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Hydrological and water temperature modelling for dam decommissioning and climate change studies

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Abstract: The Mactaquac Dam and Generating Station, a 672 MW run-of-the-river hydroelectric facility located on the Saint John River, Canada, will have to be decommissioned or reconstructed by 2030. In order to simulate the impact of reservoir emptying (drawdown) and climate change on the thermal regime of the lower reaches of the river, the CEQUEAU hydrological and water temperature model was used. The model was successfully calibrated and validated for both flow and water temperature, with Nash coefficients ranging from 0.63 to 0.86 for flow and RMSE ranging between 0.74 °C and 1.3 °C for temperature. Subsequently, different drawdown and climate change scenarios were simulated using the calibrated models. Median value of maximum water temperature in the river is expected to increase by 2-3 °C by 2100, regardless of the dam reconstruction scenario.

Key words: CEQUEAU, hydrological model, water temperature, dams, climate change

1. INTRODUCTION

A number of dams have outlived their intended duration and/or are no longer serving their initial purposes. Their presence in many riverscapes has been recognized as a potential threat to aquatic ecological communities for decades (Grant 2001). The large number of aging dams in North America and Europe has resulted in the development of a number multidisciplinary studies related to dam removals (e.g. Manatawny Creek study: Bushaw-Newton et al. 2002; Elwha River: Duda et al. 2011). In Eastern Canada, this science is in its infancy and the first major research endeavour on dam removal is currently underway on the Saint John River drainage basin in New Brunswick. The dam replacement/removal decision is to be taken among three possible options: repowering the station with a new powerhouse and spillway, rebuilding the spillway only, or removing all parts of the dam/station. One key component of this study is the implementation of a major modelling effort to simulate the possible impacts of these future management options. In addition, the modelling exercise allows for the investigation of the possible impacts of climate change on the hydrology and thermal regime of the system. This paper focuses on the hydrological/water temperature modelling component of MAES. The main objectives are: 1) to investigate the sensitivity of the model to its discretization module (i.e., the size of elementary hydrological units used in the model); 2) to simulate the most probable drawdown scenario and to investigate its potential impact on the water temperature regime of the river; and 3) to investigate the possible impacts of climate change on flows and temperature on the lower Saint John River.

2. METHODS

2.1 CEQUEAU hydrological and water temperature model

The hydrological component of CEQUEAU (Morin and Couillard 1990) decomposes the drainage basin into Elementary Hydrological Units (EHU) of equal area (called "whole squares"). For each EHU, altitude, percentage of forest cover and the percentage of EHU covered by lakes and wetlands are required as inputs. Required meteorological inputs include daily solid and liquid (or total) precipitation, as well as maximum and minimum daily air temperature.

The CEQUEAU water temperature model is based on heat budget calculations. Water temperature (T_w; °C) is calculated as the ratio of the enthalpy (H; MJ) over the product of water volume (V; m^3) and water specific heat capacity ($\theta = 4.187$ MJ/(m$^3\cdot$°C)):

$$T_w = (H/(V\,\theta)) \tag{1}$$

Change in H at each time step (ΔH) is calculated on the simulated water volume on each EHU by summing the following heat fluxes: incoming short wave radiation, net longwave radiation, latent heat loss (evaporation), sensible heat lost or gained through convection, heat advected from upstream and lost to downstream by water movement, heat fluxes from local runoff, interflow and groundwater input. To perform these calculations, solar radiation, pressure, wind velocity and cloud cover are also required.

2.2 Implementation and model calibration

Flow routing and physiographic information required as model inputs were extracted and computed using an automated GIS tool developed by the first author (Dugdale et al. 2016). Following the application of this algorithm, 650 EHUs of 100 km^2, were initially defined and further divided into 1389 partial squares.

The model boundary conditions (flow and temperature) were imposed at the outflow of the Mactaquac Dam. Reservoir water temperatures associated with this outflow (temperature at a reservoir depth of 7m) were simulated using a simple non-linear regression (Mohseni et al. 1998) with air temperature (14-day moving average, measurements taken at Environment Canada Climate station 8102536) as the predictor. Once calibrated, the model produced high R^2 (0.98) and low RMSE (0.64 °C).

Meteorological inputs used by the hydrological model were gathered from 44 Environment Canada weather stations in or close to Saint John River basin for the period 1983 – 1994, the longest period with concomitant data. This period was divided in two sub-periods, seven years for calibration and four years for validation. A block bootstrap approach was used to test different periods for calibration and validation. Model parameters were initially adjusted by hand and subsequently the CMA-ES automatic calibration algorithm (Hansen and Ostermeier 2001) was applied. Model performance was evaluated using the Nash Sutcliffe coefficient (Nash and Sutcliffe 1970; Equation 2), the root-mean-square error (RMSE; Equation 3) and the bias (bias; Equation 4).

$$NTD = 1 - \frac{\sum_{i=1}^{n}(Q_{obs,i} - Q_{sim,i})^2}{\sum_{i=1}^{n}(Q_{obs,i} - \bar{Q}_{obs})^2} \tag{2}$$

$$\%\mathrm{RMSE} = \frac{\left(\frac{1}{n}\sum_{i=1}^{n}\left(Q_{obs,i} - Q_{sim,i}\right)^2\right)^{0.5}}{\bar{Q}_{obs}} \times 100 \tag{3}$$

$$Bias = \frac{1}{n}\sum_{i=1}^{n}(Q_{obs,i} - Q_{sim,i}) \tag{4}$$

where $Q_{obs,i}$ and $Q_{sim,i}$ are the observed and simulated mean discharges respectively on day i and $\bar{Q}_{obs}$ is the mean observed discharge for the entire study period with a length of n days.

The thermal model was calibrated by comparing observed and simulated daily mean temperatures using temperature observations from a thermograph moored in 2011 and 2012 at a the Maugerville station, a few km downstream of Fredericton. Initial model calibration was conducted by hand and subsequently optimised using the Tabu Search algorithm (Zheng and Wang 1996).

Validation was completed using water temperature time series recorded in 2014 in the main stem of the Saint John River at Fredericton. Simulations were also inspected against temperature records from tributaries of the Saint John River (Nashwaak and Keswick Rivers). The RMSE, which is the most common performance metric used to assess thermal models, was used to compare observed and simulated water temperature time series.

2.3 Drawdown scenarios

The reservoir drawdown scenario for the Mactaquac headpond that was considered in the models consists of four stages: 1) An initial (~1 month) drawdown following the spring freshet, 2) a ~5 month period with no drawdown in order to demolish the existing sluiceway, 3) a second ~1 month drawdown lowering the level to its pre-impoundment state and 4) a slow final drawdown draining the remainder of the headpond over a period of 29 months.

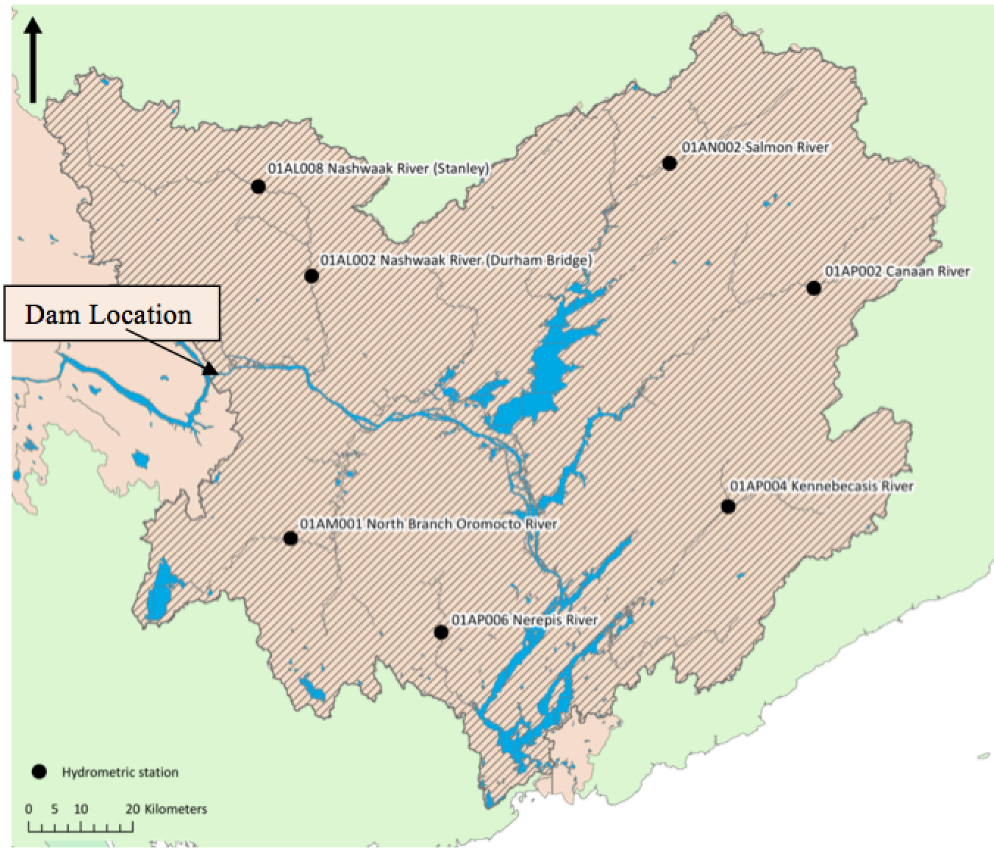

Figure 1. Map of the Lower SaintJohn River drainage basin showing the location of hydrometric gauging stations on the main tributaries.

Emptying the Mactaquac dam reservoir would therefore involve the release of a large volume of hypolimnetic water from the Mactaquac headpond. River temperatures associated with this drawdown scenario were modelled using CEQUEAU by imposing headpond outflows and temperatures at the upstream-most partial square. The model was then used to simulate water temperatures downstream of this point corresponding to varying meteorological conditions and facilitating comparison with a baseline time series of simulated temperatures from the recent past (2010-2014).

Drawdown scenarios were constructed using meteorological data from 1995 to 2014. A scenario includes 36 months and thus the historical time series were divided in sub-periods (i.e. 1995-1997, 1996-1998, etc.) starting from 7 days after the peak freshet discharge event during the first year of each scenario. In total, 15 drawdown simulations were performed.

2.4 Climate change scenarios

Meteorological inputs to the hydrological and water temperature models were extracted from 11 simulations generated by regional climate models (RCM) driven by global climate models (GCM) at the RCM boundaries. A number of more or less pessimistic greenhouse gas (GHG) scenarios were selected with a view to encompassing the range of variability in projected temperature and precipitation change. CEQUEAU flow and water temperature simulations associated with these climate change scenarios were subsequently generated and compared to the reference period.

3. RESULTS

3.1 Validation of hydrological and water temperature models

The simulated flows during the various validation periods show good agreement with observations on tributaries of the Saint John River located downstream of the dam, as shown by the NTD Values (all ≥ 0.6) reported in Table 1.

Table 1. Mean performance statistics for all block bootstrapped 4-year validation periods.

Station	Nash-Sutcliffe coefficient	RMSE	%Bias
Nashwaak at Durham Bridge	0.86	16.28	0.66
Nashwaak at Stanley	0.84	7.64	1.35
North Branch Oromocto at Tracy	0.71	10.11	-0.19
Nerepis River near Fowlers Corner	0.76	6.31	-0.35
Salmon River at Castaway	0.70	14.39	-0.98
Canaan River at East Canaan	0.62	10.52	-1.48
Kennebecasis River at Apohaqui	0.60	17.85	-3.16

An example of observed vs. simulated flows from the Nashwaak River (Figure 2) also shows strong concordance. Some of the peak discharge values were poorly simulated. However, given that the emphasis in this modelling project is on water temperature and that the highest values of temperature occur during low flow periods, the impact of peak flow underestimation on thermal modelling is minimal.

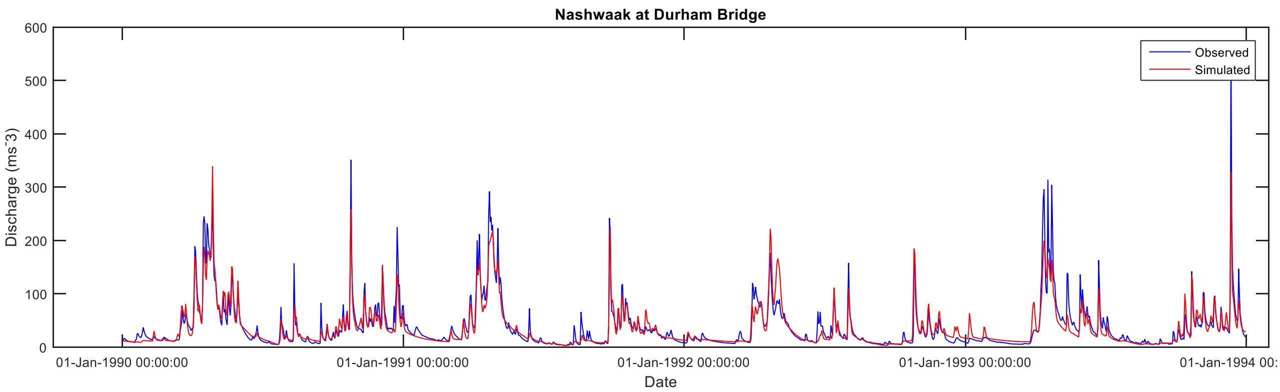

Figure 2. Observed and simulated hydrographs for gauging station at Durham Bridge on Nashwaak River showing good model fit (Nash-Sutcliffe coefficient = 0.86).

Similarly, the thermal model performed quite well (RMSE < 1.0 °C on the main river in the summer and RMSE < 1.4 °C on tributaries; see Table 2).

Table 2. RMSE for four temperature sites within the lower Saint John River watershed.

Station	Summer RMSE (°C)	Annual RMSE (°C)
Saint John River at Fredericton	0.74	0.97
Saint John River at Maugerville	0.98	1.19
Nashwaak River at Marysville	1.39	1.12
Keswick River at Keswick	1.32	1.27

3.2 Thermal modelling and reservoir drawdown/climate change scenarios

Water temperature time series were simulated using meteorological inputs for 15 different three-year periods (Figure 3). Simulated water temperatures during the first year of the drawdown event (mean = 9.8 °C, maximum 23.1 °C) are similar to current temperatures downstream of the dam (mean = 10.9 °C, max = 23.0 °C). As the river returns to more 'natural' conditions during Phases 2 and 3, the possibility for higher summer maximum temperature than baseline increases (23.9 °C) and the mean temperature decreases (9.0 °C) compared to the reference period, presumably because more 'natural' conditions can result in an increase of days with water temperature < 5 °C.

A number of temperature metrics deemed ecologically relevant, especially for stenotherm fish were calculated for the reference period (Table 3) and from the time series shown in Figure 5 for all three possible Mactaquac dam outcomes (rebuilding the dam and power house, rebuilding the dam only, or restoring the natural river). We selected a modelling threshold of 23°C based on the temperature tolerances of Atlantic Salmon (temperature threshold between $T_{minimum}$ = 20 °C and $T_{critical}$ = 25 ºC; Breau 2013), which is an endangered species in the river.

Comparison of Tables 3 and 4 show that minimum summer temperatures will likely decrease, while maximum temperatures will remain fairly constant.

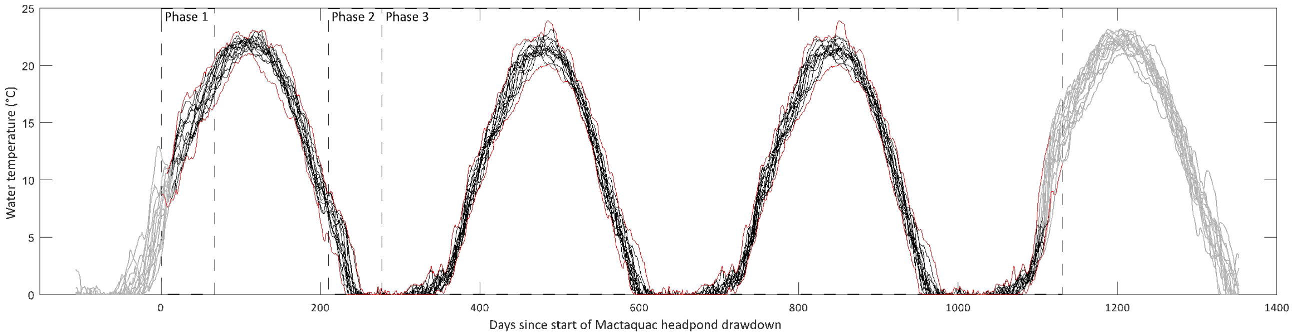

Figure 3. Temperatures generated by Mactaquac headpond drawdown for 11 different meteorological scenarios. Red lines represent upper and lower range of temperatures; grey lines represent temperatures outside of the drawdown scenario computed during model spin-up/spin-down.

This general decrease in temperature is reflected by the number of degree hours associated with the various drawdown scenarios, which also indicates that the thermal loading of the Saint John River will be lower during the drawdown than under current conditions.

Table 3. Water temperature metrics for the Saint John River near Fredericton for the reference period 2010-2014.

Year	Annual mean temp. (°C)	Annual maximum temp. (°C)	Standard deviation (°C)	No. degree hours (> 0 °C)	Minimum July – August temp. (°C)	No. of days ≥ 23 °C
2010	11.2	23.0	7.9	4085.5	18.9	0
2011	11.0	22.4	8.3	4007.6	20.1	0
2012	11.1	22.8	8.4	4051.2	21.3	0
2013	10.7	22.9	8.5	3901.2	19.6	0
2014	10.5	23.0	8.7	3820.1	20.7	1
Mean	10.9	22.8	8.4	3973.1	20.1	0.2

Table 4. Water temperature metrics for the Saint John River near Fredericton for the 15 different periods with drawdown scenarios.

Year	Annual mean temp. (°C)	Annual maximum temp. (°C)	Standard deviation (°C)	No. degree hours (> 0 °C)	Minimum July – August temp. (°C)	No. of days ≥ 23 °C
(1995-1997)	9.81	22.61	8.71	3579.5	18.55	0
(1996-1998)	9.34	21.75	8.46	3410.1	18.71	0
(1998-2000)	9.52	21.87	8.45	3473.4	17.45	0
(1999-2001)	9.97	22.59	8.61	3639.9	17.09	0
(2000-2002)	10.45	22.35	8.93	3814.6	19.80	0
(2001-2003)	9.29	21.08	8.14	3390.4	15.88	0
(2002-2004)	10.52	23.09	8.72	3839.1	19.36	4
(2003-2005)	9.26	22.50	8.65	3378.8	16.26	0
(2004-2006)	9.98	23.01	8.69	3642.9	17.74	1
(2005-2007)	9.62	22.32	8.31	3510.8	16.10	0
(2008-2010)	10.17	22.21	8.53	3712.9	17.84	0
(2009-2011)	9.40	22.04	8.13	3432.3	16.91	0
(2010-2012)	9.99	23.11	8.44	3646.4	17.24	5
(2011-2013)	9.96	22.97	8.83	3634.0	18.02	0
(2012-2014)	10.71	22.39	8.60	3910.4	19.17	0
Mean	9.87	22.39	8.55	3601.0	17.74	0.67

Figure 4 clearly shows that most climate change scenarios predict an increase in mean and maximum temperatures of nearly 2 °C on average for the 2100 future horizon. However, restoring the river to its natural state leads to greater variability in expected mean annual temperature and minimum summer temperature.

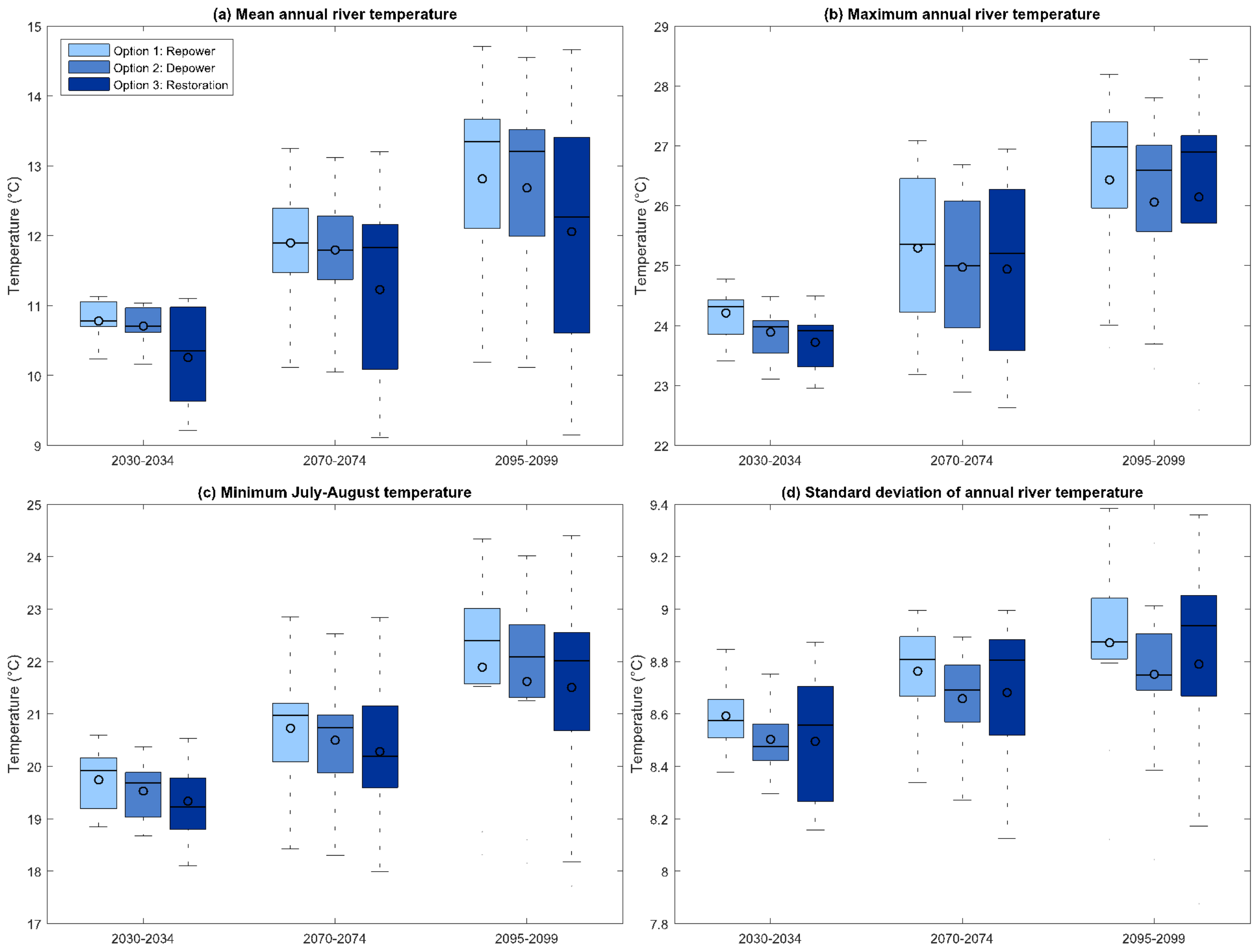

Figure 4. Variability in projected water temperature metrics for the Saint John River near Fredericton for a range of future climate scenarios (see Table 2).

4. CONCLUSION

The modelling results summarized in this paper and the effort currently underway as part of MAES (hydrodynamic, sediments, fish habitat) are crucial to the decision-making process of NB Power, the facility that owns the dam. The CEQUEAU model was used to determine provide future hydrological and thermal scenarios according to the different possible outcomes associated with dams decommissioning or reconstruction. Our results indicate that temperature increases predicted for the horizon 2100 may be problematic for stenotherm fish in the river system. A rise in minimum temperatures may mean shorten recuperation periods for fish that were thermally stressed during the day, for instance. Incorporating these predicted water temperature scenarios in fish habitat models appears to be the next logical step to further investigate such potential impacts.

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