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Impact of climate change on the hydrology of St. Lawrence tributaries

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SUMMARY

Changes in temperature and precipitation projected for the next century will induce important modifications into the hydrological regimes of the St. Lawrence tributaries (Quebec, Canada). The temperature increase anticipated during the winter and spring seasons will affect precipitation phase and consequently the snow/precipitation ratio and the water volume stored into snow cover. The impact on northern river hydrology and geomorphology will be significant. In this study we aim to assess the magnitude of the hydrological alteration associated with climate change; to model the projected temporal shift in the occurrence of winter/spring center-volume date; to assess the sensitivity of the winter/spring center-volume date to changes in climatic variables and to examine the latitudinal component of the projected changes through the use of five watersheds on both shores of the St. Lawrence. The study emphasizes changes in the winter and spring seasons. Projected river discharges for the next century were generated with the hydrological model HSAMI run with six climate series projections. Three General Circulation Models (HadCM3, CSIRO-Mk2 and ECHAM4) and two greenhouse gas emissions scenarios (A2 and B2) were used to create a range of plausible scenarios. The projected daily climate series were produced using the historical data of a reference period (1961–1990) with a perturbation factor equivalent to the monthly mean difference (temperature and precipitation) between a GCM in the future for three 30 year horizons (2010–2039, 2040–2069; 2070–2099) and the reference period. These climate projections represent an uncertainty envelope for the projected hydrologic data. Despite the differences due mainly to the GCM used, most of the hydrological simulations projected an increase in winter discharges and a decrease in spring discharges. The center-volume date is expected to be in advance by 22–34 days depending on the latitude of the watershed. The increase in mean temperature with the simultaneous decrease of the snow/precipitation ratio during the winter and spring period explain a large part of the projected hydrological changes. The latitude of the river governed the timing of occurrence of the maximum change (sooner for tributaries located south) and the duration of the period affected by marked changes in the temporal distribution of discharge (longer time scale for rivers located at higher latitudes). Higher winter discharges are expected to have an important geomorphological impact mostly because they may occur under ice-cover conditions. Lower spring discharges may promote sedimentation into the tributary and at their confluence with the St. Lawrence River. The combined effects of modifications in river hydrology and geomorphological processes will likely impact riparian ecosystems.

Introduction

The hydrological regime of northern rivers could be severely modified in response to the anticipated changes in temperature and precipitation during the present century. For the Great-Lakes-St. Lawrence watershed (USA and Canada), a reduction ranging between 4% and 24% of the mean annual discharge is projected for the next 90 years as a consequence of current scenarios of climate change (Croley, 2003). For this large watershed, increased evaporation from lakes due to a rise in temperature explains a large part of the projected reduction (Croley, 2003). Shifts in the timing and amount of input runoff are also expected to occur (Mortsch and Quinn, 1996). Downstream of Lake Ontario, seasonal changes in the discharge of the St. Lawrence River may be accentuated or attenuated by the water regulation plan in order to modulate the temporal variation in the Great Lakes levels.

Winter and spring seasons are particularly vulnerable to changes in air temperature. Warmer temperature during the winter season can increase the number of days with air temperature above zero Celsius resulting in more frequent rain events. These events will contribute to an increase of winter runoff and not to

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the accumulation of a snowpack (Whitfield et al., 2003). The relative amount of precipitation falling as rain or snow will directly affect water supplied from the snowpack in the spring and the amplitude and timing of river flows during the winter and spring (Hodgkins et al., 2003). Cooley (1990) has suggested that changing mean air temperature by 2–4 °C may have a significant impact on the accumulation and melt of a snowpack depending on the original temperature regime of the site. These changes will alter the hydrological regime.

Modification of winter and spring streamflows has been observed in southeastern Canada and northeastern USA during the course of 20th century (Hodgkins et al., 2003; Hodgkins and Dudley, 2006; Whitfield and Cannon, 2000; Zhang et al., 2001). Changes toward earlier freshet (spring thaw resulting from snow and ice melt in rivers located in the northern latitudes) were found to be significant for most of these areas. Hodgkins and Dudley (2006) also found that river flows in January, February and March show a tendency to increase from 1953 to 2002 in northeastern USA. Conversely, river flows in April and May show a relative decrease during the same period. These changes are attributed to long term changes in temperature and their impact on the phase (snow or rain) of precipitation. Decline in the annual ratio of snow to total precipitation has been reported from many climatologic stations in New-England from 1948 to 2000 with the most important decrease occurring after 1975 (Burakowski et al., 2008; Huntington et al., 2004). This negative trend has been partly linked with positive North Atlantic Oscillation (NAO) anomalies index which is associated with mild winters (in eastern USA) and low snowfall to rain ratio. Large-scale atmospheric and oceanic oscillations (e.g. North Atlantic Oscillation, Pacific Decadal Oscillation) account for most of the climate natural variability by modulating precipitation and temperature regimes through the regulation of the number and intensity of significant weather events particularly during the winter and early spring. These oscillations influence the snowpack variability and the timing and magnitude of flood peaks at a decade scale (Cayan, 1996; Hartley and Keables, 1998; Jain and Lall, 2000, 2001; Thompson and Wallace, 2001). Global warming effects will be superimposed on NAO or other large-scale oscillations and it remains uncertain whether global climate warming will influence the variability of those oscillations (Hurrell et al., 2006; Visbeck et al., 2001).

Changes in temperature and precipitation and the shift in winter precipitation from snow to rain will be crucial for the hydrological regime of St. Lawrence tributaries. For the future periods (2010–2039, 2040–2069 and 2070–2099), a few studies in Québec have already suggested an increase in winter flow and decrease in spring flow compared to a historical reference period (Fortin et al., 2007; Minville et al., 2008; Quilbé et al., 2008). Higher winter flows, lower spring flows and changes in the timing of spring runoff can also have important impacts on fluvial processes, water management and on riparian and aquatic ecosystems. The amplitude, duration and timing of spring floods play a critical role on the structure and diversity of aquatic ecosystems (Toner and Keddy, 1997). Stronger winter floods can also substantially modify the physical characteristics of habitats, enhance river channel erosion and alter stream conditions for winter spawning fish species. These effects could be enhanced as winter floods could occur under ice-cover conditions.

This study is part of a larger project that aims to model the morphological and sedimentological response of St. Lawrence tributaries to the anticipated environmental changes (hydrological and base level drop changes). The paper focuses on future changes in the hydrological regimes of the St. Lawrence tributaries as a result of projected climate changes. The specific objectives of the study are to: (1) analyze changes in the simulated river discharges at the annual to monthly scales; (2) quantify the projected temporal shift in the occurrence of spring peak discharges (represented by the winter/spring center-volume date); (3) assess the sensitivity of the winter/spring center-volume date to changes in climatic variables and (4) identify similarities and differences among the St. Lawrence tributaries. The paper presents historical (1932–2005) and projected (2020s, 2050s and 2080s) climatic and hydrological data for five tributaries with a particular focus on the winter and spring period. This research significantly adds to other recent studies in Québec and Eastern Canada because the selected watersheds cover a latitudinal range from 43.2°N to 49.1°N on both the south and north shores of the St. Lawrence. The selection of rivers spans a current seasonal mean air temperature gradient for the winter and spring period from −4 °C to 0 °C.

Methodology

All located along the St. Lawrence fluvial corridor between Montreal and Quebec City, the studied tributaries are the Richelieu and St-François rivers on the south shore and the Yamachiche, St-Maurice and Batiscan rivers on the north shore (Fig. 1). These watersheds are mostly located in low relief areas and cover close to 6° of latitude. The rivers differ in their hydrology, sedimentology and dynamics and they are representative of the diversity of tributaries along the St. Lawrence. Except for the Yamachiche River, all watersheds are exploited for hydro electricity or influenced by multiple dams used for flood control, water intake or recreational activities. Data concerning the management plan of these structures are, however, not available and cannot be accounted for in the hydrological simulations. Exploitation of the rivers for hydro electricity and flood control began before 1950 and around 1964. The impact of these structures on the natural regime of the river is low for the Batiscan and Richelieu and moderate for the St-François. The natural hydrological regime of the St-Maurice River has been substantially modified by water management for hydro electricity. To reduce the impact of this hydrological control on the St-Maurice, we have elected to study the response of a smaller watershed, LaGabelle, instead of the whole basin. The LaGabelle watershed is used by Hydro-Quebec (Québec national hydro electricity company) to study the natural response of the drainage basin to meteorological variations.

Hydrological modeling

Hydrological simulations were performed with the HSAMI model (Bisson and Roberge, 1983; Chaumont and Chartier, 2005; Fortin, 2000). This model is a lump rainfall (rain-and-snow) runoff model. It is a discrete time conceptual model containing three linear reservoirs (snow cover, surface water (surface runoff and base discharge), unsaturated and saturated zones) in cascade which generate impulses filtered by two hydrograph units. Snow accumulation (following a degree-day approach), snow melt, soil freezing and thawing, evapotranspiration (estimated from daily maximum and minimum temperatures) and vertical and horizontal transit of water are simulated by the model with a system of equations and empirical parameters which are adjusted during the calibration of the model. Simulations are carried out with a time step of one day. HSAMI model is simple and easy to use for the estimation of potential impacts of climate change on water resources. This model has been used for more than twenty years by Hydro-Quebec over the Québec province to predict runoff for their reservoirs. It has been largely tested and successfully applied over the same region and more northern watersheds (Chartier, 2006; St-Hilaire et al., 2003). It requires a small amount of input data and optimization of the parameters is done automatically using the shuffled complex evolution method (Duan et al.,