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Adaptation to Climate Change in the Management of a Canadian Water-Resources System Exploited for Hydropower

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Abstract The management adaptation potential of the Peribonka River water resource system (Quebec, Canada) is investigated in the context of the evolution of climate change. The objective of this study is to evaluate the impacts on hydropower, power plant efficiency, unproductive spills and reservoir reliability due to changes in the hydrological regimes. The climate change projections used here are from the Canadian regional climate model (CRCM) nested by the Canadian-coupled global climate model (CGCM3) forced with the SRES A2 greenhouse gas emission scenario. The hydrological regimes were simulated with the distributed hydrological model Hydrotel. They were incorporated into a dynamic and stochastic optimization model in order to adapt the operating rules of the water resource system annually, according to the evolution of the climate. The impacts were analyzed over the years 1961–2099, split into four periods for comparison purposes: control period (1961–1990), horizon 2020 (2010–2039), horizon 2050 (2040–2069) and horizon 2080 (2070–2099). The main results indicate that annual mean hydropower would decrease by 1.8% for the period 2010–2039 and then increase by 9.3% and 18.3% during the periods 2040–2069 and 2070–2099, respectively. The trend to increase is statistically

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significant starting from 2061 (Mann–Kendall with $p = 5\%$). The change in the mean annual production is statistically significant for the 2040–2069 and 2070–2099 periods (t-test with $p = 5\%$). Also, the change in the variance is significant for the periods 2010–2039, 2040–2069 and 2070–2099 (F-test). Annual mean unproductive spills would increase from 1961–2099, but the trend is not statistically significant. However, the changes in the variance of the annual mean spills are significant in the periods 2010–2039, 2040–2069 and 2070–2099. Overall, the reliability of a reservoir would decrease and the vulnerability increase as the climate changes.

Keywords Climate change · Adaptation · Water resource system · Hydrology · Regional climate model

1 Introduction

The Intergovernmental Panel on Climate Change (IPCC 2007) recognizes that climate change will exacerbate the current stress on water resources. The consequences will include modifications in flow seasonality and hydropower. The changes in temperatures and precipitations will thus have impacts on the runoff, which will increase by 10% to 40% from 2050 in the high latitudes, and decrease by 10% to 30% in the mid-latitudes (IPCC 2007). The beneficial impacts of the increases in runoff in some regions will be moderated by some negative effects, such as changes in the variability and seasonality.

The managers of water resource systems must develop policies to mitigate the effects of the anticipated climate fluctuations. Trends have been identified in hydroclimatic variable observations over the last decades in North America. Kalra et al. (2007) carried out several statistical tests to detect the trends and the changes in the streamflows and the snow water equivalent in the United States for the period 1951–2002. Their results indicate that there is a gradual trend towards an increase in the flows in the northeast and the eastern United States. Moreover, significant changes in annual and spring mean flows were detected in the Great Lakes area. However, no significant trend or change in the snow water equivalent was observed. Regonda et al. (2005) and Whitfield and Cannon (2000) analyzed the recent hydrological trends in the United States and Canada, respectively. They concluded that several rivers have presented an early spring flood and higher winter flows.

Consequently, changes in the hydrological regimes will have effects on the storage and management of reservoirs (Christensen et al. 2004). The IPPC (Kundzewicz et al. 2007) supports the view that changes in the hydrological regimes will have both positive and negative impacts. They specify that "*current water management practices are very likely to be inadequate to reduce the negative impacts of climate change on water supply reliability, flood risk, health, energy, and aquatic ecosystems*". The expected modifications in the climatic variables, such as precipitations and temperatures, will have impacts on the hydrological regimes, which will affect the management of water resource systems.

Many studies have been published recently on the impacts of climate change on hydrological regimes. In general, these works incorporate one or more climate change projections into a hydrological model. Few studies have investigated the impacts of climate change on the management of water resource systems.

Markoff and Cullen (2008) evaluated the impacts of hydrological regime changes on hydropower at the installations of the Pacific Northwest Power and Conservation Council in the United States. The main result of their study is that hydropower would decrease for the majority of climatic projections. However, they qualify their results as pessimistic, because their reservoir simulation model does not use optimized operating rules under the new hydrological conditions. It was a study that did not simulate management adapted to climate changes.

However, among those few studies that did consider the impacts on management, Payne et al. (2004), Christensen et al. (2004) and VanRheenen et al. (2004) realized, within the framework of companion papers, studies that make use of a similar methodology. Their objective was to evaluate the impacts of climate change on the management of three water resource systems intended for multiple uses in Canada and the United-States. These authors did not consider the adaptive character of the management of a water resource system and so they applied the current reservoir operating rules to the simulations with future hydrological inflows. They evaluated the impacts on the annual average hydropower, the fish target and unproductive spills, in particular. Payne et al. (2004) proposed a first-adaptation study to counter the decrease in management performance in the context of climate change. They carried out a sensitivity analysis of reservoir filling dates, energy demand and summer reservoir minimum levels, and found that adaptation could increase management performance.

The aim of this work is to evaluate the impacts of and management's adaptation to the projected climate change over 2010–2099 for a Canadian water resource system, here the Peribonka River (Quebec, Canada), a system exploited for hydropower. The study was carried out with annual adaptations to the reservoir management. A dynamic and stochastic optimization model (Turgeon 2005) was used. This model pre-calculates the weekly operating rules according to the flows given by a hydrological model and the levels of the reservoirs which compose the water resource system. These operating rules are then used with a reservoir simulation model that simulates the operations. The adaptation of the water resource system management is analyzed according to the trajectories of the reservoirs' levels, hydropower, power plant efficiency and unproductive spills. The evolution of these variables over the period is analyzed in order to detect statistically significant trends. Also, the means and variances of the indicators at the future periods 2010–2039, 2040–2069, and 2070–2099 are compared with the indicators of the control period 1961–1990 in order to detect the statistically significant changes.

The article first describes the study area. Then, the data used and the methodology followed are presented. In the third section, the results obtained for the climatic data, hydrological regimes and indicators of water resource management are described and discussed, followed by the main conclusions and recommendations.

2 Study Area

The Peribonka River watershed (Fig. 1) is located in the southern center of the province of Quebec, Canada. The water is exploited exclusively for hydropower by Rio Tinto Alcan, with an installed capacity of 1,165 MW. Power plants deliver energy to the company's various aluminum smelting facilities. Two large reservoirs

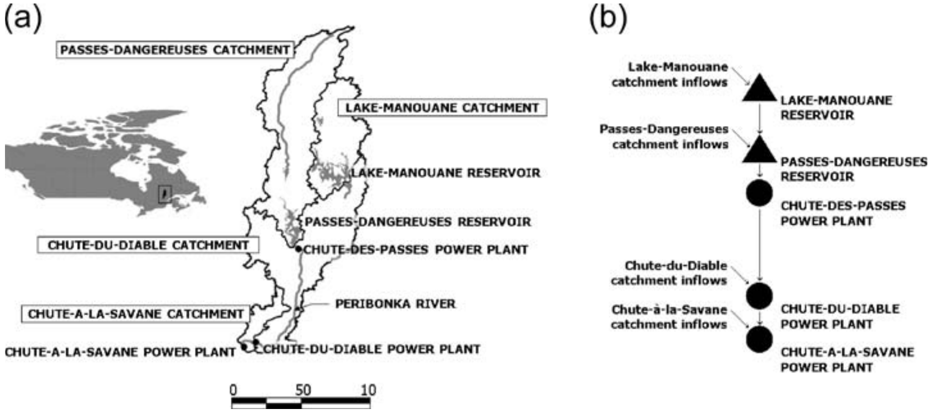

Fig. 1 **a** Peribonka River watershed and its components. **b** Water resource system scheme

store water (Lake-Manouane—2,700 hm^3 and Passes-Dangereuses—5,200 hm^3) and they feed three power plants (Chute-des-Passes, Chute-du-Diable and Chute-a-la-Savane), laid out in series on the Peribonka River. The Chute-des-Passes power plant is adjacent to the Passes-Dangereuses reservoir. The Chute-du-Diable and Chute-a-la-Savane power plants are classified as run-of-river, even though they have small reservoirs. 'Run-of-river' indicates that a power plant is supplied directly by a waterway and has virtually no reserves. Its power therefore varies depending on the flow of the waterway.

The Peribonka River watershed (27,000 km^2) is subdivided into four principal subbasins, from upstream towards downstream: Lake-Manouane (5,000 km^2), Passes-Dangereuses (11,000 km^2), Chute-du-Diable (9,700 km^2) and Chute-a-la-Savane (1,300 km^2). The watershed is mainly comprised of uninhabited boreal forest.

This region's climate is moderate, with an annual mean temperature of −0.5°C and annual mean precipitations of 1,010 mm, with 40% falling as snow (according to the records for 1953–2003). The freezing period, when the mean daily temperatures are lower than 0°C, spreads over 6 months between November and April. The annual mean flow of the Peribonka river is 635 m^3/s. Spring mean flows (AMJ—April, May and June) account for 43% of the annual mean flow, whereas the winter inflows (DJFM—December, January, February, March) account for 10% and those of summer–autumn (JASON—July, August, September, October and November) for 47%. All of the data were provided by Rio Tinto Alcan's Water Resource Group in Saguenay, Canada.

The watershed is located in the mid-latitudes and its hydrological regime is dominated by snow accumulation and snow melt. The management of the water resource system is related to the hydrological context at three distinct periods: winter, spring and summer–autumn. The hydrological year begins with the winter, when the mean temperatures are below the freezing point. Snow accumulates on the ground and does not contribute to the runoff. Some rainy events and raised-temperature episodes can occur, however, and contribute to increasing the base flow. Nevertheless, inflows to the reservoirs remain weak in general for this period. The level of the Passes-Dangereuses reservoir is held very close to its exploitation level so that the adjacent power plant benefits from a bigger water head. The Passes-

Dangereuses reservoir level must be sufficiently lowered at the end of winter in order to store the spring flood and thus minimize spills. In spring, the temperatures rise above the freezing point and there is snowmelt. The fluctuations of flows during the summer–autumn season are caused by rainy events. The Passes-Dangereuses reservoir is managed to prevent flooding while maximizing the water head of the adjacent power plant. Since there is no power plant at Lake-Manouane, this reservoir is only used as a water reserve to fill the Passes-Dangereuses reservoir.

3 Data and Methods

The methodology followed to perform this work can be summarized in four parts:

1. Climate change projection preparation and bias-correction
2. Simulation of the hydrological regimes
3. Generation of the operating rules of the water resource system
4. Simulation of the water resource system operations

The trends in the hydroclimatic variables and in the management indicators are analyzed using the Mann–Kendall test (Kendall 1975; Mann 1945). This test is widely used in hydrology to detect trends in hydroclimatic variables (Hamed 2008).The statistically significant changes in means and variances between the future periods 2010–2039, 2040–2069 and 2070–2099, and the control period 1961–1990 are identified with the *t*-test and the *F*-test, respectively. These statistical tests assume that data follows a Gaussian distribution. While more than 95% of the cases considered here can be considered Gaussian, applying a parametric test to every case is more robust. These tests are commonly used for hydrometeorological data (Hayhoe et al. 2007; Maurer 2007; Semenov et al. 1998), among others.

3.1 Climate Change Projection and Bias-Correction

3.1.1 Downscaling

Climate data from a Regional climate model (RCM) were used within the framework of this study. An interesting aspect of this method is that it simulates the climatic system at a finer resolution than General circulation models (GCMs)—up to 50 times higher. The high resolution of the RCM allows the regional climatic variables to be represented in much more detail. In comparison, CGMs are simulators of the climatic system and solve the equations of physics and thermodynamics on a grid with a resolution of approximately 350 km. However, one disadvantage is that RCMs are nested into GCMs that specify lateral and lower boundary conditions. Olesen et al. (2007) demonstrated that the variation in simulated impacts was smaller between scenarios based on RCMs nested within the same GCM than between scenarios based on different GCMs or between emission scenarios. Also, compared to large-scale projections, which are widely diffused for many CGMs and greenhouse gas emission scenarios (GHGES), RCM projections are not widely diffused or readily accessible to hydrologists for North American studies. Their application in multi-scenario impact studies has thus been limited. Many initiatives, like the North American Regional Climate Change Assessment Program and Inter-Continental

Transferability Study, are in the process of producing a bank of regional climate change projections over North America.

Among the many other downscaling methods reported in a comprehensive review in Fowler et al. (2007), Markoff and Cullen (2008) and Minville et al. (2008) used the delta change approach to carry out impact studies on water resource management with about thirty climatic projections. Studies that use many projections can investigate a broad range of potential impacts. Multi-scenario impact studies are more common with these approaches, because they have the advantage, compared to dynamic downscaling, of requiring less computer resources, and they produce a broader range of climatic scenarios (Salathé et al. 2007). The delta change approach assumes that climate is stationary over a certain period (usually 30 years), and does not allow the evolution of hydrological and management impacts to be evaluated. The use of a transient scenario from an RCM is advantageous used in an impact study for adaptive management of water resources.

3.1.2 Climate Data Grids

The climatic projection used within the framework of this study comes from the Canadian regional climate model (CRCM) (Caya and Laprise 1999; Plummer et al. 2006). The boundary conditions are prescribed by the Canadian general circulation model (CGCM3) (McFarlane et al. 1992) with the SRES A2 greenhouse gas emission scenario (GHGES) (Nakicenovic et al. 2000). The climatic data were available at the daily time step over the period 1961 to 2099, on a grid of approximately 50 km of resolution. A total of 30 grid points on and near the Peribonka River watershed were used.

The CRCM climate data for the control period were compared with the climate observed for the same period. A 10-km resolution observation grid was used, interpolated by kriging. The interpolations were carried out with data from twenty weather stations located on and close to the watershed. The comparison between CRCM and observation data was performed with the observation mean on the CRCM equivalent tile, with the expectation of equivalent comparison.

3.1.3 Climate Variables Bias

An analysis of the monthly precipitations and temperature means of the control period 1961–1990 of the CRCM showed that they presented a bias compared to the observations.

The monthly minimum temperatures of the CRCM, compared to the observations, are underestimated every month, up to a maximum of 6°C in April. The maximum temperatures are underestimated in the summer–autumn, by up to 4°C in August. Also, precipitations are over-estimated in spring and in summer–autumn, by up to 25% in June. In winter, the precipitations are underestimated by up to 18% in December.

Bias-correction of temperatures and precipitations, as well as of frequencies of precipitations, were performed to adjust the control period and future simulated data with the observations at the control period. This method assumes that the relative bias in climate model simulations will be the same in the future as it is for the current climate.

3.1.4 Bias Correction of Temperatures

A bias-correction of the monthly means was carried out for the temperatures of the CRCM. Each grid point of the CRCM was compared with the observations. The monthly mean temperatures of the CRCM and the observations for the control period were calculated. The difference between the monthly mean of the observed temperatures and the monthly mean of the simulated temperatures for the control period 1961–1990 was applied to the daily data of the CRCM 1961–2099. This technique ensures that the temperatures of the CRCM over the period 1961–1990, bias corrected at each grid point, have the same monthly means as the observed temperatures. The bias correction was performed for minimum and maximum temperatures. A similar bias correction method was published by Fowler et al. (2007), Fowler and Kilsby (2007) and Wood et al. (2004).

3.1.5 Bias Correction of Precipitation

The precipitation data were corrected for the monthly mean frequencies and the monthly mean intensities with the Local Intensity (LOCI) method, adapted from Schmidli et al. (2006). With this approach, the adjusted monthly precipitations of the CRCM have the same frequencies and the same monthly mean intensity as the observed precipitation for the control period 1961–1990.

The monthly frequency is the ratio of the number of rainy days exceeding a threshold during 1 month to the number of days in the month. The monthly intensity is the daily mean precipitation for 1 month. The adjustment was carried out initially by comparing each tile of the CRCM with the equivalent tile of the observations. This method then requires a monthly threshold to be calculated, which allows the monthly frequencies of rainy days of the CRCM for the control period 1961–1990 to be adjusted at the same frequency as the observations. Next, a monthly factor is calculated to equalize the means of the CRCM's monthly precipitations for the control period 1961–1990 with the means of the monthly precipitations of the observations. Lastly, the monthly thresholds and factors, which allow adjustment of the precipitations for the control period, are used to adjust precipitations in the 1990–2099 period.

3.2 Hydrological Simulations

Hydrological simulations were carried out with the physically-based distributed model Hydrotel (Fortin et al. 2001). It is used operationally by the Centre d'expertise hydrique du Québec (CEHQ) for forecasting the flows of hydraulic works managed by the government of the province of Quebec, Canada.

Hydrotel is a distributed model which integrates five sub-models: accumulation and melt of snowpack, potential evapotranspiration, vertical water budget, flow on the sub-watershed, and channel flow. Various options are offered to the user for the simulation of each of these hydrological processes. The hydrological processes were simulated with the options compiled in Table 1.

The calibration and validation results of the Hydrotel hydrological model for the four subbasins are synthesized in Table 2. The differences in flows and peak dates, as well as in annual volume, are presented distinctly for the calibration and validation periods. A negative value must be interpreted as an undervaluation of the model

Table 1 Models used for the simulation of the hydrological processes in Hydrotel

Sub-model	Options
Accumulation and melt of snowpack	Mixed approach: degree days and energy budget (Turcotte et al. 2007)
Potential evapotranspiration	Hydro-Québec (Fortin et al. 2001)
Vertical water budget	BV3C (Fortin et al. 2001)
Flow on subwatershed	Kinematic wave equation
Channel flow	Kinematic wave equation

compared to the observations. Also, the Nash and Sutcliff (1970) criteria quantify the model performance to reproduce the observed flows.

The flows were simulated with the grid of climatic variables of the bias-corrected CRCM climate projection over the period 1961–2099.

3.3 Optimization of the Operating Rules

There are several ways to calculate the operating rules of a water resource system. Labadie (2004) draws up the state of the art of the methods. The stochastic and dynamic programming approach (Turgeon 2005) allows the calculation of operating rules that maximize the hope for future profits. In a water resource system, the profit function is the production minus the costs of the violations of constraints. This approach is used when a water resource system requires the introduction of a restricted number of state variables, which is the case for the Peribonka River system. Two state variables describe the two reservoirs (Lake-Manouane and Passes-Dangereuses). The other reservoirs are not modelled, given their small storage capacities. The flow times between the two reservoirs and between Passes-Dangereuses and Chute-a-la-Savane are less than one week, so the problem of management is decomposable in a succession of one-week duration management problems. The operating rules are the weekly outflows from the two reservoirs, according to the week of the year, the initial levels of these two reservoirs at the beginning of the week and the flows during the week. The reservoirs' inflows are assumed to be perfectly correlated during the same week.

Weekly operating rules of the two reservoirs are generated for each year of the period 1990–2099, for a total of 110 weekly operating rules. During this period, the annual mean flows of 1990–2099 present an upward trend but respect the assumption of stationarity on 35-year mobile periods (Mann–Kendall test). For each year, the weekly operating rules were produced while using only the flows of the 35 previous years in the history of the flows, i.e. using a 35-year moving window approach.

Table 2 Calibration and validation results of the hydrological model Hydrotel

Basins	Nash-Sutcliffe coefficient		Peak flow (%)	Time of peak flow (day)	Annual volume (%)
	Calibration (1980–1985)	Validation (1986–2003)			
Chute-a-la-Savane	0.70	0.66	−11	0	−2
Chute-du-Diable	0.85	0.78	−18	+5	0
Lac-Manouane	0.54	0.47	−10	+2	−14
Passes-Dangereuses	0.76	0.69	−8	0	−5

3.4 Simulations of the Water-Resources System

The reservoirs' operations were simulated for a weekly time step with a model specifically programmed for the needs of the study, in which the characteristics of the spillways and power plants are introduced. The model calls the operating rules generated by the optimization model to simulate the operations of the water resource system, subjected to a series of weekly hydrological flows. The operations' simulation model retains the levels of the reservoirs, the hydropower and the unproductive spills for each time step.

The simulations of the operations with the climate change projection were not compared with the observed operations, but instead, compared with the operations simulated at the control period. This strategy allows any bias from the hydrological model to the inflows to be eliminated. However, it should be mentioned, as an indication, that the simulation model reproduced the observed annual average production with an over-estimate of 1.5%. The operation records used for this comparison comprised 15 years of available data.

4 Results and Discussion

The trends in the climate projection variables and the hydrological and management indicators were analyzed. The Mann–Kendall statistical test was performed to detect the year of a regime change.

The changes in means and variances were also analyzed with the statistical t-test and F-test, respectively, after checking for the assumption of normality. The t-test was carried out by fixing the probability at 5%, so that the null assumption (the means do not differ) is rejected where this is true. The changes are studied for the future periods 2010–2039, 2040–2069 and 2070–2099, compared to the control period of 1961–1990.

4.1 Climate Change Projections

Figure 2 shows the annual and seasonal evolution of minimum (lower line) and maximum (higher line) temperatures in the watershed. The bold black lines represent the mean minimum and maximum temperatures over the basin. The envelope marks the spread of the temperatures at each point of the CRCM: the higher temperatures are representative of the area in the south of the basin and the lower temperatures of the northern area.

The minimum and maximum temperatures are not stationary over the period 1961–2099 on annual and seasonal scales. The temperatures increase gradually over this period. On an annual and seasonal scale, the changes of means and variances of the minimum and maximum temperatures are statistically significant (t-test) at the periods 2010–2039, 2040–2069 and 2070–2099, compared to 1961–1990.

Figure 3 illustrates the annual and seasonal evolution of mean precipitations for the period 1961–2099. The general trend is an increase in annual and seasonal mean precipitations. However, the rate of increase in winter precipitations is greater than for spring and summer–autumn.

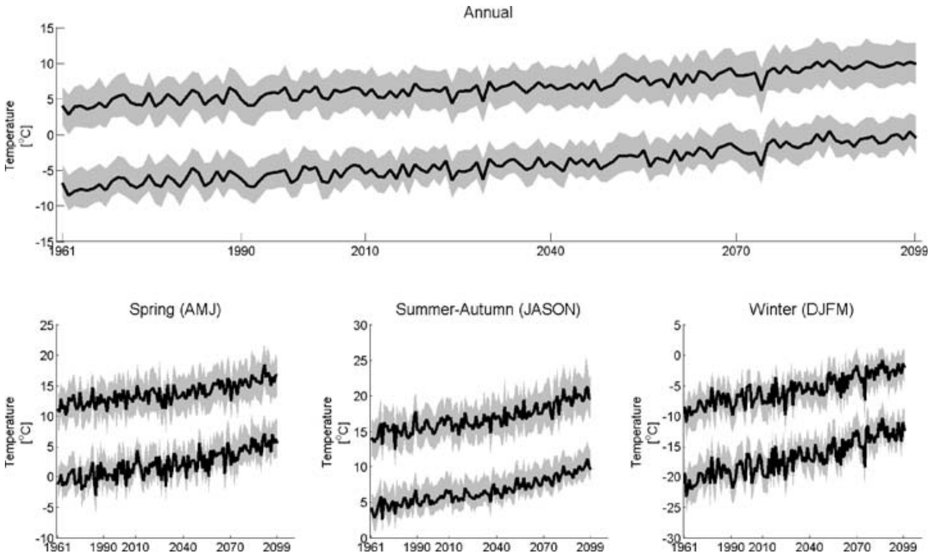

Fig. 2 Annual and seasonal temperature (minimum and maximum) over the 1961–2099 period

The change in the shade of gray of the line on Fig. 3 shows the year of the beginning of a trend detected with the Mann–Kendall test. The light gray line indicates a downward and the dark gray line an upward trend. Annual mean precipitations respect the assumption of stationarity up to 2045. After this date, the annual mean precipitations trend is statistically significant. Seasonal mean precipitations respect

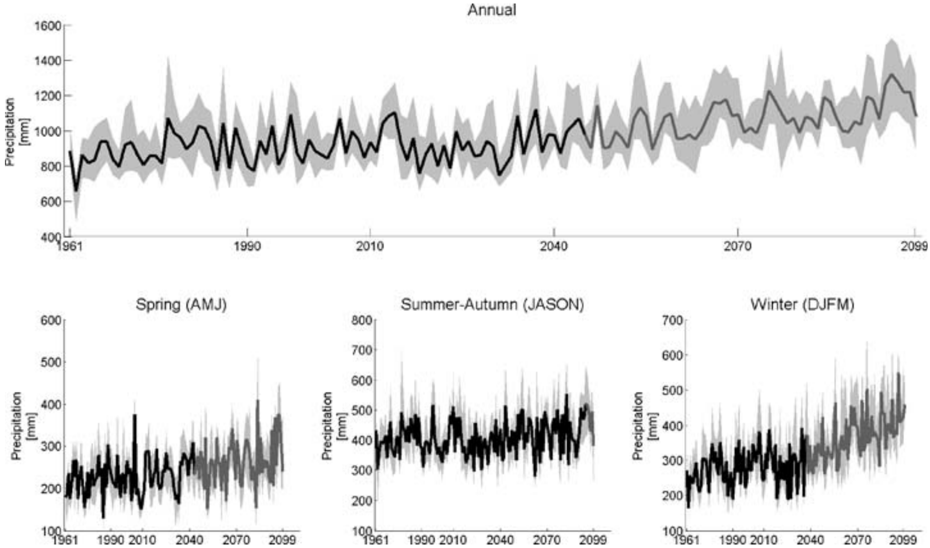

Fig. 3 Annual and seasonal precipitations over the 1961–2099 period. The *black line* indicates a stationary regime, the *light gray line* a downward and the *dark gray line* an upward trend

Table 3 Annual and seasonal mean and standard deviation of precipitations

	Mean (standard deviation) (mm)			
	Annual	Spring (AMJ)	Summer–autumn (JASON)	Winter (DJFM)
1961–1990	892 (103)	221 (45)	405 (57)	264 (49)
2010–2039	917 (109)	**235 (45)**	**391** (62)	**289 (63)**
2040–2069	**1,015** (102)	**256 (52)**	414 **(72)**	**344 (65)**
2070–2099	**1,107** (112)	**273 (65)**	**436 (74)**	**396 (67)**

Bold values indicate a statistically significant change compared to the control period

the assumption of stationarity until 2043, 2094, and 2037 in spring, summer–autumn, and winter, respectively. The increase in precipitation trends after these dates are significant.

Table 3 compiles the means and the standard deviations (between brackets) of annual and seasonal mean precipitations at each period. The statistically significant changes are in bold.

Changes in annual mean precipitations are statistically significant at the 2040–2069 and 2070–2099 periods, compared to 1961–1990. The tests show also a change in variance at the 2010–2039, 2040–2069 and 2070–2099 periods.

4.2 Hydrological Impacts

Figure 4 shows the mean annual hydrograph of the control period 1961–1990, compared to the future periods 2010–2039, 2040–2069 and 2070–2099, for each subbasin.

The same general trends are observed at each subbasin: early spring floods, flows decrease in summer–autumn and increase in winter. The spring flood is earlier by

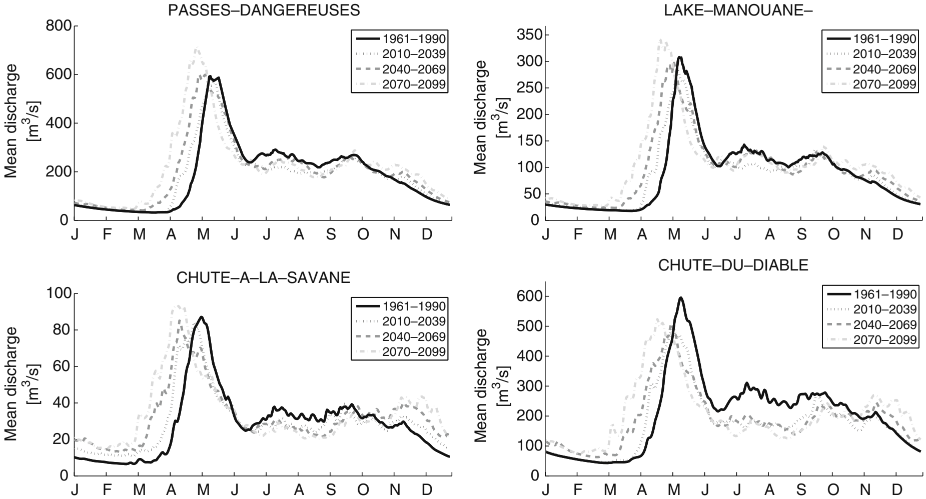

Fig. 4 Mean annual hydrographs for future periods 2010–2039, 2040–2069 and 2070–2099, compared with the control period 1961–1990 in *bold black line*, for the four subbasins

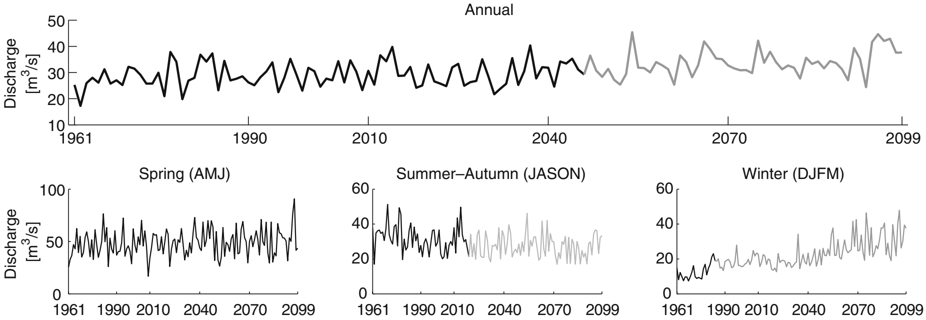

Fig. 5 Annual and seasonal mean discharge at the Chute-a-la-Savane watershed, for the period 1961–2099. The *black line* indicates a stationary regime, the *light gray line* a decreasing trend and the *dark gray line* an increasing trend

a mean of 10 days in the period 2010–2039, 20 days in 2040–2069 and 30 days in 2070–2099. Moreover, the mean spring flood peaks for the 2010–2039 and 2040–2069 periods at each subbasin are lower compared to the control period 1961–1990. These peaks are higher in 2070–2099 at all but the Chute-du-Diable subbasin. Differences in the trends are also noticed between the basins in the north (Passes-Dangereuses and Lake-Manouane) and the basins more to the south (Chute-du-Diable and Chute-a-la-Savane), where the spring flood is generally earlier and of smaller amplitude. Moreover, the winter flows increase more for the southern basins than for the northern basins.

Figures 5 and 6 illustrate the evolution of the annual mean flows of two principal subbasins of the Peribonka River watershed between 1961 and 2099: Chute-a-

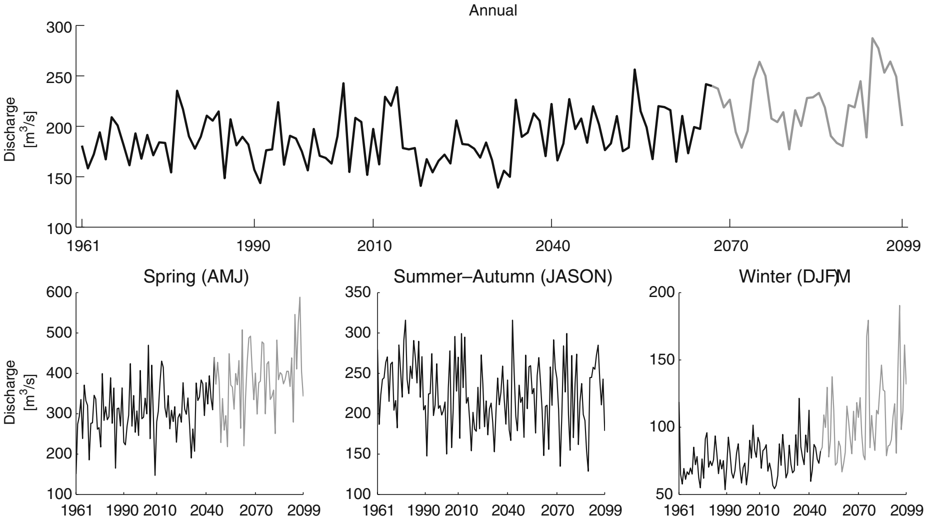

Fig. 6 Annual and seasonal mean discharge at the Passes-Dangereuses watershed, for the period 1961–2099. The *black line* indicates a stationary regime, the *light gray line* a decreasing trend and the *dark gray line* an increasing trend

la-Savane (located in the south) and Passes-Dangereuses (located in the north). These subbasins are selected in order to highlight the north–south cleavage in the hydrological impacts of climate change. The line changes its colour or shade where a trend is detected (Mann–Kendall test) in the hydrological regimes: black is for stationary, statistically significant trends are in gray (an increasing trend in light gray and a decreasing trend in dark gray).

The comparison of the annual mean flows of the two subbasins makes it clear that the southern region is influenced earlier by climate change. The upward trend is significant in 2047 with the Chute-a-la-Savane subbasin and in 2067 with Passes-Dangereuses. The annual mean flow for the Passes-Dangereuses watershed exhibits a decreasing trend until 2030; however, this trend is not statistically significant.

On a seasonal scale, the Chute-a-la-Savane subbasin presents different trends each season: the spring flows are stationary between 1961 and 2099, the flows in summer–autumn decrease with a significant trend from 2019, and the flows' increase is statistically significant in winter, starting in 1984. For the Passes-Dangereuses subbasin, only the winter season presents the same trend as Chute-a-la-Savane, with significant increases in the flows from 2047. The spring flows increase, and the trend is significant as of 2045. For summer–autumn, the trend is a decrease, but it is not statistically significant.

The differences in the regimes of the two subbasins occur for various reasons. Initially, the warmer temperatures in the south, combined with the increase in precipitations, make for an earlier increase in runoff in winter at the Chute-a-la-Savane subbasin compared to Passes-Dangereuses. Rain precipitations (instead of snow) are thus more frequent and the episodes of increases in temperature contribute to increasing the flows. The smaller increases in temperatures in the north do not create conditions favourable for the winter runoff. This situation also explains the differences in the regimes' spring flows. The increasing trend in the spring flows at the Passes-Dangereuses subbasin compared to the absence of a significant trend at Chute-a-la-Savane is explained by the fact that in winter, there is more snowpack on the ground.

The changes in the means and variances of the annual and seasonal mean flows were also investigated, and are presented in Table 4. The bold values indicate that the differences are statistically significant compared to the control period.

Table 4 Annual and seasonal mean and standard deviation of flows for the Chute-a-la-Savane and Passes-Dangereuses subbasins

		Mean (standard deviation) (m^3/s)			
		Annual	Spring (AMJ)	Summer–autumn (JASON)	Winter (DJFM)
Chute-à-la-Savane	1961–1990	28 (4.9)	46 (12)	34 (7.7)	13 (4.4)
	2010–2039	30 **(4.7)**	48**(10)**	**29 (7.9)**	19**(4.0)**
	2040–2069	**32 (4.4)**	49**(13)**	**29 (7.9)**	**25 (6.5)**
	2070–2099	**34 (4.8)**	52**(13)**	**26 (7.8)**	**31 (8.2)**
Passes-Dangereuses	1961–1990	186 (20)	291 (61)	246 (33)	73 (13)
	2010–2039	183 **(26)**	315**(56)**	**215 (37)**	**78 (16)**
	2040–2069	**204 (24)**	**364 (76)**	**224 (40)**	**92 (19)**
	2070–2099	**221 (30)**	**400 (76)**	**220 (46)**	**114 (31)**

Bold values indicate a statistically significant change compared to the control period

The changes of the annual mean flows at Chute-a-la-Savane and Passes-Dangereuses are statistically significant in the periods 2040–2069 and 2070–2099, compared to 1961–1990. The changes of variance are significant for each of the periods of the subbasins.

On a seasonal scale, the changes of mean are not statistically significant in any of the future periods at the Chute-a-la-Savane subbasin, as well as for the 2010–2039 period at Passes-Dangereuses. The changes are also not significant for summer–autumn. During winter, the changes of means are not significant for the Passes-Dangereuses subbasin in 2010–2039. However, the changes in variances are statistically significant on a seasonal scale for the two subbasins in all of the future periods.

The differences in the hydrological regime changes within the Peribonka watershed show the importance of the link between the change in precipitations and temperatures. An increase in temperatures in winter, over a certain threshold, can strongly influence snow hydrology. In summer, the hydrological impact of the increase in precipitations can be cancelled by an increase in temperatures, because of the consequent increases in evaporation and evapotranspiration (IPCC 2007).

4.3 Impacts and Adaptation of the Water Resource System

4.3.1 Reservoir Operating Rules

The change in the operating rules is initially analyzed for the weekly mean levels at the periods 2010–2039, 2040–2069 and 2070–2099, compared to 1961–1990. Figure 7 shows the mean levels of the Lake-Manouane and Passes-Dangereuses reservoirs at these periods. Two modifications arise in the management of the reservoirs: the shift in the timing of the low spring levels and the change in the mean levels at each season. These changes are accentuated the further the period is away from the control period 1961–1990.

For Lake-Manouane, the levels are higher in spring at all of the future periods. This increase is a direct consequence of the increase in the flows at this season. The levels in summer increase between July and November in 2040–2069 and 2070–2099. In 2070–2099, the reservoir levels decrease from June to November. These weak increases or decreases of the level in summer–autumn are the consequences of the

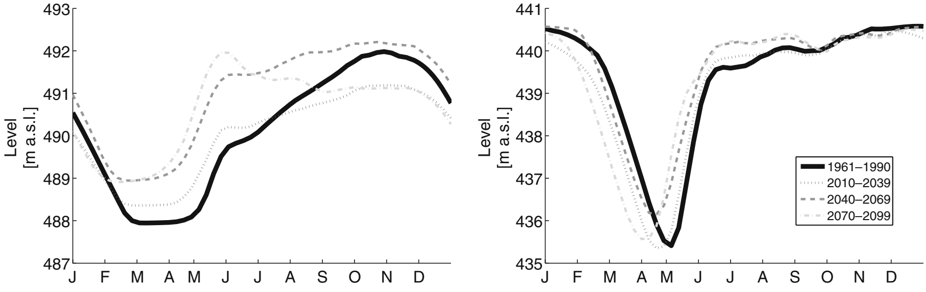

Fig. 7 Reservoirs' mean levels in periods 2010–2039, 2040–2069, and 2070–2099, compared to reservoir levels at the control period 1961–1990

decrease of the mean flows at this season. During winter, the reservoirs' levels are lower at the 2040–2069 and 2070–2099 periods than at the control period 1961–1990 because of the runoff increase at this season. The levels are maintained lower in order to avoid the violations of constraints that could result from exceeding the maximum level of exploitation.

The Passes-Dangereuses reservoir has the same trends as Lake-Manouane, except that the shift of the period of lowering in spring is more obvious. As a consequence of the shift in the beginning of the spring flood by 10, 20 and 30 days over the period 2010–2039, 2040–2069 and 2070–2099, respectively, the levels of the reservoirs are also shifted approximately for the same durations at each period. The operating rules in spring thus take into account the change in seasonal variation of the flows in the reservoirs. In summer–autumn, the levels are maintained higher because of the decrease of flows into the reservoirs. The flows being less significant at this season, the levels are maintained higher in order to maximize the water head at the power plant with the reservoir directly downstream. In winter, the levels are maintained higher in the future periods, in order to maximize the water head during the period of low flows because the accumulation of snow on the watershed.

4.3.2 Hydropower Production

Figure 8 shows the evolution of the annual mean hydropower, both overall and at each power plant, for the 1961–2099 period. The *y*-axis values are hidden to preserve the confidentiality of the owner of the water resource system.

The trend shows a reduction in the annual mean production for the run-of-river power plants (Chute-du-Diable and Chute-a-la-Savane) before 2030. For the power

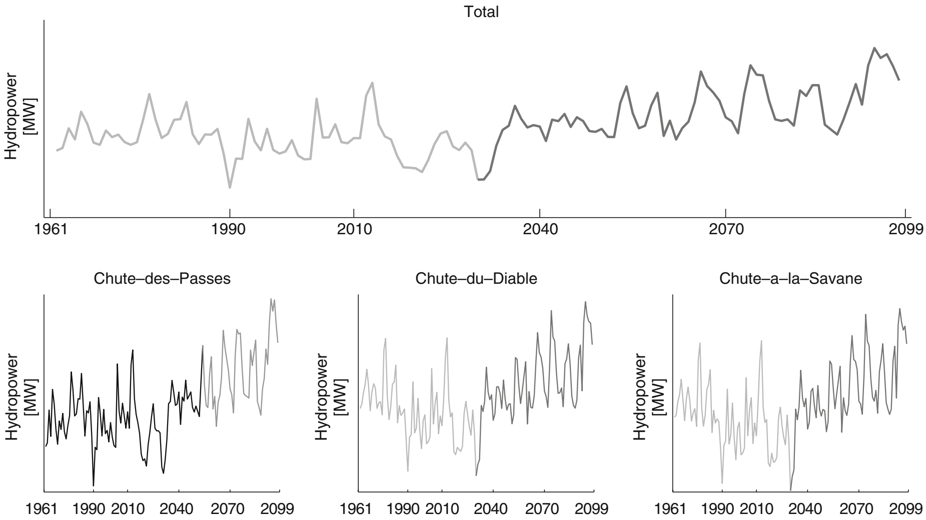

Fig. 8 Mean annual hydropower, for the entire system (Total) and at each power plant (Chute-des-Passes, Chute-du-Diable and Chute-à-la-Savane), for the 1961–2099 period. (The *y*-axis values are hidden to preserve the confidentiality of the water resource system owner.) The *black line* indicates a stationary regime, the *light gray line* a decreasing trend and the *dark gray line* an increasing trend

plant with a reservoir (Chute-des-Passes), the trend is an increase. This trend is statistically significant in 2054.

The reduction in the hydropower for the run-of-river power plants before 2030 is attributable to the decreasing flows in the Chute-du-Diable and Chute-a-la-Savane subbasins in summer–autumn, which is the high flow period because of rainy events. The increase in the production for the power plant with a reservoir, supplied by the Passes-Dangereuses and Lake-Manouane subbasins' inflows, is attributable to the absence of a significant trend of a flow decrease in summer–autumn, and the increase at the other seasons.

Figure 9 shows the seasonal hydropower for the power plant with a reservoir (Chute-des-Passes) and for the run-of-river power plants (Chute-du-Diable and Chute-a-la-Savane). The production at the run-of-river power plants has been summed, because the trends are similar given their geographical proximity.

The trend in the seasonal hydropower shows an increase each season for the Chute-des-Passes power plant. The increases in production are significant for this reservoir in spring, summer–autumn and winter, from 2054, 2058 and 2070 respectively. For the Chute-du-Diable and Chute-a-la-Savane power plants, the increases are significant at the same seasons, but from 2074, 2030 and 2050, respectively. However, a decreasing trend is predicted until 2030 for each season. This trend is significant in summer–autumn.

These results are in conformity with the trends of the seasonal mean flows. Indeed, Fig. 6 shows that the flows at the Passes-Dangereuses subbasin, representative of the northern portion of the watershed, did not present any decrease in the seasonal flows. The watersheds in the north feed the Chute-des-Passes power plant with a

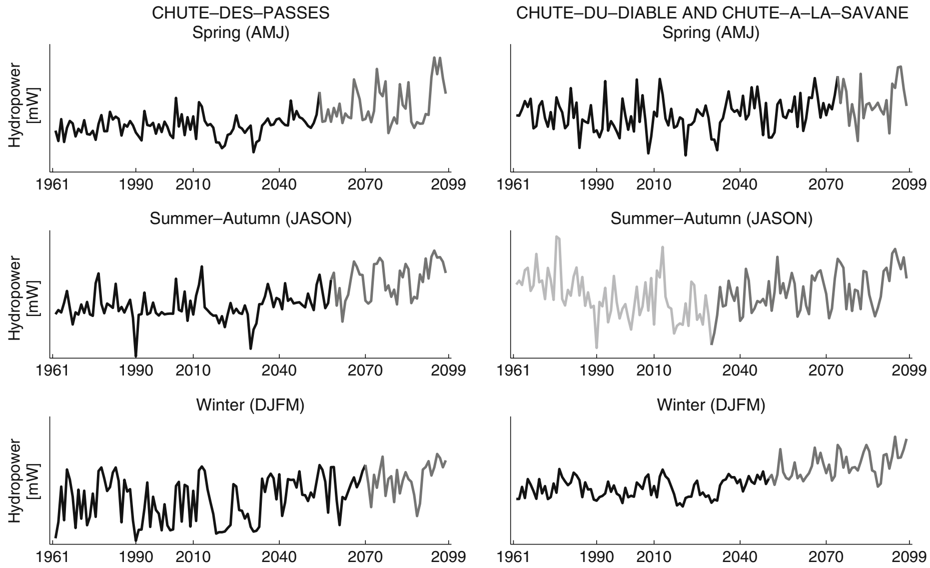

Fig. 9 Mean seasonal hydropower, for the Chute-des-Passes power plant and the Chute-du-Diable and Chute-à-la-Savane (summed), for the 1961–2099 period. The *y*-axis values are hidden to preserve the confidentiality of the water resource system's owner. The *black line* indicates a stationary regime, the *light gray line* a decreasing trend and the *dark gray line* an increasing trend

Table 5 Change in mean and standard deviations of hydropower, on an annual and seasonal basis

		Mean (standard deviation) (% of the 1961–1990 period)			
		Annual	Spring (AMJ)	Summer–autumn (JASON)	Winter (DJFM)
Total	2010–2039	98.2 (**127.4**)	98.4 (**147.0**)	99.3 (**106.1**)	97.0 (**101.6**)
	2040–2069	**109.3** (**100.3**)	115.2 (**147.9**)	109.9 (**103.3**)	**104.9** (**67.1**)
	2070–2099	**118.3** (**145.6**)	**128.8** (**280.8**)	**120.6** (**121.3**)	**109.3** (**71.4**)
Chute-des-Passes	2010–2039	94.2 (**124.9**)	97.9 (**117.4**)	89.7 (**97.1**)	98.0 (**116.0**)
	2040–2069	**102.8** (**93.1**)	**104.1** (**119.6**)	**96.0** (**76.1**)	**113.1** (**114.3**)
	2070–2099	**110.1** (**129.9**)	**110.8** (**143.1**)	**100.9** (**94.2**)	**125.2** (**142.8**)
Chute-du-Diable	2010–2039	95.1 (**130.3**)	99.1 (**121.8**)	90.2 (**102.1**)	99.3 (**115.2**)
	2040–2069	103.3 (**95.4**)	103.8 (**120.0**)	96.2 (**79.8**)	**115.2** (**114.6**)
	2070–2099	**109.9** (**128.4**)	**109.2** (**135.7**)	100.4 (**95.5**)	**127.6** (**141.0**)
Chute-à-la- Savane	2010–2039	96.8 (**136.3**)	98.4 (**169.0**)	95.5 (**105.2**)	97.5 (**105.6**)
	2040–2069	106.9 (**103.5**)	110.2 (**164.8**)	104.3 (**87.8**)	**107.9** (**71.1**)
	2070–2099	**115.2** (**150.0**)	**120.4** (**277.7**)	112.5 (**111.8**)	**114.7** (**80.6**)

Bold values indicate a statistically significant change compared to the control period

reservoir, which explains the increase in production at the annual and seasonal scales. On the other hand, Fig. 5 shows that the flows at the Chute-a-la-Savane subbasin, representative of the south of the basin, dropped significantly in the summer–autumn, a high flow period. The subbasins in the south feed the run-of-river power plants, and so this drop in flows explains their significant production decreases at this season.

The changes in the means and in the variance of the annual mean production for the future periods 2010–2039, 2040–2069 and 2070–2099, compared to the control period 1961–1990, were also investigated. The results are presented in Table 5, where the statistically significant changes are emphasized in bold. The values are expressed as a percentage of the production of the control period, in order to preserve the confidentiality of the owner of the water resource system.

The changes in total mean annual production and in the annual mean production of the power plant with a reservoir (Chute-des-Passes) are statistically significant in the periods 2040–2069 and 2070–2099. For the run-of-river power plants, the changes are significant in 2070–2099. The changes in the variance of the annual production are statistically significant for all the periods and power plants.

On a seasonal basis, the changes in mean production are statistically significant in 2070–2099. The changes in mean for winter production are significant for all of the power plants in 2040–2069 and for 2070–2099. The changes of seasonal variances are significant for each power plant at all of the future periods.

In general, the significant changes in hydropower are consequent with significant changes in the hydrological regimes. The increases in the annual mean flows in the north lead to increases in the annual mean hydropower for the Chute-des-Passes power plant. The same observation applies on the seasonal scale.

4.3.3 Power Plant Efficiency

The efficiency of a power plant is the ratio of the hydropower to the sum of the spilled and turbinated flows. Tubinated flow is water that is used to produce hydropower, in opposition to spilled flow that is evacuated by spillways. The changes in means and

Table 6 Mean and standard deviation of the power plants' total efficiency, on an annual and seasonal basis

	Mean (standard deviation) (% of the 1961–1990 period)		
	Chute-des-Passes	Chute-du-Diable	Chute-a-la-Savane
2010–2039	100.2 **(111.6)**	**101.1 (74.6)**	**101.4 (73.7)**
2040–2069	**99.3 (192.5)**	99.1 **(128.5)**	99.0 **(114.6)**
2070–2099	**98.7 (255.6)**	**98.1 (186.9)**	**97.3 (162.8)**

Bold values indicate a statistically significant change compared to the control period

variance of the annual mean efficiency at the future periods 2010–2039, 2040–2069 and 2070–2099, compared to the control period 1961–1990, were also investigated. The results are presented in Table 6, with the statistically significant changes in bold. The values are expressed as a percentage of the efficiency of the control period in order to highlight gains and losses in efficiency.

The general trend is for a reduction in the efficiency of the power plants in 2050 and 2080. For the same quantity of water used in the future, there will be less production. However, the efficiency increases in 2020. The changes in the variance of the annual mean efficiency are statistically significant for all the power plants, at each future period. The changes of variances reach 255.6% of the variance of the control period for the power plant with a reservoir. The variability of the efficiency increases as the horizon considered is further from the control period.

4.3.4 Unproductive Spills

The totals of unproductive spills, and those at each power plant, are presented in Fig. 10. The general trend of unproductive spills shows an increase. However, this trend is not statistically significant.

Table 7 compiles the changes in mean and variance of the unproductive spills, in total and at each power plant. The changes of means in unproductive spills at the

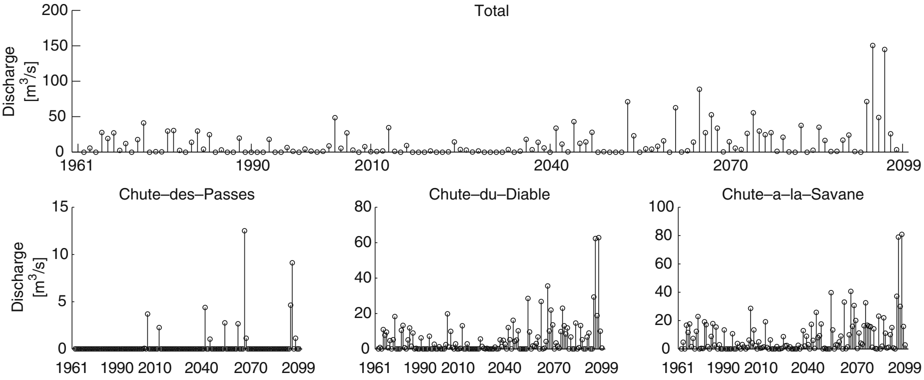

Fig. 10 Mean annual unproductive spills, totals and for each power plant, for the period 1961–2099

Table 7 Mean and standard deviations of unproductive spills, on annual and seasonal basis

		Mean (standard deviation) (m^3/s)			
		Annual	Spring (AMJ)	Summer–autumn (JASON)	Winter (DJFM)
Total	1961–1990	10.8 (12.9)	31.6 (46.2)	6.7 (15.3)	0 (0)
	2010–2039	**4.0** (**7.5**)	12.9 (**24.0**)	1.5 (**5.0**)	0.4 (**2.0**)
	2040–2069	18.4 (**24.0**)	58.7 (**90.5**)	4.4 (**11.7**)	5.7 (**17.3**)
	2070–2099	**26.4** (**37.8**)	**78.8** (**120.1**)	5.4 (14.4)	**13.5** (**28.6**)
Chute-des-Passes	1961–1990	0 (0)	0 (0)	0 (0)	0 (0)
	2010–2039	0.1 (**0.4**)	0.3 (**1.7**)	0 (0)	0 (0)
	2040–2069	0.8 (**2.4**)	3.2 (**9.8**)	0 (0)	0 (0)
	2070–2099	0.5 (**1.8**)	2.0 (**7.4**)	0 (0)	0 (0)
Chute-du-Diable	1961–1990	4.0 (5.2)	11.5 (18.7)	2.7 (6.5)	0 (0)
	2010–2039	**1.3** (**2.8**)	4.4 (**8.9**)	0.4 (**1.7**)	0.1 (**0.6**)
	2040–2069	7.2 (**9.7**)	22.9 (**37.1**)	1.8 (**5.2**)	2.2 (**6.8**)
	2070–2099	**10.4** (**16.1**)	**31.1** (**51.8**)	2.2 (6.6)	**5.2** (**11.5**)
Chute-à-la-Savane	1961–1990	6.7 (7.7)	20.1 (27.8)	4.0 (8.8)	0 (0)
	2010–2039	**2.6** (**4.4**)	8.2 (**14.3**)	1.0 (**3.3**)	0.3 (**1.4**)
	2040–2069	10.3 (**12.6**)	32.5 (**46.0**)	2.6 (**6.7**)	5.7 (**10.5**)
	2070–2099	**15.5** (**20.4**)	**45.7** (**64.7**)	3.1 (**7.9**)	**13.5** (**17.1**)

Bold values indicate a statistically significant change compared to the control period

future periods 2010–2039, 2040–2069 and 2070–2099 are generally not statistically significant compared to the spills of the control period 1961–1990. However, the changes of variance in the annual and seasonal mean unproductive spills are significant for almost all of the future periods. The changes in unproductive spills are consequent with the increase in the annual and seasonal runoff.

4.3.5 Reservoir Reliability

Reliability is the probability that a reservoir is in a state considered to be satisfactory (Simonovic and Li 2004). The Lake-Manouane and Passes-Dangereuses reservoirs are in an unsatisfactory state when their level exceeds their maximum exploitation level. A maximum exploitation level is the maximum level that a reservoir can reach in normal exploitation.

The mean reliability of the Lake-Manouane reservoir, over the 139 years evaluated, is 99.99%. The maximum level of exploitation was reached once, with an exceedence of 0.09 m. This occurred during the winter, in the 51st week of 2053. To identify the cause of this exceedence, the temperatures, precipitations and flows for this period were analyzed. The exceedence occurred during a week with a rainy event of 21 mm over 4 days, whereas the mean temperature was 1°C. These conditions caused inflows in the Lake-Manouane reservoir, whose level was maintained close to the normal level of exploitation in order to guarantee a water head during a low flow period. The operating rules under these conditions specify the allowance of spill flows to the maximum of the capacity of the spillway.

The reliability of the Passes-Dangereuses reservoir was 100%. No exceeding of the maximum level of exploitation occurred within the 139 years of simulations, while maintaining the current exploitation constraints.

5 Conclusions and Recommendations

The aim of the work was to evaluate the impacts of and the adaptation to climate change of the water resource management system of the Peribonka River, a Canadian water resource system exploited for hydropower.

Adapting the management of a water resource system to climate change is necessary because of the hydrological regime changes. The operating rules generated by optimization allow their adaptation to the new hydrological regimes. The use of unadapted operating rules in the impact studies of climate change on hydropower gives pessimistic results (Markoff and Cullen 2008).

This work adapted the operating rules annually to the new hydrological regimes, keeping a flow history of 35 years. This period was fixed according to a Mann–Kendall test of stationarity on annual mean flows, which indicated that the maximum period, for which the assumption of stationarity was respected, is 35 years. This method allows the annual flows of the previous 35 years to be used in calculating the operating rules of a given year.

The simulation of the operations of the water resource system, with the hydrological scenarios in the context of climate change and the adapted operating rules, shows that the adaptation of the management of the reservoirs appears as a change in the seasonal mean reservoir levels. In the spring, the level of the reservoirs is lowered earlier in order to contain an early spring flood. In summer–autumn, the levels are maintained higher to maximize the water head. In winter, the levels are lower in order to limit exceeding the maximum exploitation levels, leading consequently to an increase in the flows to the reservoirs.

The principle conclusion is that the hydropower for the Peribonka River water resource system would increase over the long-term for the climate projection used. The study reveals a decreasing (statistically significant) trend until 2030, and an increase (statistically significant) thereafter, until the temporal limit of the study, or 2099. The production decrease is the consequence of the reduction in the runoff in the south of the watershed, where the run-of-river power plants are. The annual and seasonal (summer–autumn and winter) hydropower presents an increasing trend. In addition to this trend, the changes of means in annual and seasonal hydropower are generally statistically significant in the future periods 2040–2069 and 2070–2099. The changes in the variance are statistically significant throughout (it generally increases), which indicates to the managers that there would be more variability in the inter-annual production in the future. The changes of variability in the hydropower are greater in spring.

The (non-significant) trend in unproductive spills also shows an increase. The reservoir levels are higher because of the increases in the runoff, starting from the year 2030. These higher levels compromise the reliability of the reservoir in winter because of the increasingly favourable climatic conditions for runoff (rain and rise in temperature). The level of a reservoir exceeds the maximum level of exploitation and changes one reservoir's reliability to 99.99%, whereas it was 100% for the control period 1961–1990. Because the reservoir's maximum level of exploitation was exceeded, for future studies it is recommended to modify the constraints of exploitation of the reservoirs' levels in order to keep the reliability of a reservoir at 100%. We predict that a lower exploitation level would imply a smaller probability of reservoir maximum exploitation level exceedence. More work is needed on the impacts of modifying the physical configurations of water resource systems.

The management indicators, such as levels, hydropower, efficiency and unproductive spills, are used to quantify the performance and the behaviour of the water resource system with a management adapted to climate change. Using a climatic projection resulting from dynamic downscaling allows the evolution of these indicators to be followed, since climatic projection is transient. RCM climate projections are not as easily obtainable as GCMs. The work presented did not compare the hydrological regimes and the management indicators under several climate projections in order to determine the uncertainty. For future work, it is recommended to use more than one RCM and GHGES, according to the data available for North America.

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References

Caya D, Laprise R (1999) Semi-implicit semi-Lagrangian regional climate model: the Canadian RCM. Mon Weather Rev 127(3):341–362

Christensen NS, Wood AW, Voisin N, Lettenmaier DP, Palmer RN (2004) The effects of climate change on the hydrology and water resources of the Colorado river basin. Clim Change 62:337–363

Fortin J-P, Turcotte R, Massicotte S, Moussa R, Fitzback J, Villeneuve J-P (2001) Distributed watershed model compatible with remote sensing and GIS data. 1: description of the model. J Hydrol Eng 6(2):91–99

Fowler HJ, Kilsby CG (2007) Using regional climate model data to simulate historical and future river flows in northwest England. Clim Change 80:337–367

Fowler HJ, Blenkinsop S, Tebaldi C (2007) Linking climate change modelling to impacts studies: recent advances in downscaling techniques for hydrological modelling. Int J Climatol 27: 1547–1578

Hamed KH (2008) Trend detection in hydrologic data: the Mann–Kendall trend test under the scaling hypothesis. J Hydrol 349:350–363

Hayhoe K, Wake CP, Huntington TG, Luo L, Shchwartz MD, Sheffield J, Wood E, Anderson B, Bradbury J, DeGaetano A, Troy TJ, Wolfe D (2007) Past and future changes in climate and hydrological indicators in the US Northeast. Clim Dyn 28(4):381–407

IPCC (2007) Climate change 2007: Impacts, adaptation and vulnerability. Contribution of working group II to the fourth assessment report of the intergovernmental panel of climate change. In: Parry ML, Canziani JP, Palutikof JP, van der Linden PJ, Hanson CE (eds) Intergovernmental panel on climate change. Cambridge, UK, 1000 p

Kalra A, Piechota TC, Davies R, Tootle GA (2007) Changes in U.S. streamflow and western U.S. snowpack. J Hydrol Eng 13(3):156–163

Kendall MG (1975) Rank correlation methods. Griffin, London

Kundzewicz ZW, Mata LJ, Arnell NW, Döll P, Kabat P, Jiménez B, Miler KA, Oki T, Sen Z, Shiklomanov IA (2007) Freshwater resources and their management. In: Canziani OF, Parry ML, Palutikof JP, van der Linden PJ, Hanson CE (eds) Climate change 2007: impacts, adaptation and vunerability. Contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, UK, pp 173–210

Labadie JW (2004) Optimal operation of multireservoir systems: state-of-the-art review. J Water Resour Plan Manage 130(2):93–111

Mann HB (1945) Nonparametric tests against trend. Econometrica 13:245–259

Markoff MS, Cullen AC (2008) Impact of climate change on Pacific Northwest hydropower. Clim Change 87:451–469

Maurer EP (2007) Uncertainty in hydrologic impacts of climate change in the Sierra Nevada, California, under two emissions scenarios. Clim Change 82:309–325

McFarlane NA, Boer GG, Blanchet J-P, Lazare M (1992) The Canadian climate centre second-generation general circulation model and its equilibrum climate. J Climate 5:1013–1044

Minville M, Brissette F, Leconte R (2008) Uncertainty of the impact of climate change on the hydrology of a Nordic Watershed. J Hydrol 358(1–2):70–83

Nakicenovic N, Alcamo J, Davis G, de Vries B, Fenhann J, Gaffin S, Gregory K, Grübler A, Jung TY, Kram T, La Rovere EL, Michaelis L, Mori S, Morita T, Pepper W, Pitcher H, Price L, Raihi K, Roehrl A, Rogner H-H, Sankovski A, Schlesinger M, Shukla P, Smith S, Swart R, van Rooijen S, Victor N, Dadi Z (2000) IPCC special report on emissions scenarios. United Kingdom and New York, NY, USA, p 599

Nash JE, Sutcliff JV (1970) River flow forecasting through conceptual models. 1. A discussion of principles. J Hydrol 10(3):282–290

Olesen JE, Carter TR, Diaz-Ambrona CH, Fronzek S, Heidmann T, Hickler T, Holt T, Minguez MI, Ruiz-Ramos M, Rubaek GH, Sau F, Smith B, Sykes MT (2007) Uncertainties in projected impacts of climate change on European agriculture and terrestrial ecosystems based on scenarios from regional climate models. Clim Change 81:123–143

Payne JT, Wood AW, Hamlet AF, Palmer RN, Lettenmaier DP (2004) Mitigating the effects of climate change on the water resources of the Columbia river basin. Clim Change 62:233–256

Plummer DA, Caya D, Frigon A, Cote H, Giguere M, Paquin D, Biner S, Harvey R, De elia R (2006) Climate and climate change over North America as simulated by the Canadian RCM. J Climate 19(13):3112–3132

Regonda SK, Rajagopalan B, Clark M, Pitlick J (2005) Seasonal cycle shifts in hydroclimatology over the western United States. J Climate 18(2):372–384

Salathé EP Jr, Mote PW, Wiley MW (2007) Review of scenario selection and downscaling methods for the assessment of climate change impacts on hydrology in the United States pacific northwest. Int J Climatol 27:1611–1621

Schmidli J, Frei C, Vidale PL (2006) Downscaling from GCM precipitation: a benchmark for dynamical and statistical downscaling methods. Int J Climatol 26:679–689

Semenov MA, Brooks RJ, Barrow EM, Richardson CW (1998) Comparison of the WGEN and LARS-WG stochastic weather generators for diverse climates. Clim Res 10:95–107

Simonovic SP, Li L (2004) Sensitivity of the Red river basin flood protection system to climate variability and change. Water Resour Manag 18:89–110

Turcotte R, Fortin L-G, Fortin V, Villeneuve J-P (2007) Operational analysis of the spatial distribution and the temporal evolution of the snowpack water equivalent in southern Quebec, Canada. Nord Hydrol 38(3):211–234

Turgeon A (2005) Solving a stochastic reservoir management problem with multilag autocorrelated inflows. Water Resour Res 41:W12414

VanRheenen NT, Wood AW, Palmer RN, Lettenmaier DP (2004) Potential implications of PCM climate change scenarios for Sacremento-San Joaquin river basin hydrology and water resources. Clim Change 62:257–281

Whitfield PH, Cannon AJ (2000) Recent variation in climate and hydrology in Canada. Can Water Resour J 25(1):19–65

Wood AW, Leung LR, Sridhar V, Lettenmaier DP (2004) Hydrologic implications of dynamical and statistical approaches to downscaling climate model outputs. Clim Change 62:189–216