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Optimal Hydropower Generation Under Climate Change Conditions for a Northern Water Resources System

Didier Haguma · Robert Leconte · Pascal Côté · Stéphane Krau · François Brissette

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Abstract This paper examines climate change impacts on the water resources system of the Manicouagan River (Québec, Canada). The objective is to evaluate the performance of existing infrastructures under future climate projections and the associated uncertainties. The main purpose of the water resources system is hydropower production. A reservoir optimization algorithm, Sampling Stochastic Dynamic Programming (SSDP), was used to derive weekly operating decisions for the existing system subject to reservoir inflows reflecting future climate, for optimum hydropower production. These projections are simulations from the SWAT hydrologic model for climate change scenarios for the period from 2010 to 2099. Results show that the climate change will alter the hydrological regime of the study area: earlier timing of the spring flood, reduced spring peak flow, and increased annual inflows volume in the future compared to the historical climate. The SSDP optimization algorithm adapted the operating policy to the future hydrological regime by adjusting water reservoir levels in the winter and spring, and increasing the release through turbines, which in the end increased power generation. However, there could be more unproductive spills for some power plants, which would decrease the overall efficiency of the existing water resources system.

Keywords Hydrologic regime · Climate change · Water resources system · Operating policy

1 Introduction

It has been established that climate change will have impacts on the availability of water resources as well as on the operating policies for water resources systems. The consequences of climate change on water resources would be an increase in precipitation variability, amplification of extreme weather events such as droughts, changes in the frequency of floods

D. Haguma (✉) · R. Leconte · S. Krau
Université de Sherbrooke, 2500, Boulevard de l'Université, Sherbrooke, QC, Canada J1K 2R1
e-mail: didier.haguma@usherbrooke.ca

P. Côté
Rio Tinto Alcan, 1954, Davis, Jonquière, QC, Canada G7S 4R5

F. Brissette
École de technologie supérieure, Montréal, QC, Canada H3C 1K3

(Bell et al. 2007), changes in the normal flow regimes of rivers and changes in the start date and length of seasons (Pietroniro et al. 2006). Increased precipitation in some areas will increase inflows to reservoirs, but rising temperatures will reduce the effect of the freezing period (Toth et al. 2006) and increase the evaporation rate in reservoirs and evapotranspiration in the watershed.

The change in the availability of water resources will affect the planning and management of water resources systems (Burn and Simonovic 1996). The impacts of climate change on water systems will include, for instance, change in the operating rules for flood control and power generation, modification of reservoir filling periods, reallocation of firm hydropower generation from the winter to summer (Payne et al. 2004), and increase in unproductive spills (Minville et al. 2009). Therefore, it is important to adapt water resources systems operating policies to potential climate change (Brekke et al. 2009).

The management of water resources is subject to various uncertainties, which are generally due to unpredictable inflows that have temporal as well as spatial variations. Most water resources management schemes assume the stationarity of hydrological regimes. That is to say, even if there is strong seasonal variation in hydrological processes, such as spring flood, statistically similar events are repeated over a certain period. This deterministic assumption is at the base of hydraulic structures design and management, where decisions are made based on past experience.

As the climate is expected to change, the assumption of stationary hydrological regimes will no longer hold (Milly et al. 2008). Available climate projections from general circulation models (GCMs) give some insight into the uncertainties of future climate and water availability (Barnett et al. 2004). The uncertainties of climate projections depend on the uncertainties of the scenarios of future emissions of greenhouse gases (GHG), and GCMs. The GCMs uncertainties result from an incomplete understanding of the climate system and representing it by mathematical models (Tebaldi and Knutti 2007). Other sources of uncertainties are downscaling methods and hydrologic modeling used to study the impacts of climate change on watersheds (Chen et al. 2011).

The uncertainties of climate change and the future non-stationarity of hydrological regimes require the use of the multi-model ensemble of climate projections (Brekke et al. 2009) in water resources system optimization (Vicuna et al. 2010). A stochastic method would better represent the impacts of climate change on water resources operation and management, and would take into account various uncertainties related to climate projections and climate models.

In this study, the Sampling Stochastic Dynamic Programming (SSDP) optimization algorithm for water resources was used to derive a weekly operating policy for a water resources system of the Manicouagan River, located in Quebec, Canada. SSDP is an optimization method used to solve decision-making processes at several stages. SSDP uses scenarios to represent the uncertainty of inflows, thus simulating the release decisions with a realistic representation of stream persistence (Faber and Stedinger 2001).

The main objectives of this study are (1) to assess the impact of climate change on the hydrological regime of the Manicouagan River using the SWAT hydrologic model and an ensemble of climate projections, and (2) apply SSDP to find optimal operating policies for the existing Manicouagan water resources system subject to future climate projections. The remainder of the paper is organized as follows. Data and methods follow in the next section. The third section presents the results and discussion. The final section concludes and provides some recommendations.

2 Materials and Methods

2.1 Study Area

The area of focus for this study is the Manicouagan River catchment, Fig. 1. The Manicouagan River catchment is located in the province of Quebec, Canada, a region rich in water resources. The river's source is the Manicouagan Reservoir. The Manicouagan River travels about 221 km before emptying into the St. Lawrence River. The reservoir has an area of 1,942 km^2 and an average depth of 73 m. The Manicouagan River catchment area is 44 500 km^2; the elevation varies between 37 and 1,143 m above mean sea level. The northern part of the watershed has steep slopes whereas in the south the river flows over mild slopes.

The mean annual precipitation in this region is around 1,015 mm, with up to one-third of this amount as snow, which accumulates in the watershed between October and May. The annual peak runoff occurs in response to snowmelt in May. The water resources system consists of two hydropower plants with reservoirs in parallel (Manic-5 and Toulnustouc) and three run-of-river hydropower plants (Manic-3, Manic-2 and Manic-1). Those plants are located at the outlet of five main sub-basins as shown in Fig. 1. The total installed capacity is 6,202 MW. Table 1 gives more details on the characteristics of the water resources system facilities.

2.2 Climate Projections

The climate projections used in the assessment of climate change impacts are subject to uncertainties from different sources: GCMs, downscaling methods and hydrologic models. A multi-model ensemble represented the uncertainty of the future climate. The ensemble included 13 GCMs (Table 2) and three GHG emission scenarios (A1B, A2 and B1). The scenarios represent different trends in the future evolution of GHG emissions. B1 is the most optimistic, A2 is the most pessimistic and A1B is the moderate scenario. The monthly data set was obtained from the World Climate Research Programme's Coupled Model Intercomparison Project phase 3 (WCRP CMIP3) multi-model data set (Meehl et al. 2007).

A downscaling method proposed by Widmann et al. (2003), which makes minimal, physically-based corrections to the global simulation while preserving much of the statistics of inter-annual variability in the climate model (Salathé 2005) was used. The method takes large-scale monthly precipitation or temperature as predictors of local precipitation or temperature, by either multiplying (precipitation) or adding (temperature) a seasonal scale factor. The scale factor eliminates the long-term bias between precipitations or temperature simulated by the GCMs and observed data for the same period. Temporal disaggregation was achieved by imposing daily variability of the daily weather sequence of a selected month from the observed records on the GCM downscaled monthly precipitation and temperature (Salathé 2005).

2.3 SWAT Hydrological Model

A hydrological model was used to produce inflow projections and to assess climate change impacts on the hydrological regime of the study area. The Soil and Water Assessment Tool (SWAT), one of the more widely used models (Ahl et al. 2008), was applied for the simulation of river flows in the Manicouagan watershed. SWAT is a physically-based, semi-distributed, continuous time, hydrologic model used for long-term hydrological simulations of watersheds.

In this study, SWAT2005 (Neitsch et al. 2005) was used together with the ArcSWAT interface, a GIS-based graphical user interface that facilitates watershed delineation and initial

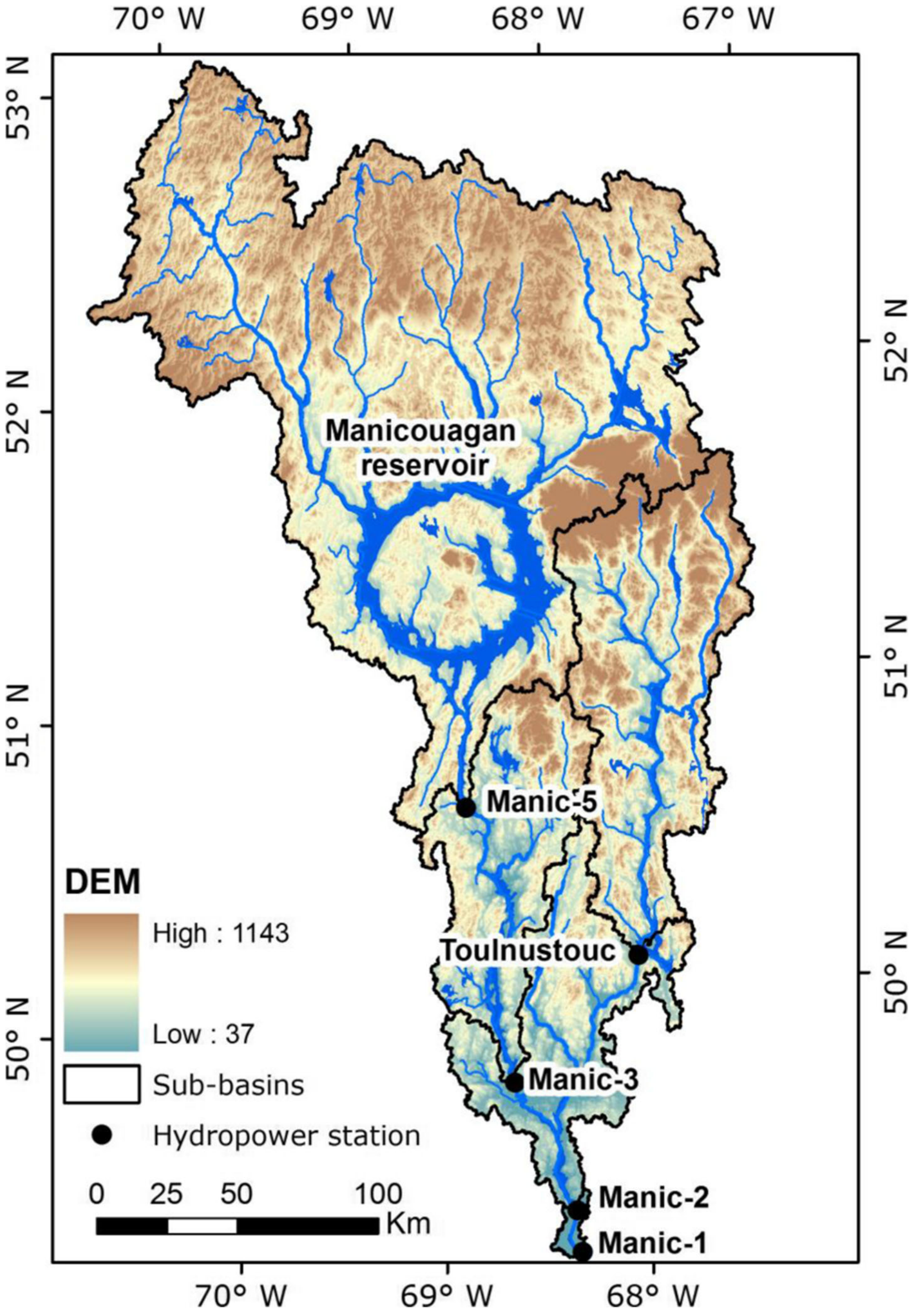

Fig. 1 Manicouagan River catchment

parameterization. The data used to develop the model are the digital elevation model, soil properties, land use and meteorological data such as precipitation, minimum temperature,

Table 1 Manicouagan water resources system (Hydro-Québec 2011)

Sub-basin name	Drainage area (km^2)	Mean basin elevation (m)	Hydropower station type	Volume (hm^3)	Head (m)	Installed Capacity (MW)
Manic-5	24,735.27	579	Reservoir	35 171	144.5	1,596
Toulnustouc	7,274.94	580	Reservoir	2 436	152.0	526
Manic-3	4,463.58	467	Run-of-river	–	94.19	1,244
Manic-2	4,394.55	394	Run-of-river	–	70.11	1,145
Manic-1	156.43	146	Run-of-river	–	36.58	184

maximum temperature, humidity, wind speed and solar radiation. The daily temperature and precipitation data are from the National Land and Water Information Service (NLWIS) database (Hutchinson et al. 2009). Data for other meteorological variables are the monthly statistics of historical a weather station data of Environment Canada.

The hydrologic model was calibrated and validated with reconstructed flow data for four sub-basins: Manic-5, Toulnustouc, Manic-3 and Manic-2. The calibration process focused on the water balance and the reproduction of the seasonality of peak flows and base flows. The future climate projections were forced into the hydrologic model to assess the impacts of climate change on the hydrological regime. The impacts were represented by the flow regime of the watershed during the study period of 2010–2099.

2.4 Water Optimization Algorithm

A reservoir optimization algorithm, SSDP, was used to derive weekly operating rules for the existing water resources system subject to future climate. Dynamic programming (DP) is an optimization method used to solve decision-making processes in several steps, and the objective function and constraints do not necessarily need to be linear, convex, or continuous (Labadie 2004). The principle of DP is to break down a complex multi-stage problem into several simple sub-problems so that each part is a new problem and the sub-problems are

Table 2 Climate model ensemble

Model	Country	Resolution
BCM2.0	Norway	1.9×1.9°
CGCM3	Canada	2.8×2.8°
CSIRO Mk3.0	Australia	1.9×1.9°
ECHAM5	Germany	1.9×1.9°
ECHO-G	Germany	2.8×2.8°
CM2.1	USA	2.0×2.5°
GISS-AOM	USA	3.0×4.0°
CM3.0	Russia	4.0×5.0°
IPSL-CM4	France	2.5×3.75°
MIROC3.2	Japan	1.1×2.8°
CMCG2.3.2	Japan	2.8×2.8°
NCAR PCM	USA	2.8×2.8°
HadCM3	UK	2.5×3.75°

solved recursively one after another. The optimal solution of the problem is deducted from the initial optimal solutions to sub-problems.

SSDP (Faber and Stedinger 2001; Kelman et al. 1990; Vicuna et al. 2010) is a variation of the DP and Stochastic Dynamic Programming (SDP). SDP uses a probability description of inflows, instead of a specific sequence of inflows to determine the optimal policies (Labadie 2004). On other hand, SSDP uses several scenarios to represent the uncertainty and non-stationarity of inflows, thus simulating the release decisions with a realistic representation of stream persistence (Faber and Stedinger 2001). In addition, the transition in the DP equation is not between different representations of the inflow terms, but between different hydrological scenarios, for instance climate projections (Vicuna et al. 2010). The formulation of a SSDP problem for a single hydropower plant is defined by the equations:

$$R_t^* = \underset{R_t}{\operatorname{argmax}} \left\{ B_t(S_t, Q_t(i), R_t) + \underset{j|i}{E}\left[f_{t+1}(S_{t+1}, j)\right] \right\} \tag{1}$$

$$f_t(S_t, i) = B_t\left(S_t, Q_t(i), R_t^*\right) + \underset{j|i}{E}\left[f_{t+1}(S_{t+1}, j)\right] \tag{2}$$

where t is the time period for a weekly time step, $B_t(\cdot)$ is the current benefit function for period t, $Q_t(i)$ is the inflow in period t for flow scenario i, i and j refer to inflow scenarios. S_t is the storage for period t, R_t is the release for period t, and $R_{t,a}^*$ is the optimal release. The cost-to-go function $f_t(S_t)$ is the sum of the current benefits plus the future benefits, $f_{t+1}(S_{t+1})$. The function $f_t(S_t)$ is computed recursively backwards from the final period T. If f_{T+1} is not known, which is usually the case, it is set equal to zero, and the recursive process is iterated until a satisfactory convergence is reached. $\underset{j|i}{E}[.]$ is the expected value of flow scenario j at time period $t+1$ given flow scenario i at time period t. Equation (3) is the mass balance equation, and Eqs. (4), (5) and (6) are constraints on reservoir storage and releases from hydropower plants.

$$S_{t+1} = S_t + Q_t - R_t \quad \forall t = 1, \cdots, T \tag{3}$$

$$0 \le S_t \le S_{\max} \quad \forall t = 1, \cdots, T \tag{4}$$

$$0 \le R_t \quad \forall t = 1, \cdots, T. \tag{5}$$

$$R_t = \min(R_{\max}, R_t) \quad \forall t = 1, \cdots, T. \tag{6}$$

where T is the final period, $S_{\max}$ is the maximum storage, and $R_{\max}$ is the maximum release. When $R_{\max} < R_t$ the water surplus is spilled, and there is no limit on the water spilled. The expected value of scenario j given scenario i uses the probability that a cumulative flow volume is equal to the volume of scenario j, given the realization of a hydrologic state variable of scenario i. The hydrologic state variable represents catchment conditions, which influence the flow volume such as the snow water equivalent (SWE) in the winter and soil moisture in other seasons (Côté et al. 2011).

2.5 Implementation of the Algorithm

The flow regimes for future climate were used to determine optimum operating policies for the Manicouagan water system in the future climate. The SSDP inflow scenarios consist of weekly inflows over a period of 1 year. The inflow scenarios represent seasonal variability in the flow regime and the transition probabilities allow the inflow variability at each time step to be taken into consideration. For the reference period (1970–1999), 30 scenarios were used to establish operating policy. Weekly inflows for each future climate projection for the period 2010–2099 provided ninety inflow scenarios. Future climate operating policies were compared to the reference period policy in order to determine the climate change impacts on the installations of the water resources system. Averages of the releases from hydropower plants, and energy production were calculated with an assumption that the climate projections have equal weight.

A backward optimization, Eqs. (1) and (2), was used to estimate the cost-to-go function from the end of the year up to the beginning and to determine the operating policy of a given climate projection with 90 inflow scenarios. A hydrologic state variable was used to capture the inflows regime and each reservoir had one state variable. After the optimization process, a forward simulation (Tejada-Guibert et al. 1995) was carried out to find an operating policy corresponding to the initial reservoir storage and the climate projection inflows. The efficiency of the water resources system, which is the amount of power in KWh produced for one m^3 of water released, was used to find the performance of the existing installation for the future climate. The released water includes productive releases and unproductive spills.

3 Results and Discussion

3.1 Climate Change Impacts on Hydrologic Regime

The impacts of climate change on the water resources system for the Manicouagan River will be an increase in temperature and a change in seasonal precipitation. The scatter plot, Fig. 2, shows the correlation between average temperature change and precipitation change for the future climate projection ensemble for three future horizons (2010–2039, 2040–2069, and 2070–2099), with respect to reference period. The temperature and precipitation will increase in the future with major changes in the 2070–2099 horizon; the GCMs predict an increase in temperature between 3 and 10 °C and an increase of precipitation between 5 and 60 % during winter.

The winter season (December through February) will experience significant changes compared to other seasons, and will have more variability in both temperature and precipitation. The summer season (June through August) will have fewer changes and, in particular, the precipitation has a projected change between −5 and 20 %. With higher temperatures, a greater proportion of winter precipitation would fall as rain rather than snow. The increase in precipitation will have a positive impact on inflows to reservoirs. Figure 3 shows the uncertainty envelope of daily inflow projections for the 1970–1999 historical period, and for three future climate horizons for Manic-5 reservoir.

The uncertainty is significant during the spring flood period. There is a small change in inflows for the 2010–2039 horizon and for all climate projections, especially, in the winter. During the 2040–2069 horizon, important changes appear in the inflow volume and timing of the spring flood. The spring flood is significantly earlier for all climate projections and inflow volume continues to increase during the winter. The change in the hydrological regime becomes more important during the 2070–2099 horizon, with the significant increase of

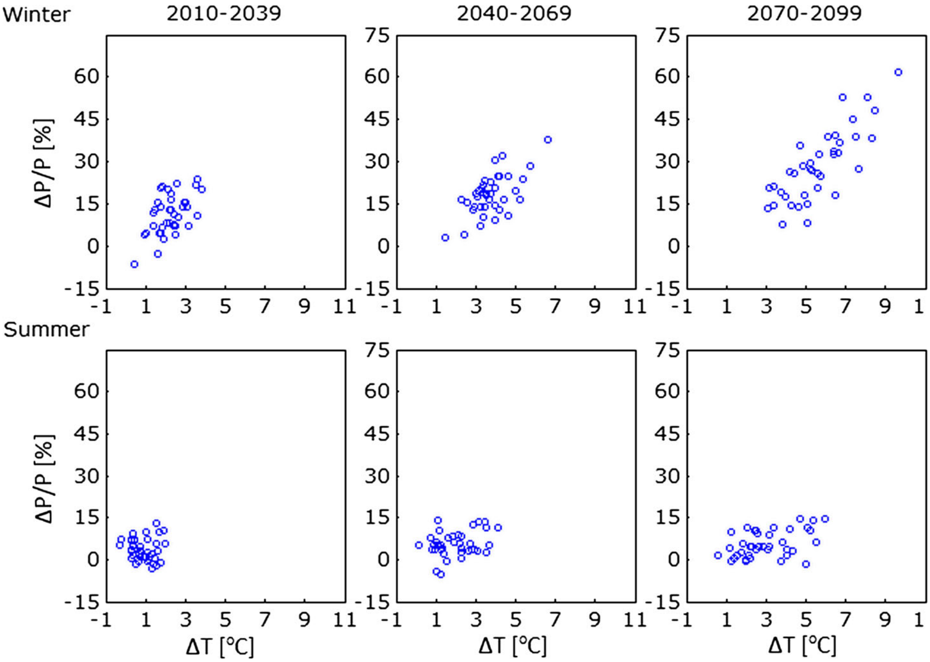

Fig. 2 Correlation between temperature change (ΔT) and precipitation percentage change (ΔP) for the future climate horizons with respect to the historical period for winter and summer

inflows in winter, the earlier timing of the spring flood, and the lessening of peak flow volume. These changes are driven by both the increase in temperature and precipitation (Fig. 2). The snowmelt, which takes place earlier in the future climate than in the current climate, triggers the earlier timing of the spring flood (Minville et al. 2009).

Figure 3 shows that in the future climate winter thaws would be frequent and would lead to significant runoff, and the spring flood would become less important. The earlier timing of the spring flood of the Manicouagan River watershed will become important in the future climate. The peak flow would be earlier by 3, 10 and 16 days on average for the three climate horizons.

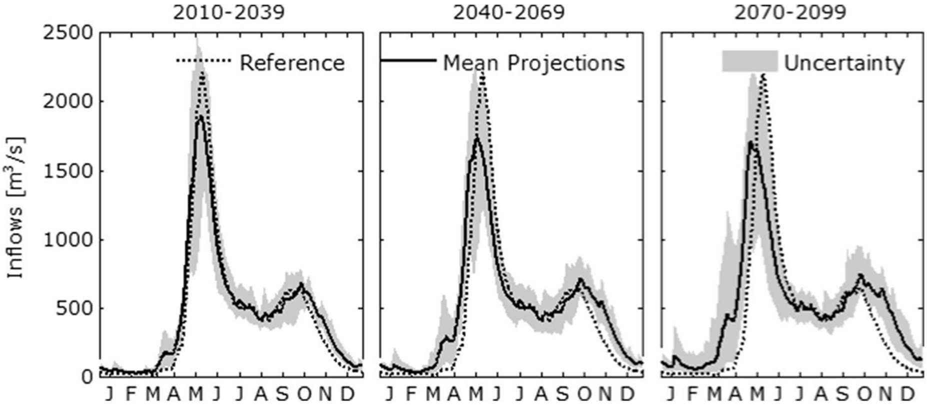

Fig. 3 Manic-5 simulated daily inflows for the reference period and the mean and uncertainty of future climate projections

Regarding the annual inflow volume, the Manicouagan River watershed will have an increase of 4.3, 9.1 and 13.5 % on average for the three climate horizons compared to the 1970–1999 reference period. Figure 4 shows the uncertainty and the trend of spring flood timing and annual inflow volume. The 2040–2069 and 2070–2099 horizons show higher variability of the spring flood timing and annual inflow volume than 2010–2039. The interquartile ranges increase with time, with a remarkable number of outliers for the spring flood timing.

3.2 Operating Policies and Climate Change Conditions

The operations for the Manicouagan River water resources system (Table 1) were optimized for a weekly time step with SSDP. The SSDP model input data consist of three data sets: the water resources system configuration, the system installation characteristics, and weekly inflows and a hydrological state variable for each facility. The hydrological variable is a linear combination of weekly SWE and soil moisture (Côté et al. 2011) for each week in the catchment, which is used to calculate the expected value of the cost-to-go function (Eqs. 1 and 2).

The objective of the optimization problem was to find a weekly operating policy for the water resources system that maximizes expected energy generation. The energy market dynamics was not considered, because of a high fluctuation in the energy price in long-term. A series of inflow projections were used to determine the optimum operating policy associated with climate projections and to establish climate change impacts on the existing system. Weekly inflows over a period of 1 year for each climate projection provided inflow scenarios for the optimization problem. The optimization problem represented the nonstationarity of the climate implicitly by various inflow scenarios.

The operating policy includes, among others, reservoir storage, releases through turbines and resulting unproductive spills for the future climate period from 2010 to 2099. Figure 5 shows the weekly operating policy for Manic-5 for the reference period and the future climate horizons. The figure illustrates the range of uncertainty for the climate projections associated with GCMs structure and the mean for all climate projections. The figure comprises water level as well as releases of the existing installations.

The changes in the hydrological regime, lessening of the peak flow volume in spring (March through May) and earlier timing of the peak flow, will cause an alteration of the

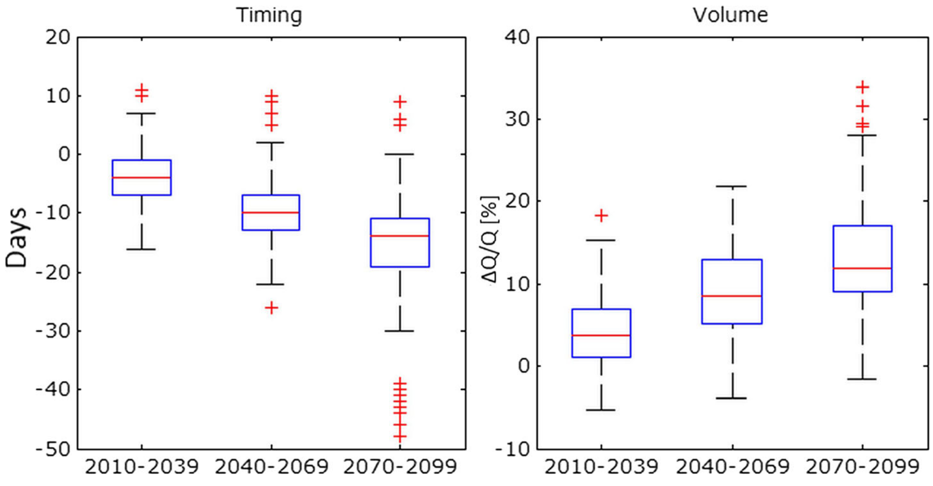

Fig. 4 Changes in the spring flood timing and the total annual flow volume of the Manicouagan River watershed

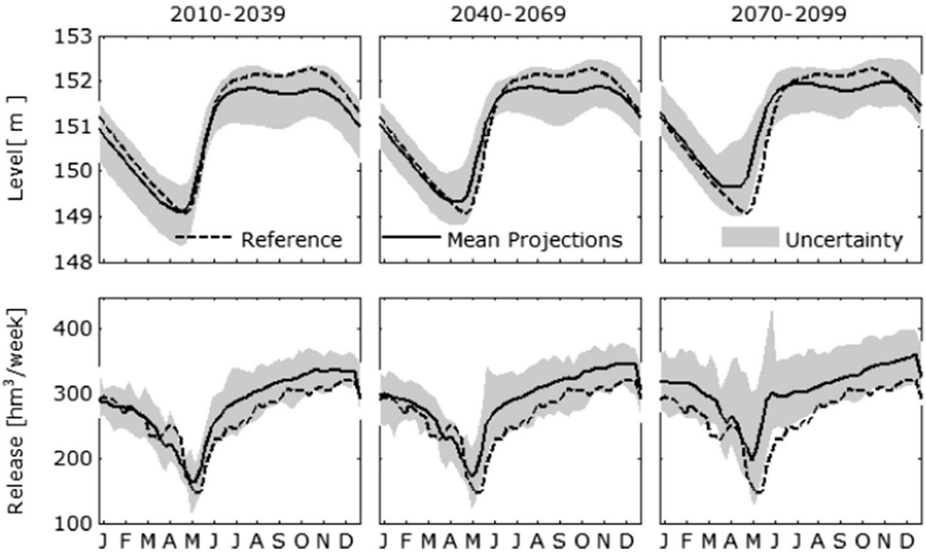

Fig. 5 Manic-5 power station weekly operating policy of the reference period and climate projections for future climate horizons

reservoir filling periods as shown in Fig. 5. In general, with frequent winter thaws, greater inflows during winter and a lower spring peak flow, there would be a time lag between the operating policy for the reference period climate and that of the future climate.

On average, the water level in the Manic-5 reservoir would be kept at a lower level in winter for the 2010–2039 and 2040–2069 horizons in order to provide enough space for snowmelt-related inflows. However, the average water level becomes higher compared to the reference period for the 2070–2099 horizon (Fig. 5). The figure shows that for the first two horizons, the water level curve for the climate projections is under the reference curve and for the last horizon, the climate projections curve passes above the reference curve. The water level follows the evolution of inflows and a low spring peak flow causes a rise in the annual lowest level of the reservoir.

The water level will be kept higher during the spring, as the peak flow will be reduced. The reservoir water levels show a shift, which corresponds to the peak flow shift. Consequently, the lowest water level in the reservoirs will rise. On average, the lowest water levels for the Manic-5 reservoir will be 2, 23 and 56 cm above the lowest water level for the historical optimum operating policy for the three future horizons. For Toulnustouc, the rise of the lowest water levels will be 87, 126 and 184 cm for the future climate horizons. The maximum water levels of the optimum operating policy will be reduced on average by 43, 39, 28 cm for Manic-5 and 31, 34 and 33 cm for Toulnustouc, for the 3 future climate horizons. The decrease of the peak flow volume causes a decrease in the highest water level.

The releases will also increase in the future climate from one horizon to another (Fig. 5) and for all power plants. The Manic-5 power plants will face the highest annual release increases: 5.5, 8.8 and 15.0 % for the future climate horizons. Manic-2 and Manic-1 will have the lowest annual release increases: 4.8, 8.8 and 13.9 % for the same period. Table 3 provides a summary of the impacts of climate change on uncontrolled and cumulated inflows for the optimum operating policy for the 2010–2099 period. The cumulated inflows represent the natural uncontrolled inflows plus releases from upstream hydropower plant. The uncontrolled inflows will increase between 0.1 and 5.6 % for the 2010–2039 horizon. At the end of the century, the increase ranges from 4.4 up to 16.5 %.

Table 3 Average increase of uncontrolled inflows, cumulated inflows and energy generation for future climate horizons with respect to the reference period

	Horizon	Manic-5	Toulnustouc	Manic-3	Manic-2	Manic-1	System
Uncontrolled inflows (%)	2010–2039	5.5	5.6	3.7	1.6	0.1	4.8
	2040–2069	10.2	10.1	5.6	5.9	4.7	9.6
	2070–2099	16.5	14.3	4.4	8.1	7.8	14.7
Cumulated inflows (%)	2010–2039	–	–	5.2	4.9	4.8	–
	2040–2069	–	–	8.9	8.8	8.8	–
	2070–2099	–	–	14.8	14.0	14.0	–
Hydropower generation (%)	2010–2039	4.0	4.7	4.3	4.2	4.1	4.2
	2040–2069	8.2	10.0	8.9	8.8	8.5	8.7
	2070–2099	14.2	14.0	14.7	13.8	13.3	14.1

3.3 Energy Generation and Unproductive Spills

With more inflows to the hydropower plants and reservoirs kept at a higher level, it is obvious that power generation will increase for the future climate (Table 3). The system annual hydropower generation average increase would be 4.2, 8.7 and 14.1 % for the 2010–2039, 2040–2069 and 2070–2099 horizons respectively. The average increase in hydropower production for the hydropower plants Manic-5, Toulnustouc, Manic-3, Manic-2 and Manic-1 would be respectively 8.2, 10.0, 8.9, 8.8 and 8.5 % for 2040–2069 horizon.

Unproductive spills would have an average increase of 122, 68 and 67 % during the future climate horizons with respect to the reference period for the Toulnustouc hydropower plant. The estimated annual spills during the reference period are 44.8 hm^3. The change in the hydrological regime is the main reason behind the increase in unproductive spills, especially for the 2010–2039 horizon. For the other horizons, the spills increase is less important than the 2010–2039 horizon. Winter thaws, lessening of the peak flow volume in the spring, and keeping the reservoir at higher level, explain why. The Manic-2 and Manic-1 run-of-river hydropower plants located downstream of Toulnustouc will have, on average, 19.4 and 24.1 hm^3 of annual unproductive spills for the 2070–2099 horizon, corresponding to an increase of 10 and 6 times respectively. The raise in cumulated inflows (Table 3) and releases from upstream plants explains the increase of spills at those plants. The releases from Manic-3 and Toulnustouc located upstream Manic-2 would have an increase of 14.1 and 14.7 % respectively.

The increase in unproductive spills will reduce the efficiency of the existing system in the future climate. That means for the same quantity of water for hydropower generation, there would be less energy produced in the future climate. Figure 6 presents the efficiency of the whole water resources system for the future climate horizons. The median efficiency is 0.2085, 0.2085 and 0.2084 KWh/m^3 for 2010–2039, 2140–2169 and 2070–2099 horizons, while the optimal operating policy for the reference period gives an efficiency of 0.2088 KWh/m^3. Given the entire Manicouagan water system inflows volume, which can reach tens of millions m^3/year, the decrease of efficiency will cause an important loss of energy in the long run.

The decrease of the system efficiency is explained by the increase of unproductive spills, especially for the Toulnustouc hydropower plant. To solve the problem of unproductive spills, the water system should be adapted to climate change. The adaptation of hydropower plants might consist of non-structural and/or structural modifications. Non-structural modifications consist of the adaptation of operation policy only. The structural adaptation requires the

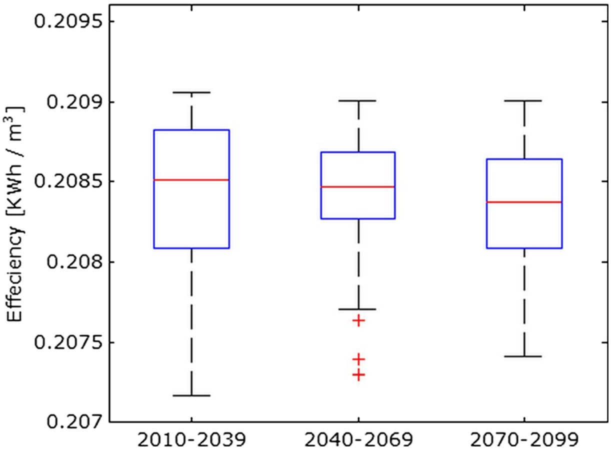

Fig. 6 Water resources system performance for the future climate for the 2010–2039, 2140–2169 and 2070–2099 horizons with respect to the historical period

increase of the generation capacity of hydropower facilities by either adding new turbine-generator units, or replacing some turbines or generators.

In summary, the Manicouagan River basin will become wetter and it will experience milder winter seasons and warmer summer seasons. Climate warming will lead to changes in the seasonality of inflows; winter inflows will increase with a part of winter precipitation falling in liquid form instead of snow, and spring inflows will decline because of earlier snowmelt and the reduced snowpack. These impacts of climate change on the hydrologic regime could be extended to snow-dominated regions especially in winter, whereby the increase of temperature will lead to more frequent thaws. Due to the specific characteristics of each hydropower system, the impacts on operating policy might differ from one system to another. However unproductive spills are susceptible to increase in run-of-river systems or in systems for which the reservoir capacity is small.

The potential for hydropower generation by existing installations of the Manicouagan River water resources system is likely to increase due to projected changes in the annual inflow volume. The optimum operating policy will also change for the future climate as well as the hydropower plant efficiency. The projected operating policy could not be used for water resources system operations as the degree of uncertainty of climate projections is high compared to hourly or daily meteorological forecasts. Nevertheless, GCMs have experienced significant developments in recent years and will continue to do so, resulting in a reduction of uncertainties. Recently, the WCRP released new multi-model data set (CMIP5). These data should not, however, change the main conclusions arising from this paper.

The projected operating policy could be used to evaluate long-term impact of climate change on hydropower generation and to plan either structural or non-structural adaptation strategies. The structural adaptation measure that could be implemented for the Manicouagan River water system is for instance, to increase the installed capacity of hydropower plants (Haguma 2013). In addition, future climate uncertainties should be included in the strategic planning and management process of water resources systems with an implicit representation of climate.

4 Conclusion

This study assessed climate change impacts on the water resources system of the Manicouagan River (Québec, Canada). The analysis of climate multi-model ensemble data showed an increase in the mean temperature and seasonal precipitation for the future climate. Consequently, there would be changes in the hydrological regime, i.e., an earlier timing of snowmelt, a decrease of the spring flood potential and an increase in the total annual runoff volume. The SSDP reservoir optimization algorithm was used to derive weekly operating policy for the existing system. The operating policy for the water resources system for the future climate was adapted by lowering and raising reservoir water levels in the winter and spring respectively. Results show that hydropower generation will increase and non-productive spills will increase for some hydropower plants, which will decrease the overall efficiency of the water resources system.

Although there is confidence that warmer temperatures will affect variables such as evaporation and snow cover, uncertainties concerning the nature of regional changes in precipitation patterns limit the ability to project hydrological changes at the watershed scale (Lemmen and Warren 2004). Therefore the results should be interpreted within their uncertainties. Uncertainties in projected changes in the hydrological system arise from internal variability of the climate system, future GHG emissions, GCMs, downscaling methods and from hydrologic models. With the help of a stochastic optimization algorithm, it was possible to evaluate the impacts of climate change on the operating policy for water resources hydropower plants. The assessment of climate change impacts on water resources systems increases the understanding of possible adaptation measures to future climate scenarios and should be integrated into the process of long-term planning and management of water resources systems.

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