HYDROLOGICAL PROCESSES
Hydrol. Process. **15**, 3167–3179 (2001)
DOI: 10.1002/hyp.323

The impact of climate change on seasonal floods of a southern Quebec River Basin

Luc Roy,[1] Robert Leconte,[1] François P. Brissette,[1]* and Claude Marche[2]
[1] *École de technologie supérieure, Université du Québec, 1100 Notre-Dame ouest, Montréal, Qué. H3C 1K3, Canada*
[2] *Département de génie civil, École Polytechnique de Montréal, C.P. 6079, Succ. Centre-Ville, Montréal, Qué. H3C 3A7, Canada*

Abstract:

Global warming predicted by general circulation models (GCM) is now a more and more generally agreed upon effect. The impact of climate change on summer and fall flooding on the Châteauguay River Basin (2500 km^2), located at the southern end of the Quebec province (Canada), was investigated using results from the Canadian GCM (CGCM1) and a coupled hydrology–hydraulics model of the basin. Three 20-year periods, corresponding to 1975–1995, 2020–2040 and 2080–2100, were used for the analysis. For each period, 24-h precipitation depths corresponding to the 20 and 100-year return periods were determined from a frequency analysis of the summer–fall maximum 24-h precipitations using a general extreme value frequency distribution. 24-h rainfall hyetographs were generated using region-specific cumulative distributions provided by the Canadian Atmospheric Environment Service. These hyetographs were then used as inputs to the hydrology–hydraulics model to simulate hydrographs, maximum discharge and maximum water levels at two sections of the river. Results indicate potentially very serious increases in the volume of runoff, maximum discharge and water level with future climate change scenarios. The changes get more drastic as longer return periods are considered. Increases of up to 250% of the maximum water discharge are encountered and water levels are significantly higher than the current flood levels. If realistic, these scenarios indicate that important decisions will have to be taken to alleviate future increases in flooding damages in what is already a flood prone river. Copyright © 2001 John Wiley & Sons, Ltd.

KEY WORDS hydrology; climate change; hydraulics; floods; forecasting; extreme events

INTRODUCTION

Climate change and global warming have been increasingly under media scrutiny over the past 20 years. During this period, the concerns over global warming and climate change issues have gradually shifted from a mainly scientific concern to mainstream media. From subjective theories, the expectations of a rapid climate change are now arguably backed by observations. In Canada, a 1 °C raise in average temperature as well as an increase in annual precipitation over the past 50 years have been observed (Koshida and Avis, 1998). Even though the Earth's climate has always been in constant evolution, the witnessed actual changes differ in both magnitude and time scale. At the planetary scale, climate change will result in variations in oceanic and atmospheric circulation which in turn affect temperature and precipitation (Hofmann *et al*., 1998), and ultimately, the hydrological response of watersheds. The main impacts are linked to water quantity and quality problems (floods, droughts, contamination) that affect emergency measures, flood plain delineation and development, water supply, water and wastewater treatment. Less conspicuous complications will also arise, such as changes in crops and vegetation (Hofmann *et al*., 1998). However, it is now recognized that the most significant change is perhaps an increase of extreme events (Fowler and Hennessy, 1995; Etkin, 1998), which has a much more significant impact than the variation of average values. This paper focuses

* Correspondence to: F P Brissette, École de technologie supérieure, Université du Québec, 1100 Notre-Dame ouest, Montréal, Qué. H3C 1K3, Canada. E-mail: fbrissette@ctn.etsmtl.ca

Received 12 June 2000
Accepted 22 January 2001

on simulated climate change scenarios and impacts on seasonal flooding of a southern Quebec watershed. This paper focuses on rain-generated floods that occur in the summer and fall season. The impact of climate change on winter floods is a more complex issue as the increase of extreme precipitation–snowfall events is potentially counterbalanced by a thinner snowpack and a reduction of ice-jams due to the warmer winter climate. Since current winter flooding events on such basins are linked to a complex combination of above-freezing temperature, snowpack water-equivalent, precipitation and ice-jams, it is much harder to infer the potential impact of climate change for winter floods.

As the magnitude and absolute direction of the expected changes in temperature and precipitation are strongly dependent on numerous factors such as topography, proximity of large bodies of water and geographical coordinates, the results presented in this paper should not be extended to other basins without a great deal of caution.

HYDROLOGY AND CLIMATE CHANGE

Several studies have looked at the potential impact of climate change on the hydrology of watersheds (Croley,1990; Morin and Slivitzky, 1992; Whetton *et al*., 1993; Kite, 1993; Knox, 1993; Chiew *et al*., 1995; Singh and Kumar, 1997; Cohen, 1997; Arora and Boer, 2000). The approaches vary from a simple sensitivity analysis toward changes in climate inputs to the study of palaeoclimatic data, spatial shifting of current climates towards polar region, or using data produced by general circulation models (GCMs). Because of its physically based nature, the latter approach is arguably the most attractive. Kite (1993) was one of the first to apply such an approach, using mean monthly values of climatological variables from the second generation Canadian Climate Center GCM. His results show an increase in high discharge events that is consistent with the projected increase in extreme rainfall events. However, such an increase in high discharge events is not observed in the recent Arora and Boer (2000) work in which they looked at the hydrology of 23 major river basins over the globe, simulated directly from the CGCM1 model. However, considering the very large scale of the chosen basins, the subgrid scale of most extreme rainfall events and the damping of any flood wave over the length of such basins, such results are not surprising. While the spatial scale of GCMs (horizontal resolution of 200–300 km) might be too coarse for traditional hydrological modelling purposes, except for very large watersheds, regional climate models (RCM), with a 45–60 km horizontal resolution, do allow its use toward a medium size basin ($>15\,000$ km^2) over which the hydrological nature of extreme rainfall event can be investigated. An additional problem with the direct use of climate data from GCMs for continuous hydrological modelling is that they may overpredict precipitation (Kharin and Zwiers, in press). However, flow discharge produced by the model agrees generally well with observed data, as evapotranspiration may also be overpredicted. As such, a continuous hydrological approach using the CGCM1 climate data might still be possible, but this places greater constraints on the calibration and validation steps. However, Kharin and Zwiers (in press) also observed that extreme rainfall data such as represented by the 20-year rainfall matched much more closely the observed data than the mean daily precipitation. This indicates that an extreme value analysis technique such as proposed in this paper may be a better alternative than a continuous hydrological modelling approach.

STUDY AREA

The Châteauguay River flows into the St. Lawrence River on the south shore of Montréal, province of Quebec, Canada. The basin overlaps the Canadian and US boundary (60% in Canada and 40% in the US) and has a drainage area of 2543 km^2 (Figure 1). It is relatively steep and densely forested in its upstream region (Adirondack mountains) and drains northward into a large agriculture-dominated plain. The average annual discharge at its mouth is 40 m^3/s, but flows in excess of 800 m^3/s have been recorded during spring flooding events. Maximum discharge is normally the result of the spring snowmelt combined with rainfall and maximal

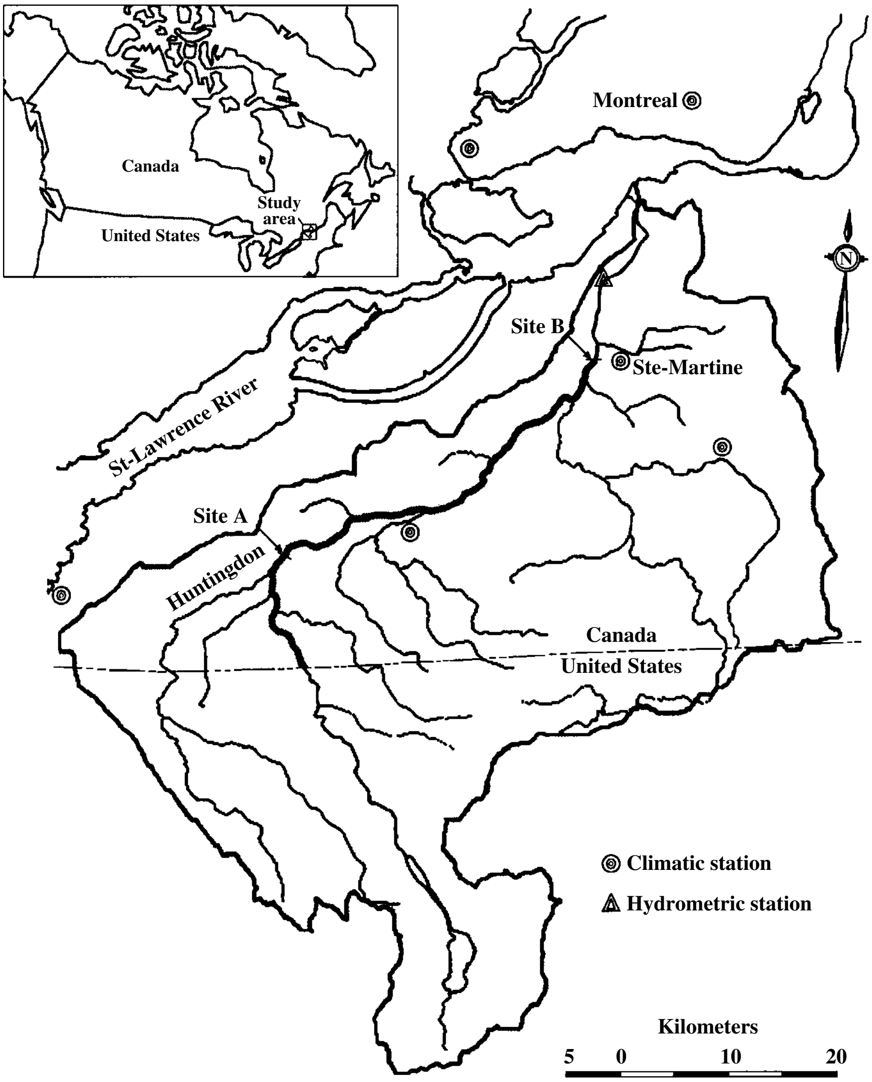

Figure 1. Châteauguay River Basin study area

flooding events are often linked to ice-jams on critical sections of the river. However, the river is also flood prone in the summer and fall season and this paper focuses on these seasons.

COUPLED HYDRAULIC–HYDROLOGIC MODEL

In order to translate climate change scenarios into hydraulically significant variables such as peak discharge and water level, a coupled hydraulic–hydrologic model is needed. For this project, the hydrologic–hydraulic simulator developed by Lavallée *et al.* (2000) was used. The simulator was developed within a set of integrated tools aimed at the short-term, real-time forecast of flooding events and automated damage estimation (Bouillon *et al.*, 1999; Brissette *et al.*, 1998). Integrated with GIS and remotely sensed data, the system can be used directly in the decision making process associated with flooding events.

The hydraulic–hydrologic simulator consists of a shell superimposed on the HEC-1 and DAMBRK packages. HEC-1 (HEC, 1990) is a widely used event-oriented lumped hydrology model whereas DAMBRK (Fread, 1984) is probably the most complete one-dimensional hydrodynamic flood-routing software available. It accounts for storage effects, flood plain overbank flow and flood wave attenuation.

Since this paper focuses on events with discharge return periods of 20 and 100 years, the simulator's hydrology model was successfully calibrated (five events) and validated (four events) with the highest summer–fall rainfall events on record. The hydraulic model was calibrated with simulations using the mean water discharge as well as 20 and 100-year flood discharges. Results were compared visually with the existing 20 and 100-year flood zones delineated under the provincial government responsibility.

CLIMATE CHANGE SCENARIO

The climate change scenarios used in this study are based on results from GCMs. Used more and more extensively over the last 15 years, GCMs are now globally accepted as fundamental tools to explore and evaluate the effects of an increase of greenhouse gases (GHG) concentration in the atmosphere (Environment Canada, 1997). There are now several GCMs used throughout the world and each uses its own physical parameterization. However, all GCMs take into account an increase of GHG concentration over the next century. The magnitude of this increase is difficult to evaluate and several possibilities have been envisioned, with a three-fold increase of the GHG concentration over the next century for the more pessimistic scenario. At the other end of the spectrum, a smaller increase of the Earth's population coupled with an optimistic increase of renewable sources of energy could result in an increase of 1·75 times the actual concentration. Nevertheless, despite different parameterization and GHG concentration estimates, all GCMs predict an average global temperature increase from 1 to 3·5 °C over the next 100 years (Koshida and Avis, 1998). For the southern Quebec region, GCMs predict an increase of 1 to 5 °C and a 10% augmentation in precipitation. However, the knowledge of how these changes will impact the nature of extreme climatic event is still limited, especially when it comes to the frequency, intensity and duration of such events, which have a great significance at the watershed scale. Despite these limitations, Environment Canada (1997) recommends that the environmental sensitivity to climate change should still be evaluated by adjusting with a scaling factor the currently known relationships between the duration, intensity and frequency of extreme events.

The climate change scenarios used in this study are based on results from the Canadian CGCM1 (Flato *et al*., submitted; Boer *et al*., in press a, b). This model uses the observed GHG concentrations from 1900 to 2000 and extrapolates from there with a concentration increase of 1% per annum until 2100. The more conservative scenario where aerosols partly compensate for the effect of GHG has been used for this study. A frequency analysis of the summer–fall 24-h maximum precipitation was performed on the CGCM1 data for three 21 year periods, 1975–1995, 2020–2040 and 2080–2100, using an approach akin to Kharin and Zwiers (in press). A generalized extreme value (GEV) distribution function was fitted to the data for each time period using the method of moments (ASAE, 1982). The chi-square test was performed to assess the goodness of fit (ASAE, 1982) and all the fitted distributions were accepted at the 5% confidence level. The mean annual temperature and precipitation are presented in Table I. As a validation step, the GEV distribution function fitted to the CGCM1 data for the 1975–1995 period was compared to fitted GEV distributions on

Table I. Mean annual temperature and precipitation simulated by CGCM1 for the region under study

CGCM1 data period	T (°C)	ΔT (°C)	P (mm/day)	ΔP (%)
1975–1995	8·8	NA	3·65	NA
2020–2040	10·2	1·4	3·57	−2·2
2080–2100	13·6	4·8	3·82	4·7

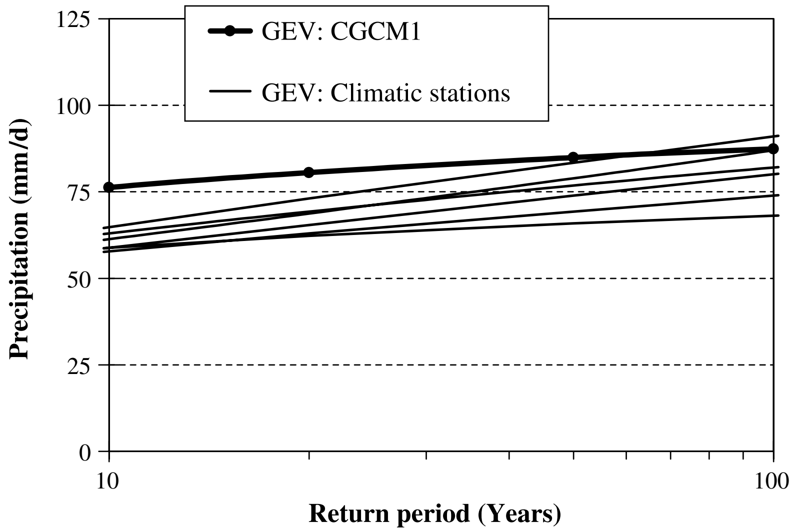

Figure 2. Frequency analysis of summer–fall maximum 24-h precipitation, 1975–1995

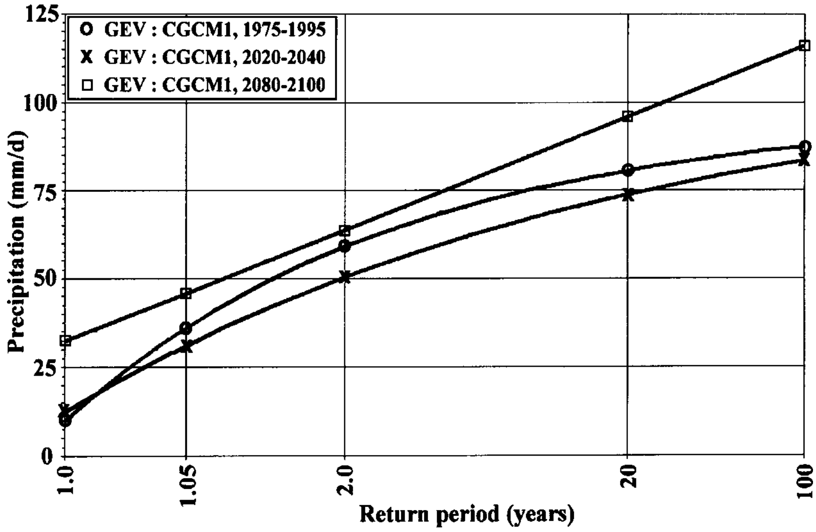

Figure 3. Frequency analysis of summer–fall maximum 24-h precipitation, CGCM1

actual data for the same period from six weather stations within or close to the basin. The results shown in Figure 2 indicate that the distribution derived from CGCM1 data is consistent with the actual data despite being slightly higher in precipitation at smaller return period. This is consistent with the observed behaviour of the CGCM1 model which overpredicts the average precipitation but matches much more closely events with a larger return period (Kharin and Zwiers, in press). Nevertheless, since the number of years used in the evaluation is relatively small (20 for the GCM data and 23 to 50 for the climatic stations), the confidence intervals of the fitted distributions are accordingly quite large for the return period in excess of 10 years, and all fitted distributions are encompassed by any distribution 95% confidence interval. One possible explanation for the fact that the observed data frequency distribution plot up beneath that derived from CGCM1 data is that all weather stations are in the northern end of the basin which has a lower elevation and flatter topography than the southern end. Figure 3 presents the GEV distributions for the three chosen periods (summer and fall) while

Table II. Summer–fall maximum 24-h precipitation for 20 and 100 year return periods

Description	P_{20} (mm/day)	ΔP_{20} (%)	P_{100} (mm/day)	ΔP_{100} (%)
Average of stations	69·1 (63 to 76)	—	82·7 (74 to 93)	—
CGCM1, 1975–1995	80·59	NA	87·39	NA
CGCM1, 2020–2040	76·29	−5·3	86·69	−0·8
CGCM1, 2080–2100	95·59	18·9	116·1	33·9

Table II presents the summer–fall maximum 24-h precipitation with 20 and 100-year return periods. These return periods were chosen because they are the most commonly used in hydraulic design in the province of Quebec. The results indicate a slight decrease in precipitation for the 2020–2040 period, and a very large increase for the 2080–2100 period. When compared to results from the 1975–1995 period, it should be noted that the relative increase in precipitation becomes more important with an increasing return period (and the slight decrease for the 2020–2040 period becomes even less important with the increasing return period). For the 2080–2100 period, the 20 and 100-year 24-h rainfall depths increase by 25 and 34% respectively over their current values. This also indicates that in the same period, a 20-year precipitation will be larger than the actual current 100-year precipitation, and that the changes in extreme events are proportionally larger than the changes in the mean values. This can also be observed from CGCM1 (and other GCMs) data, where variations are much greater than the annual mean change. For example, the increase in mean temperature for the 2080–2100 period is 4·8 °C, whereas the mean increase for the month of April is 7·3 °C. The same can be said for the precipitation data, where the average increase for the same period is 4·7%, compared to monthly averages varying from +20% in June to −18% in August. It should however be noted that the accuracy of GCMs is more disputable for precipitation than it is for temperature. This is mostly linked to the fact that precipitation, and especially events with a large return period, are orographic in nature and are not particularly well resolved by the current GCM's resolution. This point will be examined in more detail in the discussion.

The precipitation data presented in Table II were used in the hydrologic–hydraulic simulator. The daily precipitation values were distributed over a 24-h period using region-specific cumulative distribution curves provided by the Canadian Atmospheric Environment Service (Wogg, 1980; Watt, 1990).

RESULTS

The hydraulic–hydrologic simulator was run for precipitations with return periods of 20 and 100 years for the present and future climate. Besides initial soil moisture, all basin variables were kept constant for all simulations. The runs took into account two different initial soil surface moisture conditions corresponding to near saturation (0·4 volumetric soil moisture) and to very dry soils (0·15 volumetric soil moisture). The chosen range of surface soil moisture conditions represents typical values for this basin and has been validated by field studies conducted during the spring and fall periods (Galarneau *et al*., in press). Results from the simulations are presented in Figures 4 to 6 for the 20-year return period rainfall and in Figures 7 to 9 for the 100-year return period rainfall. The curves correspond to the actual conditions and future (year 2080–2100) climate conditions. Figures 4 and 7 show the computed water surface elevation profile for a 58 km section of the river starting at the US–Canada boundary. This section of the river is highlighted in Figure 1. All elevations are referenced to the mean sea level. The three sharp decreases in water surface elevation seen in those two figures represent water control structures. The black triangles represent the current flood stage water levels. These clearly indicate that most of the river section is currently flood prone. Effectively, even for initial dry soil conditions, an actual 20-year rainfall is sufficient to exceed flood stage along nearly the entire section. Figures 5 and 6, 8 and 9 present the corresponding hydrographs at two sections along the river at sites A (town of Huntingdon) and B (Ste-Martine dam) as indicated in Figure 1. In order to interpret the

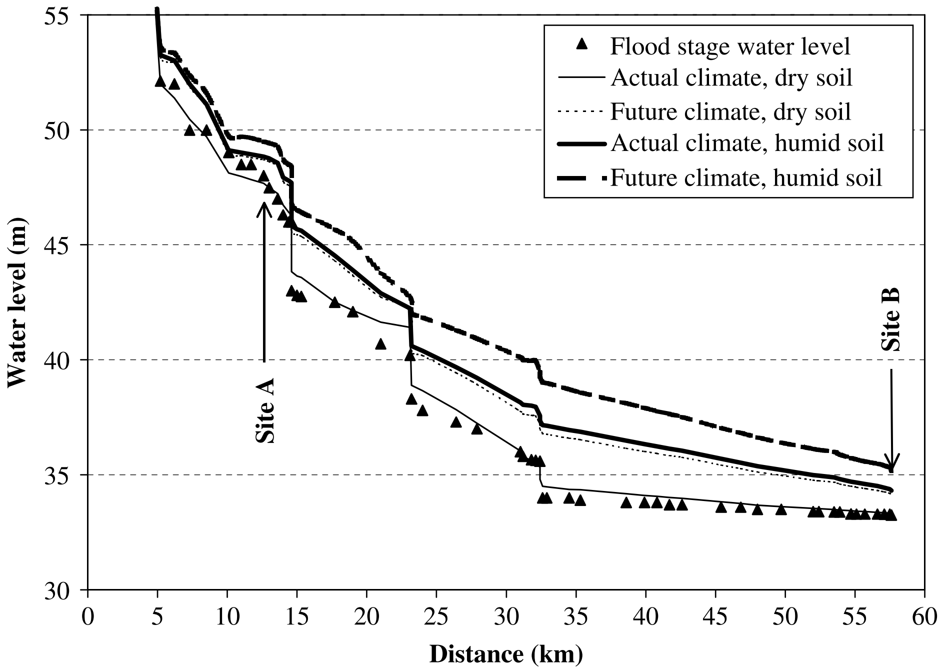

Figure 4. Maximum water level for 20-year return period rainfall

flow discharges computed at those two sections, a flood frequency analysis was performed for summer and fall data for a hydrometric station located close to site B (see Figure 1). Data were fitted with a Pearson type III distribution (method of moments) and results are presented in Figure 10. This analysis establishes the 20, 100 and 10 000-year summer–fall discharges at 381, 513 and 855 m^3/s, respectively.

DISCUSSION

The results obtained from the coupled hydraulic–hydrologic model allow the eventual impacts of a climate change on the summer–fall flooding regime of the Châteauguay River to be evaluated. For both the 20 and 100-year rainfall events, the maximum water level obtained in a future climate with dry soil initial conditions corresponds roughly to the present climate with humid initial soil conditions. However, a comparison of water levels between present and future climate for similar initial soil moisture conditions indicates an increase in water elevation of about 1·5 to 3 m for the 20-year rainfall with an additional 0·5 m for the 100-year rainfall event. In other words, the increase in water elevations between the present and future climate with similar initial soil moisture conditions is of the same magnitude as what is currently observed for the same rainfall between dry and humid conditions. These changes are very large, especially considering that in the worst case (future climate, humid initial soil conditions) the water elevations will be about 2 to 5 m above flood stage for most of the modelled section for the 20-year rainfall event, with an additional 1 m for the 100-year rainfall event. In terms of hydrographs, Table III presents the increase in water discharge and the corresponding return period for the 20 and 100-year rainfall scenarios. The numbers in Table III represent the hydrological risk, which can be linked to the flooding risk (Awadallah *et al.*, 1999). For the actual conditions (current climate), the analysis of current data indicates that a 20-year rainfall event results in a 1·4 to 10-year maximum flow discharge depending on the initial soil moisture conditions. For a 100-year event, a maximum flow discharge with a return period from 4·5 to 160 years is observed depending on the initial soil moisture conditions. In a

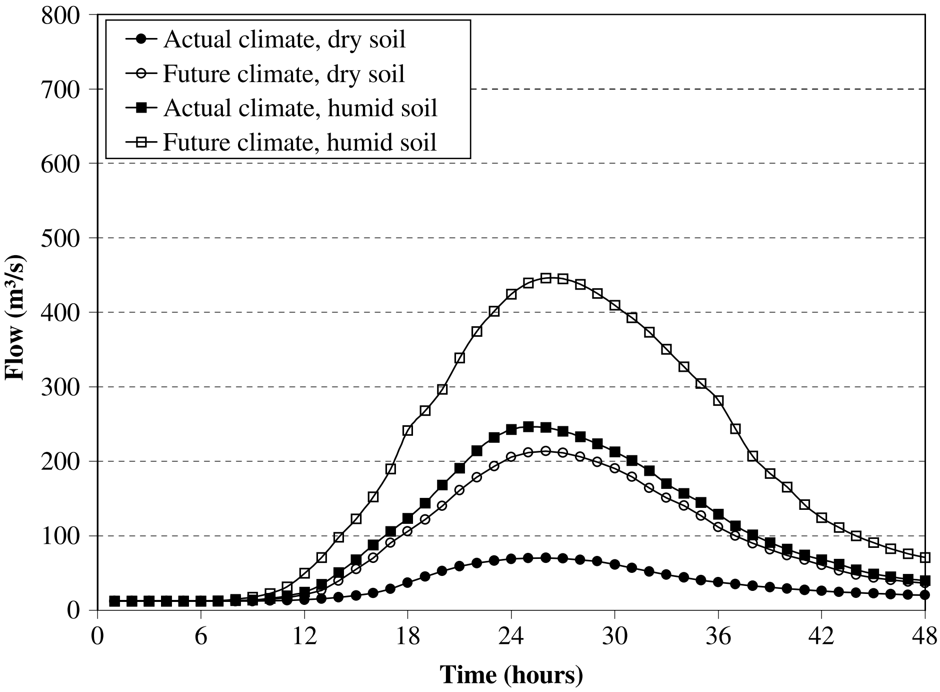

Figure 5. Site A—hydrographs for 20-year return period rainfall

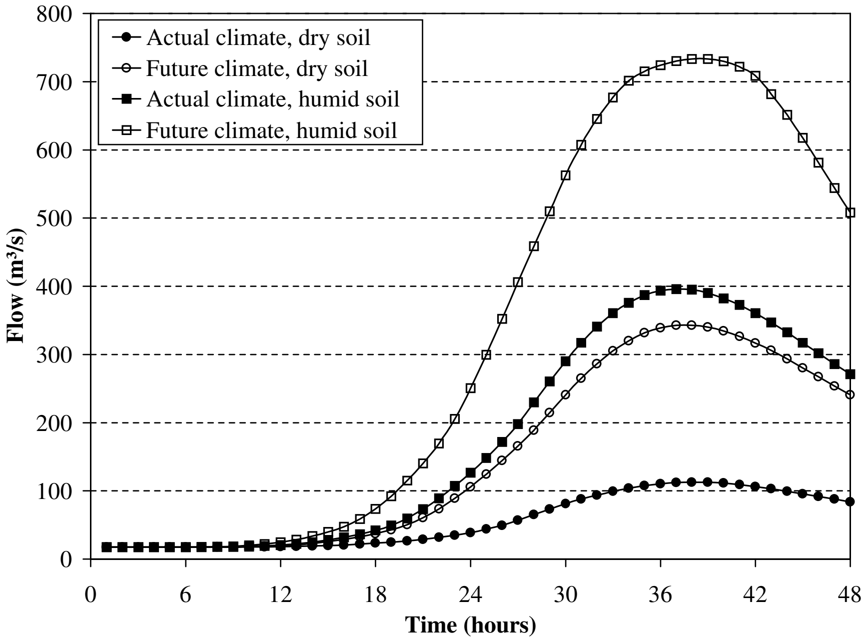

Figure 6. Site B—hydrographs for 20-year return period rainfall

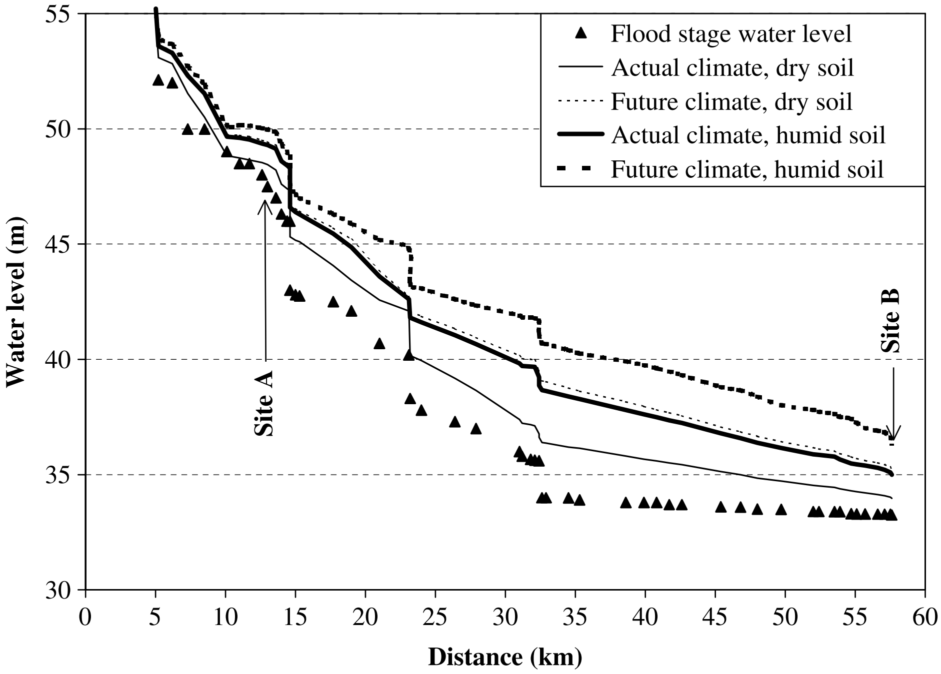

Figure 7. Maximum water level for 100-year return period rainfall

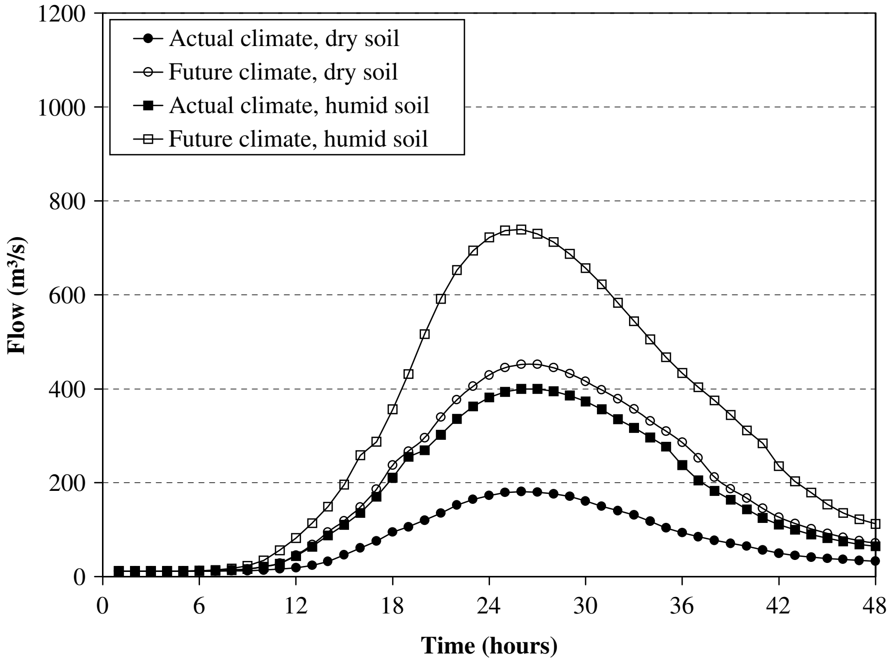

Figure 8. Site A—hydrographs for 100-year return period rainfall

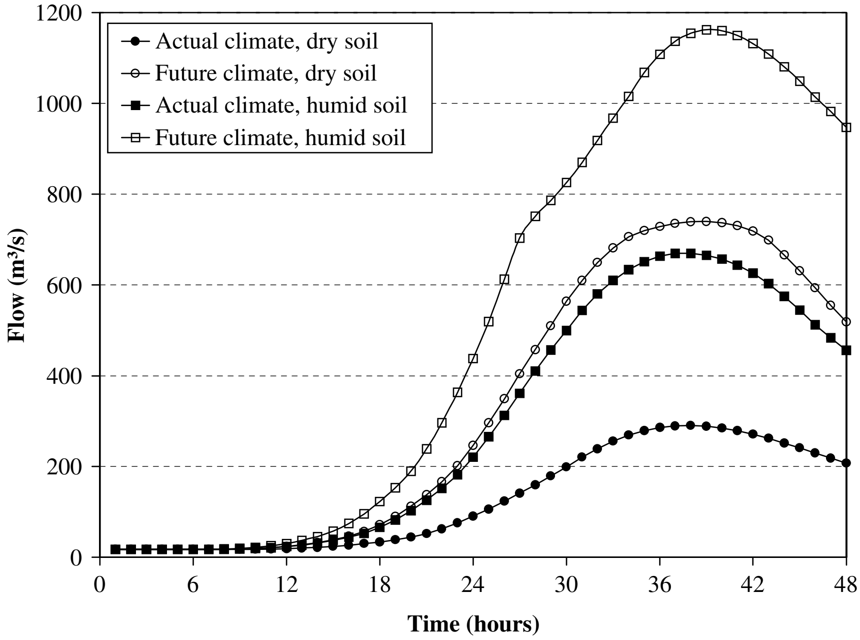

Figure 9. Site B—hydrographs for 100-year return period rainfall

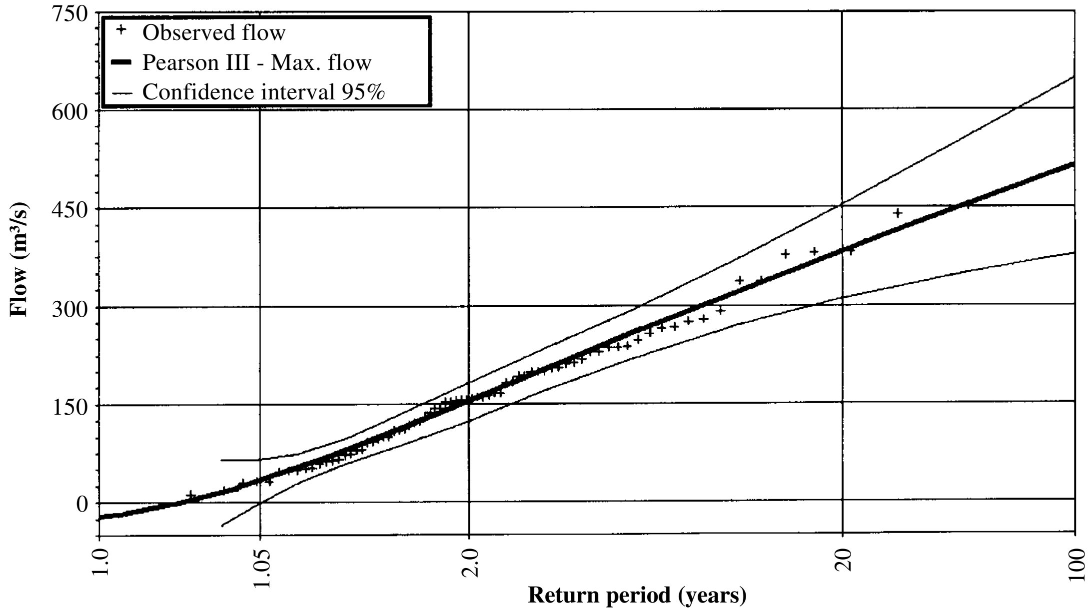

Figure 10. Site B—frequency analysis of daily summer–fall maximum flow

future climate, the situation deteriorates considerably. For the future climate 20-year rainfall event (2080–2100 period), the actual flow discharge would result in a return period ranging from 13 to 400 years (based on the frequency analysis of current data). This gets worse for a 100-year event resulting in a flow discharge

Table III. Impacts of climate change scenarios on flow discharge at site B (Ste-Martine) for the summer and fall seasons

Rainfall return period (years)	Initial soil moisture conditions	Maximum flow discharge Q_{max} (m^3/s)			Flow return period T (years) (based on actual data—Figure 10)		
		Q_{max} actual	Q_{max} 2080–2100	ΔQ	T actual	T 2080–2100	ΔT
20	dry	112	340	228	1·5	12·5	11
	humid	318	608	290	10	340	330
100	dry	232	614	382	4·0	375	371
	humid	545	968	423	150	>10 000	>10 000

with a return period anywhere from 400 to greater than 10 000 years depending on the initial soil moisture conditions. These results clearly indicate that, as was the case for extreme precipitations, the increase in the hydrologic risk due to a climate change gets more and more significant as the return period gets higher.

There are a number of limitations to the approach used in this paper, the most important probably being the accuracy of GCMs. GCMs present a simplified view of the Earth, especially in terms of topography. The ability of GCMs to adequately reproduce the actual climate is probably the best clue as to their usefulness in predicting the future climate. However, while GCMs reproduce accurately the global climate, their results are much more difficult to correlate at the regional scale. The main weakness of GCMs resides in their low spatial resolution. The CGCM1 data used in this paper has a horizontal grid resolution of $3{\cdot}7^\circ \times 3{\cdot}7^\circ$ which translates into a 200×300 km^2 mesh size over the study area. This resolution is certainly insufficient for continuous hydrological modelling over watersheds the size of the Châteauguay River Basin, and is still rough for regional climate resolution. As such, climate processes at the mesoscale are not well taken into account and the extension of these results for extreme events is uncertain (Hofmann *et al*., 1998). However, approaches based on seasonal averages such as used in this paper aim first and foremost at the assessment of the magnitude of the anticipated impacts. In this sense, GCM results are very useful to evaluate the sensitivity of the regional hydrological regime to climate changes (Environment Canada, 1997), and have been used in various such studies (Croley, 1990; Morin and Slivitzky, 1992; Cohen, 1997; Hofmann *et al*., 1998). RCMs that are run at a finer scale (Caya *et al*., 1995), as well as faster computers and better parameterization of the various physical processes, will allow more and more high resolution climate change scenarios to be evaluated. This will result in a better evaluation of the potential impact of climate change on water resources, especially at the regional scale.

Another limitation of this work resides in the fact that basin variables were kept the same for the three simulated periods. Although this is true for several variables, it is clear that a climate change will have an important effect on others. This is particularly true of vegetation cover which affects evapotranspiration and soil moisture conditions. A warmer climate will effectively increase potential evapotranspiration. Farmers will have to gradually adapt and migrate toward crops better suited to the new climate. It is probably reasonable to assume, on average, drier soil conditions for the future climate. However, soil moisture being highly variable spatially and temporally, there is still a significant uncertainty linked to these aspects and no easy way to lift it. Running a continuous mode hydrological model with future climate data might be a way to ascertain this, but even then, without fully knowing how, and how quickly indigenous vegetation and crops might evolve, the average effect of climate change on soil moisture is speculative at best. Instead, the hydraulic–hydrologic simulator was run for dry and humid soil conditions so as to leave the reader with a feel for the importance of this hydrologic variable and to evaluate to what extent drier soil conditions might counteract or not the higher extreme rainfall events.

Finally, as in the Whetton *et al*. (1993) study on the impacts of climate change on floods and droughts in Australia, the results presented in this paper should not be taken as an absolute quantitative forecast of the future hydrological response of the Châteauguay River Basin, but rather as an indicative study on the impacts of climate change on the hydrology of a basin, and to outline the potential significance of these impacts.

As mentioned previously, maximum discharge and flooding on the Châteauguay River is usually associated with snowmelt and ice-jams during the spring season. The results presented in this paper cover the summer and fall period. Results indicate that under a future climate, water discharges in the summer–fall periods could exceed the maximum flow discharge currently observed during the spring snowmelt period, which is the present most critical period. How the basin will react during the spring snowmelt period in the event of climate change is a more complex problem. GCMs predict that the temperature increase during winter months will be above the annual average and that precipitation will be lower. This should indicate less snow and a possible reduction in ice-jam events. In order to run climate change scenarios for winter months, a more complex approach including various tools such as snowfall, snowpack and river ice models would be needed. These are left for future work.

CONCLUSION

This paper presents a study of the summer–fall hydrological response of a southern Quebec river basin in the advent of a future climate change. Climate change scenarios were constructed from results of a GCM and fed into a hydraulic–hydrologic simulator in order to evaluate the future hydrological risk. Results show a very significant increase in the hydrological risk that becomes even more worrying as the rainfall return period is increased. The increase in the hydrological risk for extreme events is a lot more critical than the increase of climate mean parameters. Despite the limitations linked to the climate change scenarios, the results strongly suggest that watershed planners and decision makers ought to start immediately taking into account the potential impacts of climate change in the decision-making process. This would be particularly important for decisions linked to floodplain construction and development as well as for the design and construction of any water-regulating hydraulic structures.

ACKNOWLEDGEMENTS

This work was funded through a Fonds Concerté d'Aide à la Recherche (FCAR) Collaborative Grant (subvention FCAR-équipe 98ER2856).

REFERENCES

Arora VK, Boer GJ. 2000. The effects of simulated climate change on the hydrology of major river basins. *Journal of Geophysical Research*, In press.

ASAE 1982. *Hydrologic Modeling of Small Watershed*. ASAE Monograph number No. 5, Haan CT (ed.). American Society of Agricultural Engineers: St-Joseph, MI; 533 pp.

Awadallah AG, Rousselle J, Leconte R. 1999. Évolution du risque hydrologique sur la rivière Châteauguay. *Canadian Journal of Civil Engineering* 26(4): 510–523.

Boer GJ, Flato GM, Reader MC, Ramsden D. In press a. A transient climate change simulation with greenhouse gas and aerosol forcing: experimental design and comparison with the instrumental record for the 20th century. *Climate Dynamics*.

Boer GJ, Flato GM, Ramsden D. In press b. A transient climate change simulation with greenhouse gas and aerosol forcing: projected climate to the 21st century. *Climate Dynamics*.

Bouillon M-C, Brissette FP, Marche C. 1999. Risque d'inondation et son évolution sur la rivière Châteauguay. *Canadian Journal of Civil Engineering* **26**(2): 186–196.

Brissette FP, Leconte R, Marche C, Rousselle J. 1998. Integrated system for short term flood forecasting on the Châteauguay River. *First International Conference on New Information Technologies for Decision Making in Civil Engineering*, Montréal, October 11–13; 887–896.

Caya D, Laprise R, Giguère M, Bergeron G, Blanchet JP, Stocks BJ, Boer GJ, McFarlane NA. 1995. Description of the Canadian Regional Climate Model. *Water, Air and Soil Pollution* **82**: 477–482.

Chiew FHS, Whetton PH, McMahon TA, Pittock AB. 1995. *Journal of Hydrology* **167**: 121–147.

Cohen SJ (ed.). 1997. Mackenzie Basin Impact Study (MBIS)—Executive Summary. Environment Canada and University of British Columbia, Vancouver.

Croley TE. 1990. Laurentian Great Lakes double-CO_2 climate change hydrological impacts. *Climatic Change* **17**: 27–47.

Environment Canada. 1997. *Canada Country Study: Climate Impacts and Adaptation, Vol. V, Responding to Global Climate Change in Quebec*. Environment Canada: Ottawa.

Etkin D. 1998. Climate change and extreme events: Canada. In *Canada Country Study: Climate Impacts and Adaptation, Vol. VIII, National Cross-Cutting Issues*. Environment Canada: Ottawa; 35–82.

Flato GM, Boer GJ, Lee WG, McFarlane NA, Ramsden D, Reader MC, Weaver AJ. Submitted. The Canadian Centre for Climate Modeling and Analysis Global Coupled Model and its climate. *Climate Dynamics*.

Fowler AM, Hennessy KJ. 1995. Potential impacts of global warming on the frequency and magnitude of heavy precipitation. *Natural Hazards* **11**: 283–303.

Fread DL. 1984. *Dambreak Model*. Office of Hydrology, National Weather Service: Silverspring, MD.

Galarneau M, Leconte R, Brissette FP, Rousselle J, Pultz TJ. In press. Utilisation of Radarsat in integrated watershed management. In *Remote Sensing and Hydrology 2000*, International Association of Hydrological Sciences (IAHS) Red Book.

HEC. 1990. *HEC-1, Flood Hydrograph Package User's Manual, Computer Program Document-1A*. US Army Corps of Engineers: Davis, CA; 282 pp.

Hofmann N, Mortsch L, Donner S, Duncan K, Kreutzwiser R, Kulshreshtha S, Piggot A, Schellenberg S, Schertzer B, Slivitzky M. 1998. Climate change and variability: impacts on Canadian water. In *Canada Country Study: Climate Impacts and Adaptation, Vol. VII, National Sectoral Volume*. Environment Canada: Ottawa; 1–127.

Kahrin VV, Zwiers FW. In press. Changes in the extremes in an ensemble of transient climate simulation with a coupled atmosphere–ocean GCM. *Journal of Climate*.

Kite GW. 1993. Application of a land class hydrological model to climatic change. *Water Resources Research* **29**(7): 2377–2384.

Knox JC. 1993. Large increases in flood magnitude in response to modest changes in climate. *Nature* **361**: 430–432.

Koshida G, Avis W. 1998. *Canada Country Study: Climate Impacts and Adaptation, Vol. VII, National Sectoral Volume*. Environment Canada: Ottawa.

Lavallée D, Roy L, Marche C. 2000. Un système de prévision appliqué aux crues subites de la rivière Châteauguay. Technical Note. *Canadian Journal of Civil Engineering* **27**: 1311–1315.

Morin G, Slivitzky M. 1992. Impacts de changements climatiques sur le régime hydrologique de la rivière Moisie. *Revue des Sciences de l'eau* **5**(2): 179–195.

Singh P, Kumar N. 1997. Impact assessment of climate change on the hydrological response of a snow and glacier melt runoff dominated Himalayan river. *Journal of Hydrology* **193**: 316–350.

Watt WE (ed.). 1990. *Hydrology of Floods in Canada, A Guide to Planning and Design*. National Research Council Canada and Associate Committee on Hydrology: Ottawa; 277 pp.

Whetton PH, Fowler AM, Haylock MR, Pittock AB. 1993. Implications of climate change due to the enhanced greenhouse effect on floods and droughts in Australia. *Climatic Change* **25**: 289–317.

Wogg WD. 1980. Time distribution of short duration storm rainfall in Canada. In *Proceedings of the Canadian Hydrology Symposium 1980*. National Research Council Canada: Ottawa; 53–63.

