RAPPORT FINAL (EXTRAIT)

Impact of climate change in Canadian river basins and adaptation strategies for the hydropower industry

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Public Summary of Outcomes and Benefits to Canada

The main objective of the project is to assess the potential impacts of climate change on the hydrological regimes of Canadian watersheds and on hydropower facilities located in the provinces of Quebec and Manitoba. Hydro-Quebec, Manitoba Hydro and Ouranos are the industrial partners in this project.

A main component of the project is to evaluate the magnitude of the uncertainties in assessing the impacts because knowledge of the future climate is inherently uncertain. Sources of uncertainties are numerous and include: climate model structure and parameters, hydrological model structure and parameters, natural climate variability, greenhouse gas emission scenarios, and the downscaling of the climate output produced by the models to a spatial scale commensurate with the size of the watersheds under analysis. Furthermore, the impacts of climate change on hydrological variables other than river flow, such as snowpack and soil moisture, are difficult to assess because of the lack of observations. Finally, adaptation strategies, whether structural or non-structural, are also dependent on climate change related uncertainties.

From the perspective of the industry, the key achievements of the project include:

- Evaluation of the expected impacts of climate change on the hydrological regimes of Canadian watersheds;

- Assessment of the magnitude of the various sources of climate change related uncertainties on the hydrological regimes of Canadian watersheds;

- Assessment of various structural and non structural adaptation strategies to reduce vulnerability to climate, such as: probable maximum precipitation and probable maximum flood under current and future climate; adaptation of hydroelectric reservoir operating rules to different climate change projections; evaluation of the capacity to existing hydroelectric stations.

- Formation of highly skilled personnel in the field of hydrological modelling, water resources system management, climate change impact assessment.

- Development of methods and tools (mainly software) for assessing climate change impacts on hydropower production.

These achievements translate into benefits to Canadians as Hydro-Quebec and Manitoba Hydro have consolidated their expertise in climate change in water resources. Results from this research will help to quantify the uncertainty regarding future water availability, keeping decisions makers informed of potential changes in hydropower production.

Moreover, water management software developed in this research has been advantageously transferred to industrial partners. For example, Hydro-Quebec is currently in the process of evaluating a computer code that can produce optimized reservoir operating rules capable of handling non stationary inflows. Also, highly qualified personnel trained in this project are now contributing to the Canadian water resources industry, including engineering firms, water resources agencies, and hydropower companies. While the focus of the project has been on the hydropower industry, the project results will benefit all water-related sectors in Canada.

Report on progress

The project aimed to improve the understanding of climate change impacts on river runoff and to investigate adaptation strategies in areas of interest to Hydro-Quebec and Manitoba Hydro. We proposed a comprehensive research project with the overall objective of evaluating the impacts of climate change on hydrologic regimes and on hydropower facilities in Quebec and in Manitoba. The project had four major interconnected themes:

1. Develop climate projections at the watershed scale based on a combination of GCM, RCM, and statistical approaches;

2. Investigate changes in hydrologic variables such as streamflow, soil moisture, and snow cover over selected catchments of interest to Hydro-Québec and Manitoba Hydro through the application of hydrological models;

3. Evaluate the uncertainty related to climate change flow projections; and

4. Assess the climate change impact on hydropower facilities and explore potential adaptation strategies.

The project ended on December 15, 2011. Significant progress has been achieved towards each of the four above objectives, as detailed below. Full day workshops were held at the Ecole de technologie supérieure (ETS) in Montreal in October 2008 and November 2010 and at Manitoba Hydro's Headquarters in Winnipeg in November 2009. These workshops were a unique opportunity for students of ETS, University of Sherbrooke (UdeS) and University of Manitoba (UofM) to present their most recent research findings to the industrial partners and to engage in fruitful scientific exchange. In 2009, we initiated a comprehensive climate change impact analysis of the Manicouagan River Basin (MRB), a major hydropower system owned and operated by Hydro-Québec. Many graduate students worked on various aspects of this project, covering all four objectives stated above. The MRB served as a key study area where a host of hydrological models, downscaling approaches and water resources models were implemented to assess the hydrological impact of climate change and its associated uncertainties. A similar initiative was initiated in Manitoba where the Churchill River Basin was selected for a comprehensive climate change impact investigation.

The project allowed the training of a significant number of HQP. At ETS-UdeS, 4 PhD students, 4 MSc students, 3 postdoctoral fellows, 2 research associates, and 3 undergraduate students contributed to the project, for a total of 16 HQPs. As of today, 3 PhD are in the latter stages of their program and will have completed and defended their thesis this coming summer-fall. At UofM, 1 PhD student, 3 MSc students, 2 postdoctoral fellows, and 2 undergraduate students contributed to the project, for a total of 8 HQPs.

Objective 1: Develop climate change projections at the watershed scale

Downscaling climate change projections to a scale commensurable with hydrological models is essential for proper evaluation of climate change impact son water resources. We have investigated a number of statistical downscaling techniques; we developed a new approach to account for low frequency variability in observed precipitation and temperature time series; we proposed an hybrid approach that combines the strengths of dynamical and statistical approaches; and we demonstrated the limitations inherent in statistical downscaling approaches of daily precipitation based on transfer functions.

One limitation of daily stochastic weather generators such as the Richardson-based models is their systematic underestimation of monthly and inter-annual variability of daily precipitation and air temperature resulting from decadal oscillations. The main reason is that they do not take into account this low-frequency climate variability. As part of the project, an approach for correcting the low-frequency variability of precipitation based on the observed power spectra of monthly and annual time series has been proposed. The generation of synthetic monthly and yearly precipitation data was achieved by assigning random phases for each observed spectral component. The link to daily parameters was established through linear functions. The results showed that both means and standard deviations of monthly and annual precipitations can be reproduced almost exactly. The proposed method also preserved the autocorrelation of annual precipitation. Moreover, the results showed that the corrected weather series significantly improve the variability of simulated flow discharges at the monthly and annual scales compared to those simulated using the data generated by the standard weather generator. The spectral method was also applied to correct minimum and maximum daily air temperatures. The approach was found to successfully reproduce the observed autocorrelation of average yearly Tmin and Tmax and to preserve their inter-annual variability.

A method based on stochastic weather generators for statistically downscaling regional climate model (RCM) projected precipitation and temperature was investigated. The method can also be applied to GCM output. The method first calls for calibrating a weather generator using observed data. The parameters of the weather generator are then modified to take into account variations projected by a climate model. This variation was based on the well-known delta change approach. The weather generator selected for this research was CLIGEN, which has 9 parameters to generate daily precipitation and air temperature. The approach was compared with the classic delta change method by simulating the temporal evolution of dry and wet day spells, annual and seasonal precipitation, annual and seasonal air temperature, mean and standard deviation of daily precipitation and air temperature. An indirect comparison was also performed by simulating current and future runoff hydrographs of the Manicouagan-5 river basin using daily precipitation and temperature produced by the two downscaling approaches. Results showed that the weather generator-based approach predicted shorter dry day spells for the 2025-2084 period. The standard deviation of daily precipitation and temperature differed markedly depending on the downscaling method. The comparison also highlighted that temperature and precipitation variability play an important role in the processes leading to runoff. This is an important finding as climate variability will be increasing in the future and downscaling methods that cannot take into account these changes are inappropriate for climate change studies.

Direct use of RCM data as input to hydrological models to study climate change impacts is particularly attractive in areas where meteorological data are sparse. However, RCM data often contain biases in both temperature and precipitation data and it is imperative to correct for theses biases before application in hydrologic models. As part of this research, we performed detailed analyses of temperature and precipitation biases of the Canadian Regional Climate Model (CRCM) over the Northern Quebec and in the Canadian Prairie region. Two approaches have been proposed for bias correction: an external approach, based on statistical relationships between bias and CRCM variables affecting temperature and precipitation regimes, for example soil moisture; and an internal approach, which consists in modifying the land surface scheme (LSS) used in the CRCM to better represent the water and energy budgets. We are currently investigating the effect of introducing lateral moisture movement into MESH (modélisation environnementale – système hydrologique) and GEM (Global environmental multiscale) LSS (both developed by Environnement Canada) on the estimation of surface temperature (MESH) and precipitation (GEM). The effect of a change of spatial resolution of the LSS is also currently being investigated.

The project has also investigated how precipitation Intensity-Duration-Frequency curves may change in future climates. IDF-curves are an important engineering tool in urban hydrology. Regional climate models provide information about current and future extreme precipitation down to 15 minute durations. However, with decreasing durations, there is increasing uncertainty and potential biases in climate model estimations of extreme rainfall. Also, climate model data provide information about areal precipitation which introduces some difficulty in comparing with weather station data that represent point observations. To overcome some of these issues, we have investigated the scaling properties of observed and simulated precipitation. Past studies have demonstrated that in many cases extreme precipitation distributions obeys simple scaling laws that seem to be an inherent property of nature and not likely to change in the future, even if the overall climate changes. In the project, we have considered both simple scaling and multi-scaling of IDF curves. The simple scaling generalized extreme value distribution and multi scaling log normal (LN) distribution have been used to generate IDF curves from observed data and from regional climate model data. Several bias correction techniques have been applied and compared. A theoretical approach based on geostatistical considerations has been implemented to derive reasonable areal-reduction factors that allow for a direct comparison of observed and modelled data. The techniques developed in this part of the project were applied to a set of high-quality precipitation stations from Manitoba.

Objective 2: Assess hydrological impacts of climate change

Our contribution to this theme included implementing a number of hydrological models on the Manicouagan River Basin in Quebec and the Churchill River Basin in Manitoba/Saskatchewan. We also completed a study aimed at evaluating the potential for using soil moisture and snow accumulation as climate change indicators.

Spatially distributed and lumped hydrological models have been implemented on the Manicouagan River Basin to assess the impacts of climate change on its hydrological regimes. The following models have been implemented and used in individual students projects: HSAMI (Hydro-Québec), Hydrotel (INRS-ETE), MESH (Environment Canada), SWAT (U.S. Department of Agriculture), HBV (Swedish Meteorological and Hydrological Institute), and HMETS (ETS). An inter-comparison was performed using these models and results are reported in the next section (evaluating uncertainties). Other watersheds were also investigated using these models and include the Gatineau River Basin and the Peribonka River Basin. This was a substantial effort as Hydrotel, MESH, SWAT and HBV are spatially distributed models, and as such they require many layers of data (digital elevation model, land cover, soil type etc.) to operate. All these models, with the exception of MESH and HBV, were calibrated using the Shuffled Complex Evolution algorithm. The HBV and the MESH were manually calibrated.

In the Prairie region, two hydrologic models have been implemented for the Churchill River basin: the Watflood model and the VIC model. Because of the lack of observed weather records in the region, the two models were calibrated using climate data from the North American Regional Reanalysis.

Although diversified in scope and objectives, student projects shared a common feature of assessing climate change impacts on hydrological regimes. Major findings of two studies are now presented. For the other projects, please refer to sections: Objective 1, Objective 3 and Objective 4.

1- Use of snow cover and soil moisture as potential climate change indicators.

The effects of climate change on the snow cover and the soil moisture regimes were assessed on the Gatineau River Basin by driving the Hydrotel model with temperature and precipitation output from the CRCM. The methodology consisted in the following steps: hydrological model calibration using observed meteorological data; model validation by comparing observed and simulated flows; further validation and analysis of the spatial and temporal patterns of snow cover extent and soil moisture for three soil layers (approx. 0-10; 10-30; and 30-100 cm) using satellite-derived observations (for snow) and reanalyses (for soil moisture), and comparison with snow and soil moisture values produced by the CRCM; simulation of the snow and soil moisture regimes under future climate as generated by the CRCM; analysis of the results and determination of promising metrics for climate change detection. Results indicate that the snow cover spatial and temporal regimes are expected to change dramatically by year 2050-2070, with reductions in the order of 50% for the maximum and average snow water equivalent. Moreover, some areas of the basin are more sensitive to changes in snow cover conditions (which appear to be related to land cover types) and therefore more amenable to be used as potential climate change indicator sites. Climate change is expected to decrease soil moisture in the watershed and the magnitude of the decrease varies geographically (due to soil types). However the signal is not very strong, therefore soil moisture does not appear as a promising indicator of climate change, at least for that river basin. Investigations on other watersheds are required in order to draw more definitive conclusions.

2- Impact of climate change on the Churchill River Basin

Several hydrological models of varying complexity were set up to simulate streamflow in the Churchill River basin. The different models were used to simulate the hydrological impact of climate change using data from a large number of GCMs and different emission scenarios. The delta method was applied to adjust the input data and develop projected future flows. This methodology has allowed the development of hydrograph envelope curves that encompass the full range of predicted hydrological regimes in the basin. The results were analyzed statistically to determine the major sources of uncertainty. The results of this portion of the project provide information which will allow the development of a resource utilization strategy based on the predicted availability of water within the basin.

For the Churchill River basin, we also conducted a more detailed analysis of various components of the climate and hydrologic cycles. Present and future moisture flux convergence over the basin was calculated from the climate model's atmospheric data and compared to observed reanalysis data from NARR. Changes in hydrological processes were assessed by using CRCM data as input to the Variable Infiltration Capacity (VIC) hydrology model over the basin.

Annual means of water budget components shows an overall good agreement with observed data. The CRCM atmospheric moisture flux and storage tendencies are consistently represented and show reasonable agreement with NARR, partly because atmosphere-land surface interactions are well represented by the land-surface scheme in the CRCM. The VIC model was used to study changes in the regional hydrological cycles, including evaporation, snow water equivalent (SWE) and stream flow. Results from VIC simulation using CRCM climate (1976-2005 and 2020-2049) shows increase in evaporation during spring and summer and the SWE also shows increase during January to April with a decrease in total snow duration. An overall increase in streamflow volume is observed with the highest increase occurring in summer.

Objective 3: Evaluate uncertainties

Our contribution to this theme includes: an analysis of the significance of hydrological model parameters and structure as sources of uncertainty in modelling future river flow conditions; a global uncertainty study of the hydrological impacts of climate change for a Canadian watershed; the uncertainty of downscaling methods in quantifying the impact of climate change on hydrology; the establishment of a conceptual framework for assessing climate change uncertainties in modelling river regimes; and a comparison of performance of different evapotranspiration algorithms in the performance of the HSAMI model for climate change studies.

The role of hydrological model structure and parameters to the uncertainty related to hydrological modelling was established through the use of two very different simulation tools (structural uncertainty) and by performing multiple automatic calibrations with each model (parameter uncertainty). The study site was a sub-watershed of the Gatineau River Basin. The analysis was first carried out under recent past climate and then under modified climate conditions following two scenarios analysed separately. Results show that for both hydrological models, parameter uncertainty is more important in some specific periods of the year: summer and fall for the physically-based model, and winter and spring peak flood for the conceptual model. Overall, this study revealed that the impact of hydrological model structure uncertainty is more significant than the effect of parameter uncertainty, under recent past climate as well as future climate conditions.

The role of hydrological model structure and parameter uncertainty was further investigated through a global uncertainty study by combining results from an ensemble of 6 GCMs, 2 greenhouse gas emission scenarios (GGES), 5 GCM initial conditions, 4 downscaling techniques, 3 hydrological models, and 10 sets of hydrological model parameters. Each climate projection was equally weighted to predict the hydrology of the Manic-5 watershed for the 2081-2100 horizon. The results showed that the choice of the GCM is consistently a major contributor to uncertainty. Other sources of uncertainty, such as the choice of a downscaling technique and the GCM initial conditions also have comparable or even larger uncertainty for some hydrological variables. Uncertainties linked to GGES and the hydrological model structure are somewhat less than those related to GCMs and downscaling techniques. Uncertainty due to the hydrological model choice of parameters has the least contribution among all variables selected.

A specific study was conducted using 6 downscaling methods to investigate the uncertainties in quantifying the impacts of climate change on the hydrology of the Manic-5 river basin. The downscaling methods regrouped dynamical and statistical approaches. Results indicate a general increase in winter discharge while summer discharges are predicted to decrease by most methods. The regression-based statistical methods showed severe increases in winter flows and considerable reductions in peak discharge. The uncertainty envelope was found to be comparable to that of the GCM uncertainty and much affected by the regression-based statistical downscaling methods.

The global uncertainty and downscaling method studies above assumed each scenario to be equiprobable. In another study, we investigated the effect of assigning unequal weights to various components of the uncertainty analysis. A conceptual framework for incorporating various sources of uncertainty into climate change studies based on a Monte-Carlo approach was proposed, by which each major source of uncertainty is represented by a probability distribution. The sources of uncertainty considered were: climate model structure; climate sensitivity; climate variability and hydrological model structure. These were elected based on current scientific literature and recent work by our team. For the climate models, precipitation and temperature output from 10 GCMs were obtained from Ouranos. A software, called

MAGICC-ScenGen, developed at UCAR in Boulder, Co., was used to emulate various GCMs with different climate sensitivities, to increase the number of temperature and precipitation time series. Six hydrological models (see Objective 2 above) were calibrated on the Manic-5 River Basin to assess model structure uncertainty. Unequal weights were assigned to GCM structure based on the Reliability Ensemble averaging (REA) method of Mearns and Giorgi (2002). A triangular shape probability distribution was assumed for climate sensitivity based on suggestions by New and Hulmes (1999). Equal weights were assumed to hydrological model structure as well as natural climate variability scenarios. Results have shown that considering unequal weight distributions influenced the distribution of some hydrological variables. e.g. winter flows, while the influence on other variables, such as spring peak flow, was less significant.

We have evaluated the evapotranspiration equation in HSAMI against 6 other equations available in the literature. The aim was to compare the relative performance of the various equations for their use in climate change studies. This was accomplished by modifying the HSAMI code for calling the selected ET routines and calibrating HSAMI with flows from three watersheds for each ET equations. Modelled ET for current and future climates were compared with CRCM's ET estimates. Results show that the original ET equation in HSAMI outperforms the other equations for climate change impact modelling.

Objective 4: Climate change impacts on hydropower facilities and adaptation strategies

Our contribution to this theme includes a comparison study of two optimisation techniques for use in climate change studies: adaptation of the stochastic dynamic programming approach to account for non-stationary inflows; investigation of structural and non-structural adaptation strategies for maximizing hydropower production; and the estimation of the probable maximum precipitation under current and future climates.

We examined the problem of finding an optimal operating strategy for HQ's Manicouagan River and Outardes River hydroelectric installations. More specifically, we compared the stochastic sampling dynamic programming algorithm (SSDP) against the lag-1 stochastic dynamic programming (SDP) already implemented at HQ. The SSDP approach uses inflow scenarios in the calculation of the cost-to-go function, as opposed to the classic SDP which is based on a statistical distribution of inflows. The interest of directly using inflow scenarios is that, contrary to the SDP approach, inflows do not have to be stationary. Therefore, this approach appears to be more amenable to climate change impact studies. A drawback of the approach is that it requires observations of a basin state variable, such as snow water equivalent. The two approaches were tested with inflows simulated using a lumped hydrological model with precipitation and temperatures produced by a stochastic weather generator. Results showed that SSDP handled inflow variability better than SDP, as more energy was produced either by a reduction of the total amount of water spilled (Manicouagan system) or by operating the reservoirs at higher water levels (Outardes systems). The SSDP and SDP programming codes were delivered to HQ and are currently being tested by the company.

An approach was also proposed to adapt the classic SDP algorithm to handle non stationary inflow time series. The stochastic dynamic programming (SDP) approach, applied to a multi-reservoir hydroelectric system, is an optimisation technique which determines reservoir operating strategies by maximizing expected benefits subject to hydraulic constraints such as target reservoir levels, while considering the natural variability of observed flows. As mentioned above, the method assumes the inflow to be stationary. In a previous CRD project, simulated non stationary inflows caused by climate change were handled by considering a 30-year backward moving time window where stationary climate was assumed.

The approach, applied on the Peribonka river system, was shown to result in an increased hydropower production compared to using the entire time series in which non stationary inflows existed. In this project, we relaxed the stationary inflows constraint by using a mixture of Bayesian Dynamic Models (MBDM). The approach enables the model to self-adjust according to the degree of non stationarity found in the time series as new observations are obtained and can be linked to the SDP algorithm. Results revealed that the MBDM resulted in improved reservoir operating strategy compared to the classic SDP approach with a moving time window.

The above approaches used simulated future time series from a single climate model. An extension was developed using multiple time series, each originating from a different GCM. Probabilities of switching between GCM scenarios were added in the SDP approach. The approach was used to optimize the operating strategy of the Manicouagan River system and also to investigate the feasibility of adding capacity (turbines) to the existing system for further increasing hydropower production. Results indicate that adding turbines will increase production but the economic feasibility of this strategy is uncertain.

We also have developed an approach for evaluation the summer-fall probable maximum precipitation (PMP) using CRCM data as main input to the model. The approach is based on the concept of precipitation maximization into an atmospheric column and follows the general guidelines presented by the World Meteorological Organization, with the exception that we are using information such as specific humidity and dew point temperature over an entire atmospheric column, as opposed to surface information provided by weather stations. Results were obtained for a region covering the Manic-5 River Basin. A comparison with the approach developed by SNC Lavalin indicates that our estimate of 24-h, 48-h and 72-h PMP is lower than that of SNC by about 30%. However, we utilised information from only one CRCM tile. An evaluation of the PMP in a changed climate by using the CRCM output for the 2011-2040, 2041-2070 and 2071-2100 horizons was also performed. Although CRCM output clearly shows an increase of the precipitable water in an atmospheric column as we go further in the future, the time evolution of the summer-fall PMP did not follow a distinct upward trend pattern. Nevertheless, taking the average of the 2041-2070 and 2071-2100 horizon PMPs shows that future PMP could be more important than current PMP for the 24h, 48-h, and 72-h duration rainfall. An evaluation of the probable maximum flood (PMF) using a hydrological model with PMP as input will also be carried out over the Manic-5 River Basin. The temporal evolution of the various percentile flood values did not display an obvious upward or downward trend, which was expected given the PMP estimates. Moreover, interactions with soil moisture/evapotranspiration were found to affect the magnitude of the simulated PMF and therefore its evolution with climate change.

Dissemination of Research Results

Refereed Journal Articles Submitted :	4
Refereed Journal Articles Accepted or Published:	8
Conference Presentations/ Posters:	24
Other (Technical Reports, Non-Refereed Articles, etc.):	0
How many of the publications, conference presentations, etc. identified above were co-authored with a non-academic partner?	8

Published/accepted papers

1) Chen, J., Brissette, F., Leconte, R. Global uncertainty study of the hydrological impacts of climate change for a Canadian watershed. Accepté à *Water resources research*, oct. 2011.
2) Côté, P., Haguma, D., Leconte, R. et Krau, S. Stochastic optimisation of Hydro-Quebec hydropower installations: A statistical comparison between SDP and SSDP methods. Accepté à la *Can J. Civ. Eng.*
3) Poulin, A., Brissette, F., Leconte, R., Arsenault, R., Malo, J.-S. Uncertainty of hydrological modelling in climate change impact studies. Sous presse. *J. Hydrol*.
4) Tareghian, R. and P.F. Rasmussen. 2011. Analysis of Arctic and Antarctic sea ice extent using quantile regression. International Journal of Climatology. Sous presse.
5) Chen, J., Brissette, F. and Leconte, R. 2011. Assessment and improvement of stochastic weather generators in simulating maximum and minimum temperatures. *American Society of Agricultural and Biological Engineers*, 54(5):1627-1637.
6) Chen, J., Brissette, F., Leconte, R. 2011. Uncertainty of downscaling method in quantifying the impact of climate change on hydrology. *Journal of Hydrology*, 410(3-4):190-202.
7) Chen, J., Brissette, F.P., Leconte, R. 2010. A daily stochastic weather generator for preserving low-frequency variability. *J. of Hydrol.,* 388(3-4):480-490.
8) Minville, M., Krau, S., Brissette, F. and Leconte, R., 2010. Behaviour and Performance of a Water Resources System in Québec (Canada) Under Adapted Operating Policies in a Climate Change Context. *Water Res. Mgt*, 24(7): 1333-1352.

Submitted papers

9) Haguma, D., Leconte, R., Brissette, F. Optimization of hydropower generation under climate change conditions. Soumis à ASCE Journal of Water Resources Planning, Mars 2012.
10) Haguma, D., Leconte, R., Krau, S. Water resources optimization method in the context of climate change. Submitted to Water Resources Research, Mars 2012.
11) Arsenault, R., Malo, J., Brissette, F., Minville, M., Leconte, R. Structural and non-structural climate change adaptation strategies for the Péribonka water resources system. Soumis à Water Resources Management, Sept 2011.
12) Beauchamp, J., Leconte, R. Probable maximum Precipitation and Flood of a Northern Canadian River Basin under Climate Change conditions. Soumis Revue can. des ress. hydriques.

Conferences presentations/posters

13) Haguma, D., Leconte, R., Krau, S., Côté, P. 2012. Optimization approach for water resources long term planning and management. European Geophysical Union Conferene, Vienna, Austria, April 23-28, 2012.
14) Chen, J. Brissette, F., Poulin, A., Leconte, R., 2011. Global uncertainty of the hydrological impacts of climate change for a Canadian watershed. 2011 World environmental and water resources congress, Palm Springs, California, May 22-26, 2011.

15) Alassimone, C., Leconte, R., Brissette, F. 2011. Analysis of temperature and precipitation from the canadian regional climate model...: Assessment ... new bias correction method. World environmental and water resources congress, Palm Springs, California, May 22-26, 2011.
16) Zhao, Y., Leconte, R., Brissette, F. 2011. Uncertainties of GCM structure and climate sensitivity in the hydrologic response of a Northern river basin to climate change. World environmental and water resources congress, Palm Springs, California, May 22-26, 2011.
17) Côté, P., Leconte, R., Trudel, M. 2011. Stochastic optimization of reservoir operation using primary-dual nonlinear interior point method. World environmental and water resources congress, Palm Springs, California, May 22-26, 2011.
18) Poulin, A., Côté, P., Brissette, F., Leconte, R. 2011. Hydrological model calibration : battle of the global optimization methods. 2011 World environmental and water resources congress, Palm Springs, California, May 22-26, 2011.
19) Tareghian, R., Rasmussen, P.F., Kim, S.J., and J. Anderson. 2011. A comparative study of observed and North American Regional Reanalysis climate extremes changes over the Canadian Prairies using quantile regression. AGU Fall Meeting, San Francisco, December 5-9, 2011.
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21) Zhao, Y., Leconte, R., Brissette, F. 2011. Assessing climate change impacts on hydrology with uncertainties of GCM structure and climate sensitivity. International Symposium on Climate Change and Water, Nanjing, China, April 20-21, 340-346.
22) Chen, J., Brissette, F., Leconte, R. 2011. Reliability assessment of statistical approaches in downscaling precipitation for North America. International Symposium on Climate Change and Water, Nanjing, China, April 20-21, 249-256.
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25) Leconte, R., Brissette, F. et al. 2010. Climhydro : impact des changements climatiques sur les bassins versants des rivières canadiennes et stratégies d'adaptation pour l'industrie hydroélectrique canadienne. 4ième Symposium scientifique Ouranos, Québec, 17 et 18 novembre 2010.
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27) Poulin, A., Brissette, F.P., Leconte, R. 2009. The uncertainty of hydrologic models and calibration in a changed climate. 62e congrès annuel de l'ACRH: tendances et défis à venir dans la gestion des ressources hydriques, Ass. can. des ressources hydriques, Québec, Can.

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29) Poulin, A., Brissette, F.P., Leconte, R. 2009. Can we use hydrological models calibrated with past data for climate change studies? AWRA Spring Specialty Conference: Managing Water resources and Development in a Changing Climate, Anchorage, ÉU.
30) Desrochers, G., Roy, R., Roy, L., Pacher, G., Guay, F., Tapsoba, D., presented by R. Leconte. 2009. Comparing methods to investigate the impacts of climate change. AWRA Spring Specialty Conference: Managing Water Resources and Development in a Changing Climate, Anchorage, Alaska, May 4-6 2009.
31) Beauchamp, J., Leconte, R. et Brissette, F. 2009. Estimation d'une précipitation maximale probable sur un bassin non jaugé sous un climat modifié. 2nd Climate Change Technology Conference, Hamilton, ON, May 12-15.
32) Yi, Y., and Rasmussen, P. 2009. Studying hydrological response of the Churchill River to climate change using distributed hydrological models. AGU 2009 Joint Assembly, Toronto, ON, May 24-27.
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Future Plans

Describe any follow-up or related work that will be undertaken as a result of this project, who will be involved in this work (including partners) and how it will be funded.

The project allowed investigating a number of adaptation strategies to cope with potential climate related impact changes for the hydroelectric industry. It also highlighted the importance, and challenges of incorporating the many sources of uncertainties in quantifying the impacts of climate change on hydropower production.

These findings sustained the interest of Hydro-Quebec (HQ) for a follow-up project. Moreover, a research assistant involved in the project moved in January 2011 to Rio Tinto Alcan (RTA) as a research scientist, where he heightened company's awareness of to the importance of better coping with climate variability in the management of RTA's hydropower facilities. As a consequence, both HQ (hydropower production Division and Institut de recherche d'Hydro-Québec) and RTA (Energy Division) decided to embark on a follow-up project.

A research proposal was submitted in January 2012 in NRSERC's CRD program. The main focus of the 4-year proposed project is on the development of tools and methods for optimizing hydroelectric production given increased climate and hydrological variability. The project will involve the participation of University of Sherbrooke, École de technologie supérieure (ÉTS) and University du Québec à Chicoutimi (UQAC). Project leader is professor Robert Leconte, and co-applicants are professors François Brissette, from ETS and Marie-Amélie Boucher from UQAC.

Knowledge and Technology Transfer

Briefly describe these outcomes

Stimulus for future R&D

A follow-up project was submitted to NSERC in January 2012, involving Hydro-Quebec and a new industrial partner, Rio Tinto Alcan. The project is currently undergoing an evaluation process. The project, which will hopefully start in summer-fall 2012, will focus on the development of tools and techniques for better handling climate variability and change in the planning and operation of current and future hydropower systems.

Enhance skills and knowledge of personnel in the partners' organisation

Students that were involved in the project obtained positions in the partners' organization are:

A master's student (name not given to preserve confidentiality) acquired an expertise in hydrological modelling and water resources management. He currently works at Hydro Quebec' Production Division and assists in the day-to-day operations of HQ's facilities.

A research assistant worked on developing optimization programs to handle non stationary inflows for producing reservoir operating rules. After one year, he obtained a position at Hydro-Quebec where he pursued the development of the programs and was a main scientific liaison between our research team and HQ.

A research assistant acquired an expertise in hydrological modelling and hydrological forecasting and in using these technologies in reservoir models for optimizing hydropower production. He now works as a researcher for Rio Tinto Alcan.

A master's student completed his degree at the University of Manitoba during which he acquired an expertise in hydrological modelling and climate change. He obtained a position at Manitoba Hydro soon after graduation.

Lastly, the project allowed personnel already in place in the partner's organisation to enhance skills and knowledge in hydrological modelling and climate change impacts. James Merleau, a research scientist from the Institut de recherche d'Hydro-Québec, who is an expert in statistics, closely collaborated in our project and developed an approach to handle hydrological non stationarities in reservoir optimization models. His involvement in the project allowed him to develop knowledge in climate change impacts, hydrological modelling and water resources models.

Improve an existing product

Hydro-Quebec currently owns a computer program for optimizing reservoir operating rules to maximize hydropower production. The program was developed for a single reservoir. As part of this project, we developed a computer program to handle two reservoirs in parallel and two reservoirs in series. The computer program was transferred to Hydro-Québec who is currently testing and adapting the program for its specific uses.

Develop a new product

We have developed a computer program to optimize reservoir operating rules for two reservoirs in series and two reservoirs in parallel based on a programming technique capable of directly handling inflow scenarios. The computer program was recently transferred to Hydro-Québec who is currently testing and adapting the program for its specific uses.

Knowledge and Technology Transfer

Describe any environmental or social benefit that resulted or could result in the future from this research

Climate change, its potential impacts and how to adapt to these impacts is a pressing issue, as there are evidences that these impacts have started to manifest. This is particularly true of hydrological impacts of climate change. In Canada, recent research has shown that our rivers are more and more experiencing high and low flows at an increasing frequency and severity. Establishing and quantifying potential environmental and socio-economic impacts and adapting strategies to better cope with adverse impacts or to capitalize on positive repercussions of climate change is still a challenge. This is because of the many sources of uncertainties characterizing such estimation. Significant progress was accomplished in this project, which will result in environmental and social benefits.

Benefits to Hydro-Québec and Manitoba hydro

Perhaps one of the most significant benefits to the partners is that we now better know the magnitude of the various sources of uncertainties affecting our estimation of future hydrological regimes in Canadian rivers. The project confirmed that the global climate models are the major source of uncertainty in projecting annual and seasonal runoff as well as spring peak flow and summer/winter low flows. However, we have demonstrated that the downscaling approach used to global climate model projection at the watershed scale cannot be neglected, nor the structure of the hydrological model used in these studies. Better quantifying the importance of these sources of uncertainty will help industry at better quantifying the impacts of climate change on their water resources. Adaptation strategies were also investigated, namely non structural alternatives such as modifying reservoir operating rules; probable maximum precipitation and probable maximum flood under future climate conditions; optimisation software for reservoir management capable of better handling non stationary of reservoir inflows; and structural alternatives such as adding hydropower capacity to existing facilities to maximize hydropower production by reducing unwanted spills. Although more research is needed in these areas, our study has shown that non structural alternatives offer greatest potential to cope with climate change issues, at least for the hydropower systems investigated, although adding capacity may be an attractive alternative if the unwanted spills are significant, which may occur in run of river stations.

Benefits to the Canada

Hydropower and other water resources managers and planners tend to neglect climate change impacts in their decision making process, often because they are ill informed about the magnitude of the impacts and their related uncertainties. The project helped filling these gaps, for example by an improved quantification of future flows and associated uncertainties. Better information results in more sound decisions and therefore improved social, environmental and economic benefits. For example, other hydropower companies, such as Rio Tinto Alcan (RTA), will be able to adapt their hydropower facilities to maximise energy production under changed climate conditions, thereby maximising aluminum production. Findings of this study are already raising interest from RTA, who recently started to collaborate in a follow-up study.
The remarkable geographic, ecological and economic diversity of Canada means that vulnerabilities to climate change vary significantly across the country. Understanding those vulnerabilities is essential for effective adaptation strategies. In addition to hydropower, findings from this project can also be applied to other water resources related sectors, which will benefit from this research. For example, the agricultural industry will be confronted with increased extreme events such as droughts/floods. Agriculture will benefit from this research as it will be possible to investigate various adaptation strategies, e.g. improved irrigation scheduling, to cope with climate change impacts, now that we have a better understanding of hydrological impacts and associated uncertainties. Other Canadian sectors include public safety (flood control), municipal engineering (urban drainage) and the forest industry (forest fire management).