from August 2005. Annual discharge varied between 500 and 1,000 mm from 1931 to 1960 (Environment Canada 1986). Monthly air temperature (T), precipitation (P), discharge (Q), and evapotranspiration (ET) values were calculated from monitored data (2006 to 2009) in the Bras d’Henri micro-watershed, Quebec, and are summarised in Table 1.

The Bras d’Henri micro-watershed is located in an area dominated by rolling terrain, with Precambrian outcrops interspersed with mantles of glacial moraine (Wiken 1986). According to the Canadian System of Soil Classification, podzolic soils (Beaurivage, Valère, and Neubois series) represent 45% of the area while gleysoic soils cover 44% (LeBras series). The dominant soil textural class is sandy loam. The land is mainly used for agriculture: 55% annual crops (corn, soybean, oat); 30% pasture; 13% forest; and 4% other surfaces (settlements, roads, and ditches). The mixed forest is comprised of maple, spruce, and spruce mew trees.

The Bras d’Henri micro-watershed was selected for the current study because it has existing rich sources of water quality, soil, agricultural management practices, and has hydrometric data available too. This watershed also has one of the highest concentrations of animal production in the province of Quebec. It ranks as the second poorest in Quebec in terms of its phosphorus load (Agriculture and Agri-Food Canada (AAFC) 2007). In addition, it is a part of the Watershed Evaluation of BMP project (WEBs) because of its intensive agricultural production and resultant substantial decrease in surface water quality.

Model description

The ability of the WaSiM-ETH (Water Flow and Balance Simulation Model) (Schulla & Jasper 2000) to describe the hydrological processes of lowland catchments with possible temporal climatic changes was evaluated. WaSiM-ETH is a spatially distributed and grid-based hydrological catchment model which was developed primarily to simulate the water balance of mountainous regions (Bormann & Elfert 2010). The model is fully distributed, and uses physically-based algorithms to describe most of the hydrological processes. It facilitates modelling of the watershed hydrology,
including subsurface processes, within different levels of complexity. WaSiM-ETH has been successfully applied to a wide range of scales, from lysimeter sites to macro-scale river basins (Jasper et al. 2004). The main model components are specified in Jasper et al. (2004).

**CC scenarios**

Regional CC scenario models (CM) were used in this study because they provide more realistic scenarios of CC on a regional scale than direct applications of GCM. Regional
Climate models provide highly resolved information (spatial and temporal) derived from physically-based models that apply many variables, which represents some weather extremes better than GCM. These CM were: CGCM1 (Coupled Global Climate Model, version 1) (Flato et al. 2000), here named CX1 and HadCM3.1 (Hadley Centre Coupled Model, version 3.1) (Gordon et al. 2000), here named HAD and used to predict the potential CC effect at a daily time step. These models included the anthropogenic involved CC as well as its natural variability. Both models used transmission studies for the continual increase of GHG with the AOGCM. The emission scenario IS92a GHG + A was adapted for the model CX1, and the scenario SRES-A2 was adapted for the model HAD. The emission scenario IS92a GHG + A included a 1% equivalent CO₂ increase per year and sulphate aerosols (Flato & Boer 2001). The SRES-A2 scenario dataset included GHG (CO₂, CH₄, N₂O) and sulphate aerosol direct effects, which increased slightly less than 1% per year, based on IPCC SRES-A2 for 1990–2100. Generally, the IS92 scenario was characterised by more warming and more substantial changes in precipitation than the SRES scenario (Jasper et al. 2004). Archived Agriculture and Agri-Food Canada climatic data were used to interpolate data for past time horizons in order to develop the climatic scenarios for the centroids of Ecodistrict 540. The meteorological input data for these CMs were: average daily temperature, total daily precipitation, and average incoming daily solar radiation. The daily data for these variables were extrapolated from the historical meteorological series. An agricultural eco-district climatic database was developed from climate station data using a spatial interpolation procedure; missing data were filled-in by using estimates from nearby stations. The spatial interpolation procedure combined inverse distance-squared weighting with the nearest-neighbour approach. Cross-validation was performed to evaluate the accuracy of the interpolation procedure (Xu et al. 2010).

**MATERIALS AND METHODS**

For potential ecological impacts of CC on water quality in the watershed, the projections were constructed in three steps (Figure 2). In the first step, the model WaSiM-ETH was calibrated and verified for the present time period and climatic conditions, represented by the years 2006–2009. In the second step, the calibrated model was applied for the past time horizon (TH), named baseline in this study, and represented by years 1951–2004. Finally, climatic scenarios were selected and applied with the same model parameters for the future. The future is expressed by TH 2040, 2070, and 2100 integrated respectively by the periods 2010–2039, 2040–2069, and 2070–2099.

**Model calibration and verification**

Calibration years (2006 and 2008) and validation years (2007 and 2009) were randomly selected. One-day time step and grid cells of 2 m were used. The following climatic data were selected from 13 available regional stations

Table 1 | Monthly air temperature (T), precipitation (P), discharge (Q) and evapotranspiration (ET) values calculated from monitoring data (2006–2009) in the Bras d’Henri micro-watershed, Quebec, Canada

<table>
<thead>
<tr>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>Aug</th>
<th>Sept</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Total average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tmax average (°C)</td>
<td>2.9</td>
<td>–5.6</td>
<td>1.5</td>
<td>9.8</td>
<td>14.9</td>
<td>20.4</td>
<td>22.6</td>
<td>22.2</td>
<td>18</td>
<td>11.7</td>
<td>1</td>
<td>–1</td>
</tr>
<tr>
<td>Tmin average (°C)</td>
<td>–18.3</td>
<td>–18.4</td>
<td>–12.6</td>
<td>–0.2</td>
<td>6.1</td>
<td>12.8</td>
<td>16.1</td>
<td>13.1</td>
<td>8.7</td>
<td>12</td>
<td>–5.8</td>
<td>–13.8</td>
</tr>
<tr>
<td>Ptotal (mm)</td>
<td>60</td>
<td>66</td>
<td>54</td>
<td>81</td>
<td>68</td>
<td>100</td>
<td>133</td>
<td>92</td>
<td>116</td>
<td>57</td>
<td>93</td>
<td>1004</td>
</tr>
<tr>
<td>Pmax total (mm)</td>
<td>110</td>
<td>128</td>
<td>87</td>
<td>102</td>
<td>88</td>
<td>154</td>
<td>149</td>
<td>104</td>
<td>119</td>
<td>170</td>
<td>86</td>
<td>118</td>
</tr>
<tr>
<td>Pmin total (mm)</td>
<td>16</td>
<td>21</td>
<td>30</td>
<td>71</td>
<td>53</td>
<td>60</td>
<td>119</td>
<td>71</td>
<td>65</td>
<td>79</td>
<td>54</td>
<td>69</td>
</tr>
<tr>
<td>Q total (mm)</td>
<td>12</td>
<td>14</td>
<td>58</td>
<td>117</td>
<td>35</td>
<td>23</td>
<td>18</td>
<td>22</td>
<td>34</td>
<td>39</td>
<td>40</td>
<td>27</td>
</tr>
<tr>
<td>ET real (mm)</td>
<td>5</td>
<td>8</td>
<td>18</td>
<td>29</td>
<td>46</td>
<td>68</td>
<td>71</td>
<td>58</td>
<td>34</td>
<td>18</td>
<td>7</td>
<td>5</td>
</tr>
</tbody>
</table>
(Figure 1(b)) to run the model: average daily temperature from 10 stations (Chabot, Giroux, Scott, Beauceville, Quebec, Saint Flavien, Beaurivage, Charny, Valle Jonction, Kinnear's Mills), the sum of daily precipitation from 13 stations (Chabot, Giroux, Scott, Beauceville, Quebec, Saint Flavien, Saint Pierre, Beaurivage, Saint Severin, Beausejour, Charny, Valle Jonction, Kinnear's Mills), wind speed from three stations (Chabot, Giroux, Charny), relative air humidity from three stations (Chabot, Giroux, Charny), and vapour pressure from two stations (Chabot, Giroux). The stations were selected according to the nearest distance and the data availability. Less than 5% of the meteorological data were missing, the periods were varying depending on measurement errors and the instrument defectiveness. Values not available on a daily basis were interpolated to obtain the same temporal resolution as for those from automatic stations.

The spatially distributed data used were: digital elevation model (acquired from a GPS-RTK (Global Positioning System – Real Time Kinematic) survey over the watershed in 2005–2006), zone grids, land use (obtained annually from farmer’s survey), texture class (derived from an intensive soil survey from 2004–2005), slope angle, and exposition (Figure 3). Data were weighted according to the inverse distance interpolation method. The most sensitive parameters for manual calibration within the WaSiM-ETH model were: the control soil percolation, direct runoff, direct runoff from snowmelt, baseflow, and interflow generation. The most sensitive parameters within the snow model were: threshold temperature for snowmelt, the temperature at which 50% of the precipitation falls as snow and 50% as rain, and the temperature range for the transition from snow to rain, and degree-days. Parameters were considered to be uniformly distributed within the feasible parameter range according to Wriedt & Rode (2006).

Model calibration was initially carried out for the principal parameters in the watershed. These parameters, such as recession of surface runoff and interflow, scaling of interflow calculation, and leakage factors, were used as conceptual model components. Subsequently the groundwater parameters (drainable porosity, hydraulic conductivity), river channel parameters (width, depth) and drainage parameters (depth, horizontal spacing) were calibrated as well, because those parameters cannot be derived directly from the available data (Bormann & Elfert 2010). On the basis of a successful calibration in our study watershed, a regionalisation of the parameters was applied to an unobserved basin using the same parameter set (Schulla 1997) for validation. During the analysis of CC scenario effects on the water balance, soil and water management parameterisation remained constant while the following land cover vegetation parameters were changed: fraction of vegetation cover per cell, albedo, leaf area index, canopy height,
canopy resistance, interception capacity, rooting depth, and hydraulic head for beginning dryness stress.

Precipitation correction

The use of hydrological models in climate impact studies requires the correction of precipitation data to reduce and correct systematic errors. According to Goodison et al. (1998), the wind-induced average loss of 2 to 10% of rain measured values accounted for up to 60% of snow measured values from unshielded gauges that had wind speeds greater than 4 m s$^{-1}$. The correcting precipitation measurements methodology according to Sevruk (1986) is applied for the WaSiM-ETH sub-model. The precipitation correction was carried out separately for rain and snow using the wind speed factor within the model. The differentiation between rain and snow was identified by using the threshold temperature for snow changing to rain. The precipitation correction was used for the daily values measured in the Bras d’Henri watershed, and for future climatic scenarios.

RESULTS

Two durations covering 223 days in 2006 and 214 days in 2008 were used for model calibration, while the verification period included 229 and 84 days in 2007 and 2009, respectively. Only continuous discharge durations (750 days) were included in the modelling simulations because winter discharge measurements were missing for the frozen stream durations (497 days). Verification was achieved by comparing the modelled discharge values with measured discharge data. The accuracy of the model simulations varied from moderate to strong (Table 2) to compare simulated and measured daily discharges: Pearson correlation r, Nash-Sutcliffe efficiency coefficient E (Nash & Sutcliffe 1970), and coefficient of Nash-Sutcliffe efficiency with logarithmic values ln E.

Figures 4(a) and 4(b) show the CC in average monthly temperature and precipitation for TH comparing the present state based on CX1 and HAD scenarios. Model simulation results according to CC scenarios (CX1 and HAD) and three TH in the Bras d’Henri micro-watershed are presented in Table 3. These simulations show that annual P and ET will generally and steadily increase by 7 to 33% between baseline and 2100, while Q will irregularly intensify by 16 to 45%. Average monthly temperature and precipitation also show increasing trends (Figures 4(a) and (b)).

Temperature trends

The CC scenarios indicate varying seasonal deviations from baseline data for all TH. Monthly temperatures generally
<table>
<thead>
<tr>
<th>Period of the year</th>
<th>Pearson correlation coefficient $r$</th>
<th>Coefficient $r$ interpretation</th>
<th>Nash-Sutcliffe coefficient $E$</th>
<th>Coefficient $E$ interpretation</th>
<th>Nash-Sutcliffe efficiency with log values $\ln E$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Apr–Nov 2006</td>
<td>0.87</td>
<td>Strong, high correlation</td>
<td>0.85</td>
<td>Good efficiency</td>
<td>0.86</td>
</tr>
<tr>
<td>Apr–Nov 2008</td>
<td>0.78</td>
<td>Strong, high correlation</td>
<td>0.60</td>
<td>Satisfactory efficiency</td>
<td>0.49</td>
</tr>
<tr>
<td>Validation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Apr–Nov 2007</td>
<td>0.60</td>
<td>Moderate correlation</td>
<td>0.52</td>
<td>Satisfactory efficiency</td>
<td>0.48</td>
</tr>
<tr>
<td>Mar–May 2009</td>
<td>0.76</td>
<td>Strong, high correlation</td>
<td>0.74</td>
<td>Satisfactory efficiency</td>
<td>0.55</td>
</tr>
</tbody>
</table>

Figure 4 | Changes in monthly mean temperature ($T, ^\circ C$) and total monthly precipitation ($P, \text{mm}$) for time horizons of 2040, 2070, and 2100 compared with the baseline years (1951–2004) in the Bras d’Henri micro-watershed, Quebec, Canada, as estimated by the model WaSiM-ETH according to CC scenario CX1 (a) and CC scenario HAD (b).
remain negative from December to March and positive from April to November for both CC scenarios and for all evaluated TH. According to the CC scenario CX1, average monthly temperatures increased over time; 1.22°C in 2040, 2.37°C in 2070, and up to 4.06°C in 2100 as indicated by significant deviations from the baseline (Figure 4(a)). All monthly temperatures increased for the three evaluated horizons, except November for TH 2040 and December for THs 2040 and 2070 which remained stable. Similar trends were predicted by the HAD for the Bras d’Henri river basin (Figure 4(b)). In fact, average annual temperatures deviated from the baseline in the range of 1.21°C in 2040, 2.61°C in 2070, and 4.79°C in 2100. Following the latest CC scenario, no temperature change was predicted for February 2040 but all monthly temperatures increased for the modelled TH. The range spanned by CX1 was greatest in February, April, and October; by HAD in April, August, and November. Similarly, the range spanned by CX1 and HAD was least for December.

Precipitation trends

Similar to changes in temperature, total monthly precipitation values differed from the baseline for both CC scenarios and all evaluated TH (Figures 4(a) and (b)); precipitation according to CC scenarios was highly variable relative to the baseline.

According to the scenario CX1, mean annual precipitation increased from 15% (136 mm) in 2040, 16.9% (149 mm) in 2070, and up to 17% (150 mm) in 2100. Total monthly precipitation was predicted to increase in January, March, April, May, August, September, November, and December for all three TH from about 3 mm in September 2100 up to 40 mm in May 2070. For July it is considered to decrease about 1 mm in 2040 and 16 mm in 2070. However, results differed for the TH from February, June, and October. In fact, precipitation decreased in February and October (1 mm), but increased in June (6 mm) for TH 2040. For TH 2070, precipitation increased in February (8 mm) and in June (1 mm), but decreased in October (4 mm), and increased for TH 2100 in February (6 mm) and October (30 mm), but decreased in June (4 mm).

The CC scenario HAD showed monthly precipitation increases for all evaluated TH: 18% (163 mm) in 2040, 32.9% (290 mm) in 2070, and 29.9% (264 mm) in 2100. For TH 2040, the least increase is expected in April (2 mm) and the greatest in May (30 mm). Finally, it showed increases of 2 mm for April, up to 48 mm in September for 2070, and of 7 mm in April and up to 41 mm in May for 2100. According to this scenario, there were only two

| Projected total annual precipitation (P), evapotranspiration (ET) and discharge (Q); surface runoff (Qsurf), infiltration (Qinf), snow runoff (Qsnow), their changes (Δ) and runoff coefficient (RC) in the Bras d’Henri micro-watershed according to two CC scenarios (CX1 and HAD) and three THs (2040, 2070 and 2100). The changes were calculated using the baseline period (1951–2004) average values

<table>
<thead>
<tr>
<th></th>
<th>P (mm)</th>
<th>ΔP (%)</th>
<th>ET (mm)</th>
<th>ΔET (%)</th>
<th>Q (mm)</th>
<th>ΔQ (%)</th>
<th>Qsurf (mm)</th>
<th>ΔQsurf (%)</th>
<th>Qinf (mm)</th>
<th>ΔQinf (%)</th>
<th>Qsnow (mm)</th>
<th>ΔQsnow (%)</th>
<th>RC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>882</td>
<td></td>
<td>366</td>
<td></td>
<td>440</td>
<td>85</td>
<td>355</td>
<td>44</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.50</td>
</tr>
<tr>
<td>CX1 2040</td>
<td>1018</td>
<td>15</td>
<td>393</td>
<td>7</td>
<td>539</td>
<td>23</td>
<td>107</td>
<td>20</td>
<td>433</td>
<td>18</td>
<td>45</td>
<td>2</td>
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</tr>
<tr>
<td>CX1 2070</td>
<td>1031</td>
<td>17</td>
<td>406</td>
<td>11</td>
<td>538</td>
<td>22</td>
<td>105</td>
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<td>434</td>
<td>18</td>
<td>54</td>
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<td>0.52</td>
</tr>
<tr>
<td>CX1 2100</td>
<td>1032</td>
<td>17</td>
<td>432</td>
<td>18</td>
<td>512</td>
<td>16</td>
<td>76</td>
<td>13</td>
<td>436</td>
<td>19</td>
<td>32</td>
<td>38</td>
<td>0.50</td>
</tr>
<tr>
<td>HAD 2040</td>
<td>1045</td>
<td>18</td>
<td>402</td>
<td>10</td>
<td>553</td>
<td>26</td>
<td>109</td>
<td>21</td>
<td>444</td>
<td>20</td>
<td>51</td>
<td>15</td>
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</tr>
<tr>
<td>HAD 2070</td>
<td>1172</td>
<td>33</td>
<td>440</td>
<td>20</td>
<td>636</td>
<td>45</td>
<td>130</td>
<td>34</td>
<td>506</td>
<td>30</td>
<td>46</td>
<td>3</td>
<td>0.54</td>
</tr>
<tr>
<td>HAD 2100</td>
<td>1146</td>
<td>30</td>
<td>463</td>
<td>26</td>
<td>512</td>
<td>16</td>
<td>100</td>
<td>14</td>
<td>490</td>
<td>28</td>
<td>35</td>
<td>26</td>
<td>0.45</td>
</tr>
</tbody>
</table>
exceptions for TH 2100, where precipitation would decrease by 4 mm in July and by 7 mm in September (Figure 4(b)).

**Evapotranspiration trends**

Changes in average daily temperature trends and total annual precipitation amounts increase ET significantly. The highest ET increase is expected for the May to August duration for both CC scenarios and all TH. Figure 5 shows a significant total monthly ET increasing trend for both CC scenarios. The annual ET will increase by 7% (27 mm) in 2040, 11% (40 mm) in 2070, and up to 18% (66 mm) in 2100 according to CX1 scenario results. For HAD, annual ET will increase by 10% (36 mm) in 2040, 20% (74 mm) in 2070, and 26% (96 mm) in 2100. The greatest ET increases are expected in 2100 by 49% (February) for CX1 and 36% (May) for HAD, respectively.

**Discharge trends**

Annual and seasonal changes in precipitation are key for predicting changes in annual runoff. Figures 6(a) and 6(b) represent changes in average monthly discharge as predicted by the two CC scenarios in comparison with the baseline years of 1951–2004. Discharge values were projected daily for evaluated THs. Results from both CC scenarios show significant increases in discharge. The estimated increase in precipitation will also enhance runoff peaks occurring earlier in the season and with greater intensity. According to the CC scenario CX1, total annual discharge will increase by 23% (100 mm) for TH 2040, by 22% (98 mm) for TH 2070, and by 16% (72 mm) for TH 2100. For the CC scenario HAD, total annual discharge will increase by 26% (113 mm) for TH 2040, by 45% (196 mm) for TH 2070, and by 34% (150 mm) for TH 2100.
The runoff coefficient (RC), expressed by the ratio of modelled discharge to precipitation, can indicate the environmental humidity of a region (Yan & Liu 2001): RC < 0.1 indicates a drought zone, 0.1 < RC < 0.3 indicates a transitional belt, 0.3 < RC < 0.5 a humid area, and RC > 0.5 represents a wet area. The modelling results (Table 3) suggest that the RC will increase from 0.50 (1951–2004, baseline value) to 0.53 in 2040 for both CC scenarios and up to 0.52 and 0.54 in 2070 for CC scenarios CX1 and HAD, respectively. However, the modelling results for TH 2100 revealed lower RC of 0.50 and 0.45 for CC scenarios CX1 and HAD, respectively, which means decreasing water storage in the micro-watershed.

Discharge decreased in July and October for TH 2070 and in June, July, and September for TH 2100 by CX1 (Figures 6(a) and 6(b) for July and September for TH 2100 by HAD). This effect is closely related to the monthly sum precipitation decrease or with a slight precipitation increase during these periods (Figures 4(a) and 4(b)).

**Surface runoff and infiltration trends**

The combined effects of temperature and precipitation affect surface runoff and infiltration differently. According to model results, an increase in surface runoff would be most apparent in the spring (February to March) for all evaluated TH. It is assumed that liquid winter precipitation will directly contribute to the total discharge instead of being deposited to the snow cover directly. Because average precipitation is assumed to increase for most TH, and temperatures are expected to be negative in January, surface runoff tends to decrease for CX1 and all TH, as well as for HAD in TH 2040 with an increasing trend in TH 2070 and TH 2100.
Surprisingly, decreased surface runoff is expected in April despite snowmelt due to a higher infiltration capacity as a result of increasing average air temperatures. This effect is predicted for both CC scenarios (Figures 7(a) and 7(b)). A higher infiltration capacity is mainly predicted during the summer and autumn for all TH, with the exception of summer months and winter months for HAD (Figures 8(a) and 8(b)). Increasing infiltration capacity is closely related to increasing temperature trends which decrease soil moisture (Figures 9(a) and 9(b)).

**Snow water equivalent and snowmelt trends**

Results indicate that CC will have a broad influence on snow water equivalent (SWE) and snowmelt timing in this watershed due to differences in the type and amount of precipitation. In the Bras d’Henri micro-watershed, the CC scenario CX1 indicates that SWE will increase by 11% (56 mm) in TH 2040 and 19% (62 mm) in TH 2070, but will decrease by 43% (32 mm) in TH 2100 (Figure 10(a)).

An SWE increase of 23% (69 mm) is also predicted by HAD for the TH 2040, but SWE will decrease by 8% (52 mm) in TH 2070 and 32% (38 mm) in TH 2100 (Figure 10(b)). CCs will also reduce the number of days with snow cover compared with the baseline period; by 3 days in TH 2040, 7 days in TH 2070, and 20 days in TH 2100 according to the CX1 scenario, and 9 days in TH 2040, 10 days in TH 2070, and 28 days in TH 2100 for the HAD scenario.

The snowmelt hydrology will continue to dominate in this watershed. Changes in precipitation during the winter will increase SWE, whereas rising temperature effects with prevailing precipitation trends will result in increased snowmelt runoff in the spring. However, results also show a decline in snowmelt amounts for the whole inter-winter period. Therefore, reduced SWE in further time periods

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**Figure 7** | Changes in average monthly snow water equivalent (SWE, mm) for time horizons of 2040, 2070, and 2100 compared with the baseline years (1951–2004) in the Bras d’Henri micro-watershed, Quebec, Canada, as estimated by the model WaSiM-ETH according to CC scenario CX1 (a) and CC scenario HAD (b).
will produce an earlier snowmelt and a higher runoff from snow in March and May for both CC scenarios (Figures 10(a) and 10(b)).

Water quality

Total suspended solids (TSS), nutrients: nitrogen (NO₃-N), and total phosphorus (TP), were summarised according to daily loads and are presented as total loads (Table 4). These values were computed using surface and total discharge daily values determined by the WaSiM-ETH model for the evaluation period from 2006 to 2009. For the winter and snowmelt period (November–April), water quality attributes were not determined because the watershed was mostly frozen. During times of surface runoff, TSS export tended to be higher. Annual TSS varied from 146.28 kg ha⁻¹ in 2006 to 493.64 kg ha⁻¹ in 2009 during the monitoring period, and from 28.98 kg ha⁻¹ in 2008 to 442.22 kg ha⁻¹ in 2009 during the monitoring period with surface runoff. Sediment yield is a key indicator of sediment transport and erosion in catchments. Elevated TSS values during surface runoff indicate a higher risk of erosion.

Values of (NO₃-N) varied from 13.60 kg ha⁻¹ in 2008 to 21.30 kg ha⁻¹ in 2009 during the monitored period, and from 1.90 kg ha⁻¹ in 2008 to 10.99 kg ha⁻¹ in 2009 during the monitoring period with surface runoff.

According to these results, TP annual flux shows variation, but increases with the total discharge (Table 4), and fluctuates during the vegetative period (data not shown). In general, TP quantity increased with increasing TSS content. Because the soils are heavily fertilized, excess TP varied from 0.36 kg ha⁻¹ in 2008 to 0.88 kg ha⁻¹ in 2009 during the monitoring period, and from 0.04 kg ha⁻¹ in 2008 to 0.69 kg ha⁻¹ in 2009 during the monitoring period with surface runoff. Consumption of TP depends on the amount and type of available P and
intake is limited by excess nitrates. However, vegetative dynamics are driven primarily by soil nitrogen rather than soil phosphorus.

On the basis of these results and according to Government of Quebec criteria (2002), overall water quality of the watershed has the worst properties (category E) in the profile St. Gilles (second order watershed). For TSS, it varies from very good to good (categories A and B). For the range of values for nitrates and nitrites, water quality attributes are worst (category E), but for TP characteristics, water quality attributes are good (category B).

DISCUSSION

Changes in the annual water balance of the Bras d’Henri watershed are considerably modified according to both CC scenarios for all evaluated TH. The most significant change is revealed for TH 2100 for both CC scenarios. Projected changes in average annual temperature vary from 1.22 to 4.79 °C. According to IPCC (2007a), changes are from 1.5 to 4.5 °C, while Roy et al. (2001) predicts an increase of 1 to 5 °C for the southern Quebec region.

Precipitation changes vary depending on CC scenario and TH, i.e., annual precipitation amounts vary from 15 to 33% for this investigated watershed; about 10% according to Roy et al. (2001).

Annual increase in ET varies from 7 to 18% according to CX1 and from 10 to 26% using HAD, which agrees with Quilbé et al. (2008a, b). A substantial increase in ET was also reported in Michaud et al. (2005) and Fluet et al. (2009). The current study indicates that over the basin, precipitation and ET will increase for most of the seasons but their variation depends on CC scenario and TH. Hydrologic changes result mainly from a combination of these variables.

Total discharge increased during the winter due to higher temperatures but decreased during the summer and fall for TH 2040. Increased annual discharge was 16 to
23% for CX1 and 16 to 45% for HAD. Similar results are reported in Minville et al. (2013), i.e., an increase in peak discharge for all projections and TH of CGCM3 and HadCM3.1. Singh et al. (2013) reports an increase from 6.7 to 20.2% for GCM: GISS84 and GFDL80, and up to 250% of the maximum water discharge was reported by Roy et al. (2013). Likewise, as in Roy et al. (2001), the maximum discharge values under Quebec conditions are usually associated with spring snowmelt (Su et al. 2011). Under a future climate, the basin will react differently during spring snowmelt according to temperature increases and storm runoff events. This result indicates that maximum water discharge in the spring will occur sooner and the amount will exceed the maximum flow discharge currently observed in the autumn period.

Snowmelt events dominate surface and subsurface events in this watershed (Jamieson et al. 2005) and will be affected by CC. The present paper confirms this too. The

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**Figure 10** Changes in average monthly snow water equivalent (SWE, mm) for time horizons of 2040, 2070, and 2100 compared with the baseline years (1951–2004) in the Bras d’Henri micro-watershed, Quebec, Canada, as estimated by the model WaSiM-ETH according to CC scenario CX1 (a) and CC scenario HAD (b).

**Table 4** TSS, nutrients: nitrogen (NO₃-N) and total phosphorus (TP) as daily and total loads calculated using surface and total discharge values estimated with the WaSiM-ETH model for the evaluated period of 2006 (20 April to 30 November), 2007 (2 May to 20 November), 2008 (6 May to 25 December), and 2009 (10 April to 30 November) in the Bras d’Henri micro-watershed (2.36 km²)
climate scenarios predict that precipitation increases during the winter months will increase SWE, mainly for TH 2040. However, due to higher annual average temperatures, SWE will be lower for further TH. This prediction would indicate a decreasing number of days with snow cover and lower SWE values. As emphasised by Jasper et al. (2004), more definitive conclusions can be drawn for parameters closely correlated with temperature (ET and SWE), whereas a significantly greater spread is found for parameters dominated largely by changes in precipitation, especially discharge.

The present state of water quality in the watershed is in category E (from A-E classification), which is the worst classification. Moreover, as CC affects water balance redistribution, subsequent erosion will threaten agricultural productivity and sustainability, thereby adversely affecting water quality. Because agricultural soils are susceptible to extreme environmental events, i.e., drought and flooding, which are commonly predicted to increase due to CC, land use change could exacerbate these effects. The presented paper confirms results of Bullock et al. (2001), those report that warmer winters may decrease the protective snow cover, thereby increasing soil exposure to water and wind erosion. Increases in the frequency of freeze-thaw cycles would hasten the breakdown of soil particles and increase the risk of soil erosion, especially if producers respond to drought conditions by increasing their use of tillage summer fallow.

The advantage of this small river basin scale study is that it provides greater efficiency and effectiveness, applicable as a tool for integrated catchment management. The possible runoff change predictions are caused by changing snow cover and frozen ground over different THs. The impact of CC on snow and frozen ground as sensitive storage variables in the water cycle is highly non-linear and more physically- and process-oriented modelling is required in accordance with United Nations Environment Programme (UNEP) (2010). The models of less complexity react more sensitively to the changing climate conditions (Ludwig et al. 2009).

Jasper et al. (2004) outline a potential limitation of a scenario-based approach to impacts assessment. The plausibility of CC scenarios considered was the main concern. This issue is most important for total monthly precipitation, where they noted significant variation in annual courses and spatial distributions. Other problems with the considered CC scenarios were: (1) the reference period of observational data, which enabled a comparison between modelled (predicted) and baseline (observed) data; (2) possible shifts in the occurrence and intensity of extreme events that CC scenarios did not take into account; and (3) changes in the distribution of temperature as well as more frequently occurring heat waves as emphasised by Jasper et al. (2004) and in accordance with Schär et al. (2004). Use of only two CC scenarios is another limitation of this study, according to Minville et al. (2008); more CC scenarios would be very time-consuming.

The great uncertainty about all projected future hydrologic variables depends on both climate data and simulated hydrologic regimes (Prudhomme et al. 2003; Minville et al. 2008). Since uncertainty in climate studies does exist, the presented outputs could be of use to policymakers and state data- and water resource-managers in adapting affected agricultural systems to CC. The results of the current study, therefore, demonstrate the important role that soil and water management in agricultural ecosystems need to play to mitigate and adapt to CC impacts.

**CONCLUSIONS**

In the current study, the WaSiM-ETH model was used to evaluate the effect of CC on river discharge under different CC scenarios. Input data were taken from a high resolution regional climate model driven by different datasets. Modelling the probable CC consequences on the water balance in this intensively managed agricultural micro-watershed identified significant changes in the individual water balance variables (IPCC 2007a). The WaSiM-ETH model, initially established to simulate the watershed water balance of mountainous regions mainly covered by forests, was applied to lowland areas. It was also applied to agricultural land to simulate hydrological processes on a small watershed scale under cold climatic conditions. The model reproduced water discharge fairly well with good correlation during both the calibration and verification periods. This result indicates the model’s suitability to be extended to lowland agricultural land and the greater watershed scale. Applying a high resolution regional climatic model in conjunction
with a conceptual hydrological model enables the capture of local variability of river discharge for present-day climate, using boundary values that are also assimilated with predicted future climatic conditions. Model simulations detected significant changes in the water balance of the Bras d’Henri micro-watershed for both CM.

Regardless, the results of the current study improve our understanding of future climatic effects on a local scale. These results corroborate early reports (i.e., Mokhov et al. 2003), and the outputs can be used to predict future climatic changes concerning watershed hydrology for watersheds with similar climatologic variables. Moreover, this study highlights the importance of using different methods and data sources to assess potential CC effects on watershed hydrology. Finally, the predicted CC impact on micro-watershed hydrological parameters, such as increased precipitation and discharge and decreased snow cover, will increase surface water quality problems. The CC effects on stream water quality will increase agricultural soil erosion on frozen soils at snowmelt and during the snow-free season on bare soils. Current agricultural BMP must be better adapted to CC in order to reduce, or decrease, sediment and nutrient losses to streams during intense runoff events on soils at risk of erosion. Cover crops could be used to protect land from water erosion and new plant species could provide a buffer to protect dormant plants that are covered by snow and ice during the winter and spring seasons.

As proposed by Oleson & Porter (2009), particular thought should be given to reduce soil erosion, prevent nitrogen and phosphorus leaching, conserve soil moisture, increase crop rotation diversity, modify microclimates to reduce temperature extremes and provide shelter, and consider carefully any land-use changes, especially those that involve the abandonment or intensification of existing agricultural land or the cultivation of new land. In conclusion, the methodology presented here can be used to ascertain climatic and hydrologic characteristics linked to geographical location and climatic zone.

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