

**Mactaquac Aquatic Ecosystem Study
Report Series 2015-023**



**MAES 1B.2.2 Interim Report:
Implementation of a Temperature
Model for the Saint John River
River**

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DISCLAIMER

Intended use and technical limitations of the report, “MAES 1B.2.2 Interim Report: Implementation of a Temperature Model for the Saint John River”. This report describes the ongoing development of a temperature model for the Saint John River. The CRI does not assume liability for any use of the included information outside the stated scope.

1. Context

Any modification to the Mactaquac Headpond will likely affect the thermal regime of the reaches of the St John River located downstream of the current dam structure. In order to quantify such a change to the river's thermal regime, we are calibrating a hydrologic and temperature model for the St John River capable of simulating water temperatures under a range of possible future flow scenarios. Deterministic temperature models are well suited to application in heavily impacted watersheds (Morin and Couillard, 1990; Caissie et al., 2007) and offer the ability to model the complex impacts of reservoirs and dams in large river basins (Morin and Couillard, 1990; Caissie, 2006; Caissie et al., 2007). We therefore are using CEQUEAU (Charbonneau et al., 1977; Morin and Couillard, 1990; St-Hilaire et al., 2000), a coupled deterministic model capable of simulating flow and temperature at discrete points within a watershed. CEQUEAU is a semi-distributed model (Morin and Couillard, 1990; St-Hilaire et al., 2000) that can simulate flows and water temperatures at any location in the watershed. The CEQUEAU model is capable of predicting flows in impounded water courses by incorporating appropriate data concerning reservoir/dam flow regimes (Morin and Couillard, 1990). It is therefore well suited to the St John River watershed. In addition, known (i.e. observed or modelled) water temperatures at the outlet of a reservoir can be used as inputs to CEQUEAU, giving it an upstream boundary condition to simulate the thermal regime downstream of the structure.

2. CEQUEAU hydrological model implementation

Prior to the simulation of water temperatures using CEQUEAU, it is necessary to implement and calibrate the hydrological component of the model. This is because the simulation of water temperature requires discharge information at all points throughout the watershed. The implementation of the hydrological model has been our principal objective during the last 6 months and is now largely complete. We are now looking to move forward to implementing the temperature component of the model. Details regarding the implementation and calibration of the hydrological model are given in the following sections.

2.1 Hydrological model details

CEQUEAU's hydrological component computes discharge by calculating a water budget on each elementary hydrological area (whole square) and by subsequently simulating the downstream transfer of water across the grid of square cells into which a watershed is divided (figure 1a; Morin and Couillard, 1990). These whole square cells form the basis of the CEQUEAU model, and are referred to as elementary representative areas. The ERA grid is subsequently divided into a series of partial squares created through intersecting the ERAs with watershed sub-basin drainage divides (figure 1b). These are used to determine the transfer of water (flow routing) in a downstream direction from each partial square to the next.

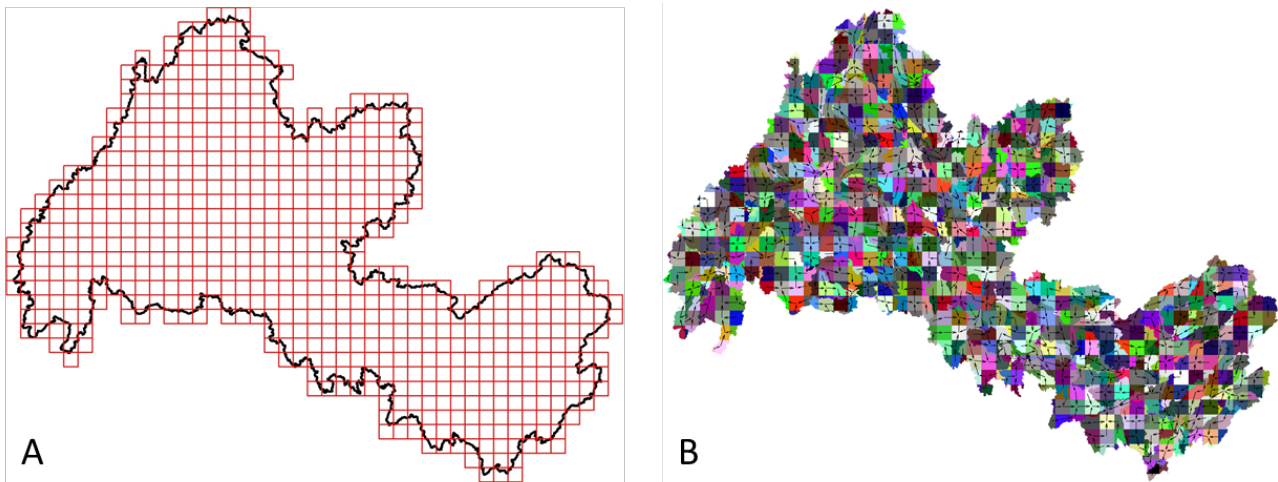


Figure 1A. Grid of ERAs (whole squares) imposed on St John River watershed. **B)** ERAs divided into partial squares using watershed divides

2.2 Flow routing

In the past, the division of ERAs into partial squares and the computation of downstream flow routing was accomplished manually. However, in a watershed as large and complex as the St John, this would have been an extremely labour-intensive process and also subject to potential of user-input error. Instead, we developed a Matlab (MathWorks, 2009) algorithm that automates this process using flow accumulation data generated by applying Arc Hydro Tools (Maidment, 2002) to a digital elevation model of the St John River watershed. Following the application of this algorithm, the CEQUEAU model of the St John River watershed comprises 650 ERAs of 100 km², subdivided into 1389 partial squares.

2.3 Physiographic data

In addition to watershed flow routing, the hydrological model requires information concerning the physiographic characteristics of each ERA and partial square in terms of their altitude, wetland cover, lake cover, bare soil cover and forest cover (Morin and Couillard, 1990). Altitude data were assembled from a 1/3 arc second (~25 m) Digital Elevation Model of the St John River watershed derived from NASA's Shuttle Radar Topography Mission dataset (Farr et al., 2007). Wetland information was assembled by merging vector GIS data from the US National Wetlands Inventory (Tiner, 2009), the *Milieux Humides Potentiels* dataset made available by the Québec (Dufour-Tremblay, 2011) and the New Brunswick Hydrographic Network (New Brunswick Department of Natural Resources, 2013). Waterbodies data were derived from the US National Hydrography Database (NHD) and the Canadian National Hydro Network (NHN) vector GIS databases (Simley and Carswell, 2009; Canada Centre for Mapping and Earth Observation, 2015). Data concerning bare soil and forest cover were extracted from a 250 m land use raster acquired from the North American Land Change Monitoring System (Rasim et al., 2012).

2.4 Meteorological data

Meteorological data necessary to run the model (comprising daily precipitation, minimum temperature and maximum temperature) were assembled from 27 Environment Canada weather stations in or near the lower St John River basin (appendix figure A1). Because optimum model

calibration is reliant on detailed meteorological data, we chose to use meteorological data for the period 1978 – 1994, the longest period for which we have a reasonable amount of concomitant data. Although some areas (notably the north-east portion of the lower St John River basin) are not particularly well covered by meteorological stations, the portion of most interest (ie. around Fredericton) is well covered, and therefore allows for the simulation of flows with a good degree of accuracy.

2.5 Integration of Mactaquac Headpond

The CEQUEAU model allows for the representation of relatively complex watersheds, with the presence of dams and reservoirs. This is accomplished by fitting a polynomial regression between reservoir volume and dam outflow for the dam/reservoir which is to be modelled, and then imposing this volume – discharge relationship in the partial square corresponding to the dam’s actual location. However, following inspection of the volume – discharge series for the Mactaquac Headpond, it was not possible to achieve any significant relationship, presumably due to the fact that reservoir level (and hence volume) varies at a temporal resolution finer than that captured by the level/discharge gauges installed within the Mactaquac headpond/dam (figure 2). Because of this, it is not currently possible to model flows out of the Mactaquac Headpond within the CEQUEAU model. It was therefore necessary to devise a new modelling strategy.

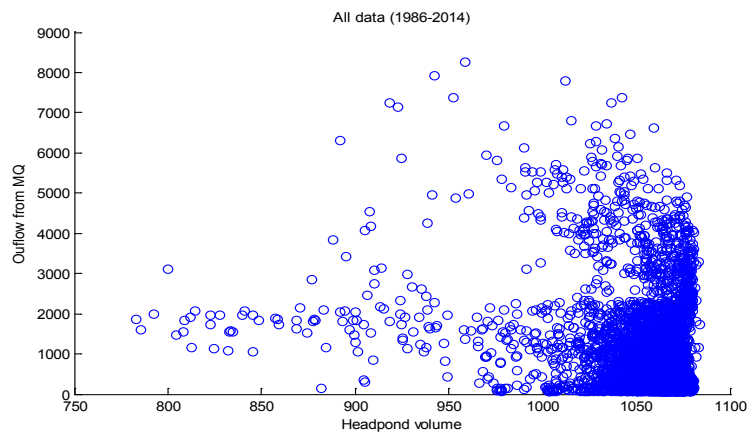


Figure 2. Daily Mactaquac Headpond volume vs. outflow for period 1986 – 2014 showing absence of relationship between volume and discharge

2.6 New modelling strategy

Owing to our inability to implement the Mactaquac Headpond/Reservoir in the CEQUEAU model, it was decided instead to implement the model solely in the portion of the St John watershed downstream of the Mactaquac Dam. This was achieved by re-computing the flow routing and physiography necessary to run the model so that the model now comprises only those sub-basins that discharge into the main stem St John River below the Mactaquac dam. Because the model no longer includes the upstream portion of the watershed, discharges in the main stem St John River are accomplished by imposing flows from the Mactaquac Dam outflow time series in the partial square corresponding to the location immediately downstream of the Mactaquac Dam (figure 3). This new CEQUEAU model for the lower St John River watershed now comprises 689 ERAs of 25 km², subdivided into 1271 partial squares. This higher resolution (in comparison to the model for the whole watershed) means that model calibration using lower order tributaries should be easier.

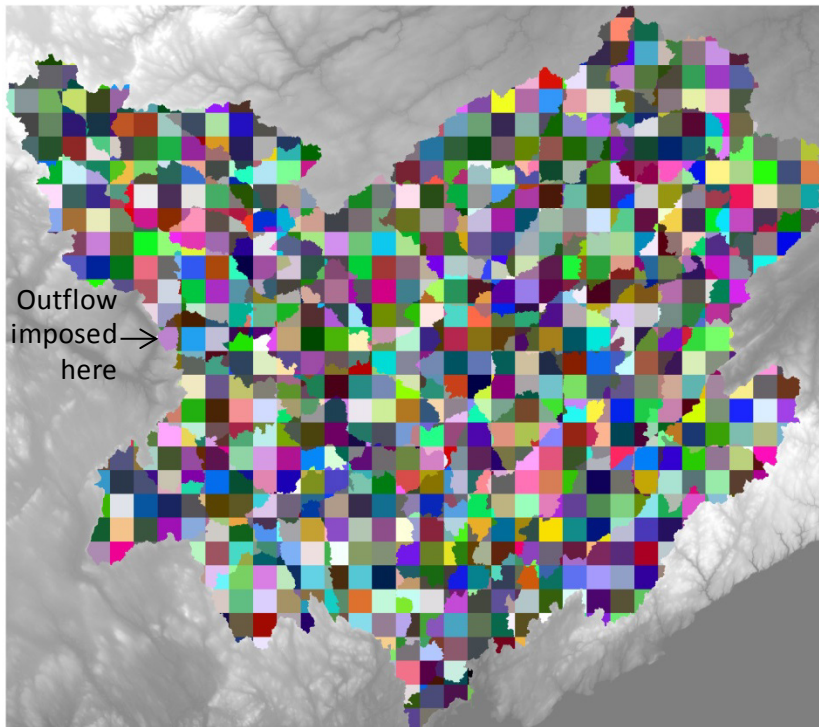


Figure 3. CEQUEAU model grid for downstream for lower St. John River downstream of Mactaquac Dam

3. Hydrological model calibration

Once the flow routing/physiographic data needed to run the hydrological component of CEQUEAU were assembled, the model was calibrated to ensure that it provided a reasonable simulation of discharge within the lower St John River watershed. Model calibration was achieved by adjusting the various model parameters until simulated flows produced a reasonable estimate of discharge values recorded by a number of hydrometric stations within the lower St John River basin.

3.2 Hydrometric data

Owing to the absence of discharge gauges in the main stem St John River downstream of the Mactaquac Dam, it was necessary to calibrate the model using hydrometric gauges situated in the various tributaries of the St John River. Observed flows used to calibrate the model were assembled from 7 hydrometric stations located within the various tributaries of the downstream St John River (table 1, appendix figure A2). Gauged discharges were available for the period 1965 – 1995. Because our main concern is the simulation of river flow and temperature in the reaches of the St John River around Fredericton, NB, our efforts were concentrated on calibrating the model using the hydrometric station at Durham Bridge on the Nashwaak River. This is because the topography/hydromorphology of the Nashwaak River sub-basin is more likely to provide a good analogue of the area around Fredericton than other gauged sub-basins further downstream in the watershed (eg. Nerepis River, Kennebecasis River). However, the ability of the model to simulate discharges was assessed at all of the 7 hydrometric stations, to ensure that any simulated flows further downstream are well simulated.

Table 1. Available hydrometric (discharge) data for the lower St. John River basin and associated model calibration results

Station	Upstream area	Notes
Nashwaak at Durham Bridge	1 450 km ²	Hydromorphology similar to St. John at Fredericton
Nashwaak at Stanley	641 km ²	
North Branch Oromocto at Tracy	557 km ²	
Nerepis River near Fowlers Corner	293 km ²	Very small watershed area
Salmon River at Castaway	1050 km ²	No nearby meteorological stations
Canaan River at East Canaan	668 km ²	
Kennebecasis River at Apohaqui	1100 km ²	

3.3 Calibration/validation strategy

The optimum overlap between available meteorological and hydrometric data for the lower St John River basin (ie. most concomitant data) was for the period 1983 – 1994. It was therefore decided to use this period for model calibration/validation. Within this period, 7 years of data were used for model calibration and the remaining 4 for validation. Model calibration was achieved using a two-stage process. First, the various model parameters (see St-Hilaire et al. (2000) for details) were adjusted manually to ensure that the components of the hydrological model (soil water level, groundwater table, lake levels, evaporation) stayed within real-world values. Following this manual phase, the CMA-ES optimisation algorithm (Hansen and Ostermeier, 2001) was applied to further refine the calibration of model parameters. This process was repeated multiple times choosing different 7 and 4 year windows to ensure that the calibration provided an accurate estimate of river discharge for all times within the 1983-1994 time period, and was not overly influenced by extreme weather events during one or more particular time periods. Model quality was assessed by calculating the Nash–Sutcliffe model efficiency coefficient and the Log Nash-Sutcliffe coefficient (Nash and Sutcliffe, 1970) for each 4-year validation period and subsequently taking the mean of all validation periods. The model's root mean-squared error (RMSE) and bias were also calculated.

3.4 Calibration results

Preliminary validation results show that the CEQUEAU model for the lower St John River basin provides a good estimate of river discharge in the various tributaries of the St John (table 2), particularly those in the upstream-most portions of the watershed (eg. Nashwaak at Durham Bridge; figure 4). It is to be expected that the Nashwaak hydrometric stations perform particularly well (Nash-Sutcliffe \approx 0.85) as model calibration validation was performed principally at these sites. The relatively good validation achieved for the Salmon River hydrometric station (Nash-Sutcliffe = 0.76) was also achieved, in spite of the fact that this river is in a portion of the watershed lacking in meteorological data. However, it appears that the surrounding meteorological stations, despite being relatively distant, provide sufficient data to achieve a reasonable calibration. Model accuracy is lower further downstream in the watershed (Kennebecasis and Nerepis Rivers). This is presumably because topography and hydromorphology in this region of the watershed is sufficiently different to that of the upstream

reaches that the model is poorly conditioned at these locations. However, this is unlikely to be a problem for modelling potential thermal regime modifications in the reaches around Fredericton.

Table 2. Mean Nash-Sutcliffe model efficiency coefficient for all 4-year validation periods during 1983-1994

Station	Nash-Sutcliffe coefficient
Nashwaak at Durham Bridge	0.86
Nashwaak at Stanley	0.84
North Branch Oromocto at Tracy	0.71
Nerepis River near Fowlers Corner	0.76
Salmon River at Castaway	0.70
Canaan River at East Canaan	0.62
Kennebecasis River at Apohaqui	0.60

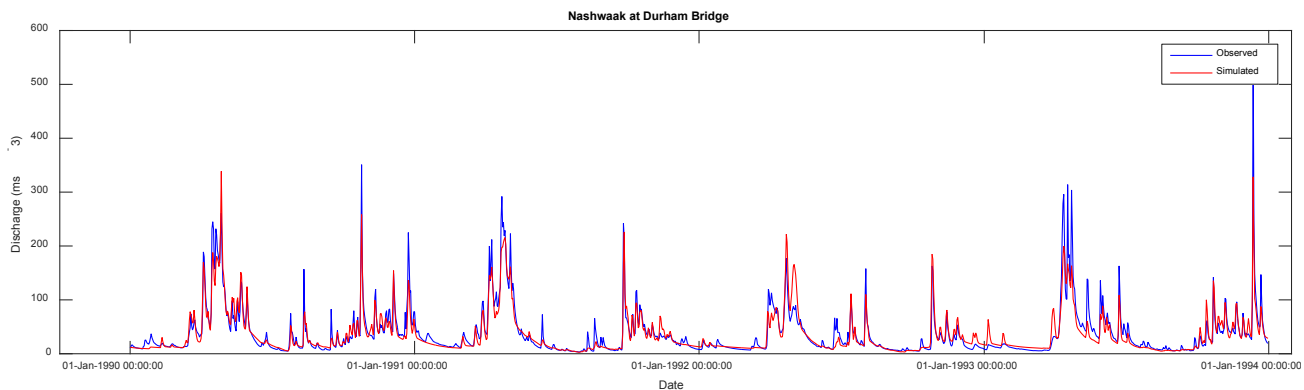


Figure 4. Observed and simulated hydrographs for gauging station at Durham Bridge on Nashwaak River showing good model fit (Nash-Sutcliffe coefficient = 0.86)

4. Temperature model implementation

The hydrological component of the CEQUEAU model appears to have reached a reasonable state of maturity and is capable of simulating river discharges with a good degree of accuracy. The next stage of model implementation is therefore to implement and calibrate CEQUEAU's water temperature component.

4.1 Temperature model details

The water temperature model uses an energy budget method to calculate the temperature of water within each partial square as a function of the enthalpy of the river reach within the partial square, the estimated water volume within that reach and the specific heat capacity of water (Morin and Couillard, 1990). The enthalpy for each partial square is calculated as a function of

energy inputs from net radiation, evaporation, convection, runoff, groundwater and advection from the volume of water transferred from and to neighbouring partial squares.

4.2 Physiographic data

In addition to the physiographic data required for execution of CEQUEAU's hydrological model component, the temperature model also requires information concerning the length of the main river stem within each partial square, the width and depth of the river at the downstream end of the partial square and the channel altitude and slope (Morin and Couillard, 1990). There are two potential sources for this data. The primary approach will be to use the downstream hydraulic geometry equations contained in the CEQUEAU user manual (Morin and Paquet, 2007) which are intended to estimate these parameters for each partial square as a function of the partial square's location within the watershed. However, should this fail to produce reasonable simulations of water temperature, these data will instead be extracted from the same GIS data sources used to assemble the physiographic data for the hydrological component of the CEQUEAU model.

4.3 Meteorological data

Further to the meteorological data required to run the hydrological component of CEQUEAU, the temperature model also requires observations of solar radiation, vapour pressure, cloud cover and wind direction (Morin and Couillard, 1990). These data will be acquired from Environment Canada's Fredericton Airport (climate ID 8101500/8101505) and Gagetown A (climate ID 8101792) meteorological stations and from an INRS/CRI meteorological station recently deployed immediately downstream of the Mactaquac dam at the Mactaquac Biodiversity Facility. Although this data should be sufficient for modelling water temperatures in the lower St John River downstream of the Mactaquac Dam and around Fredericton, no other solar radiation/cloud cover data exist for the St John watershed. If possible, this data will therefore be supplemented by meteorological records from NASA's MERRA program (Rienecker et al., 2011) to achieve better temperature predictions in other portions of the lower St John River basin.

4.4 Head pond outflow temperature

In order to simulate water temperatures in the lower St John River, it is necessary to assign a bulk water temperature to the Mactaquac Headpond outflow imposed at the upstream-most partial square in the model. The outflow water temperature will be assumed to be equal to the Headpond water temperature at a depth equivalent to the Mactaquac Dam intakes. However, without prior knowledge of Headpond water temperatures, it will be necessary to develop a predictive function to calculate Headpond water temperature as a function of air temperature. We initially thought that a 1D lake temperature model would be required to achieve this. However, preliminary inspections of temperature data from the Headpond (taken from a series of Onset HOB0 UA-002-64 logger strings with a vertical resolution of 2 - 5 m, see appendix figure A4) indicate that water temperature within the reservoir at a depth equivalent to the Mactaquac Dam intakes can be approximated using a sigmoidal function (figure 5; see Mohseni et al., 1998) applied to mean air temperature recorded by Environment Canada's Mactaquac Provincial Park weather station (climate ID 8102536). This function is currently being refined to account for minor temperature variations resulting from changes in Headpond level.

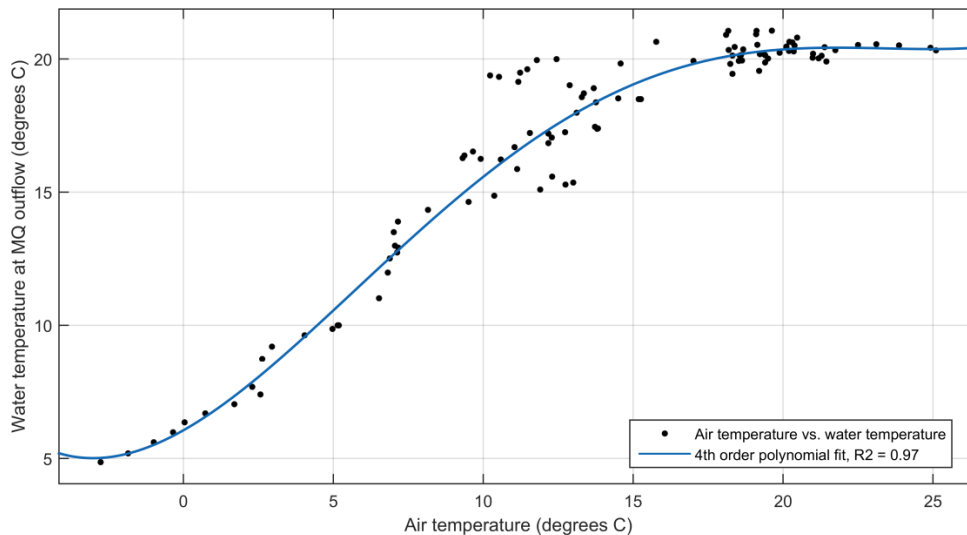


Figure 5. Air vs Mactaquac Headpond water temperature at depth equivalent to turbine intakes

5. Temperature model calibration

Once the data needed to run the temperature model component of CEQUEAU are assembled, it will necessary to calibrate the model to ensure that it provides a reasonable simulation of water temperature at discrete points within the lower St John River watershed. The meteorological data necessary to execute the temperature model will be assembled and used to simulate water temperature during a given time period. The model will be calibrated by adjusting the model parameters until simulated temperatures produce a reasonable estimate of observed values recorded by thermographs installed in the lower St John River.

5.1 Temperature data

In-situ records of water temperature acquired during the summer and autumn of 2014 and 2015 will be used to calibrate/validate the CEQUEAU temperature model. A series of Onset HOBO UA-002-64 loggers were deployed at a range of locations in the main stem St John River between the Mactaquac Dam and Oromocto and also within the Naswaak and Oromocto Rivers (2014 and 2015, see appendix figure A3). The recorded temperature data will be used to assess the accuracy of the water temperature model at a range of sites. Because of the relatively short time period of these temperature records, we will also attempt supplement this data with longer term records of water temperature provided by other project stakeholders (eg. watershed organisations, etc).

5.2 Calibration/validation strategy

We are still currently assembling the data needed to run and calibrate the CEQUEAU temperature model, so the calibration strategy is incomplete. At the very least, the model will be calibrated/validated using the *in-situ* temperature records from thermographs installed in the lower St John River by INRS/CRI in 2014 and 2015. It is hoped that supplementary temperature data from other sources will facilitate calibration/validation over longer time periods. However,

this is reliant on us finding a suitable longer term source of the meteorological data required to run the model.

Model calibration will again be achieved using a two-stage process. The various model parameters will first be adjusted manually to ensure that the model stays within real-world values. This will be followed up by the application of the CMA-ES optimisation algorithm (Hansen and Ostermeier, 2001) to further refine the model parameters. Model quality will be assessed using the model's root mean-squared error (RMSE) and bias; other goodness-of-fit measures such as the Nash–Sutcliffe model efficiency coefficient are not applicable due to the inherently autocorrelated nature of water temperature data.

6. Scenario development

Once calibrated, the coupled hydrological-water temperature model will be used to simulate the impacts of NB Power's proposed reservoir drawdown scenario on the thermal regime downstream of the Mactaquac Headpond. This will be achieved by imposing the drawdown outflows simulated by the Delft-2D hydrodynamic model (MAES project component 1B.1.4) at the upstream-most partial square within the model, allowing us to simulate the corresponding change in downstream water temperature. This process will be repeated for a range of different hydrometeorological conditions (ie. wet years, dry years, 'normal' conditions) to examine the full range of water temperature scenarios that may be generated.

7. Further model enhancements

Following the completion of the drawdown scenarios, we will attempt to further refine the hydrologic – water temperature model by improving its resolution and adding the upstream portion of the watershed. Model resolution will be increased by decreasing the size of the ERAs (whole squares) from 25 km² to 6.25 km². Although this will require recomputation of the model's physiography and flow routing data, the potential increase in resolution will allow for better simulation of flow and water temperatures within the tributaries of the St John River watershed, while also yielding simulations at finer scale. The higher resolution of the model will mean that it should be possible to produce more accurate discharge/temperature simulations on smaller order watercourses. However, such a resolution has never been attempted on a watershed as large as the St John, and it is possible that current computing restrictions will place limits on our ability to run CEQUEAU at this high resolution.

Modelling of the upstream portion of the St John watershed will be accomplished either through implementing a second CEQUEAU model to simulate this section separately, or by achieving a useable volume – outflow relationship following the installation of a water level logger within the Mactaquac Headpond. A working volume-outflow relationship would allow us to simulate the Mactaquac headpond/dam within the one CEQUEAU model for the entire St John watershed, allowing us to dam removal scenarios in the lower St John by 'deleting' the dam from the model. This would potentially allow us to simulate the absence of the Mactaquac Dam using historic flows, yielding data for 'natural flow' scenarios. However, this will require a number of substantial modifications to the existing model, including the extraction of physiographic and meteorologic data for the entire watershed, as well as the associated changes in model resolution necessitated by running CEQUEAU on such a large area.

8. References

- Caissie, D. (2006). The thermal regime of rivers: a review. *Freshwater Biology*, 51, 1389-1406
- Caissie, D., Satish, M.G., & El-Jabi, N. (2007). Predicting water temperatures using a deterministic model: Application on Miramichi River catchments (New Brunswick, Canada). *Journal of Hydrology*, 336, 303-315
- Charbonneau, R., Fortin, J.P., & Morin, G. (1977). The CEQUEAU model: description and examples of its use in problems related to water resource management / Le modèle CEQUEAU: description et exemples d'utilisation dans le cadre de problèmes reliés à l'aménagement. *Hydrological Sciences Bulletin*, 22, 193-202
- Dufour-Tremblay, G. (2011). *Cartographie des milieux humides potentiels: Structure physique des données*. Québec, QC: Ministère du Développement durable, de l'Environnement et de la Lutte contre les changements climatiques, 8 p
- Farr, T.G., Rosen, P.A., Caro, E., Crippen, R., Duren, R., Hensley, S., Kobrick, M., Paller, M., Rodriguez, E., Roth, L., Seal, D., Shaffer, S., Shimada, J., Umland, J., Werner, M., Oskin, M., Burbank, D., & Alsdorf, D. (2007). The Shuttle Radar Topography Mission. *Reviews of Geophysics*, 45, n/a-n/a
- Hansen, N., & Ostermeier, A. (2001). Completely Derandomized Self-Adaptation in Evolution Strategies. *Evolutionary Computation*, 9, 159-195
- Maidment, D.R. (2002). *Arc Hydro: GIS for water resources*. Redlands, CA: ESRI Press, 203 p
- MathWorks (2009). MATLAB R2009b. In. Natick, MA, USA: The MathWorks
- Mohseni, O., Stefan, H.G., & Erickson, T.R. (1998). A nonlinear regression model for weekly stream temperatures. *Water Resources Research*, 34, 2685-2692
- Morin, G., & Couillard, D. (1990). Chapter 5: Predicting river temperatures with a hydrological model. In N. Cheremisinoff (Ed.), *Encyclopedia of Fluid Mechanics: Surface and Groundwater Flow Phenomena* (pp. 171-209). Houston, TX: Gulf Publishing
- Morin, G., & Paquet, P. (2007). *Modèle hydrologique CEQUEAU, rapport de recherche no R000926*. Québec, QC: Université du Québec, INRS-Eau, Terre et Environnement, 458 p
- Nash, J.E., & Sutcliffe, J.V. (1970). River flow forecasting through conceptual models part I — A discussion of principles. *Journal of Hydrology*, 10, 282-290
- Canada Centre for Mapping and Earth Observation (2015). *National Hydro Network (NHN)*. Sherbrooke, QC: Natural Resources Canada, Earth and Sciences Sector, 18 p
- Rasim, L., Colin, H., Rainer, R., Darren, P., SheikhNazmul, H., René, R.C., Ian, O., Chandra, P.G., & Arturo, V. (2012). North American Land-Change Monitoring System. In C.P. Giri (Ed.), *Remote Sensing of Land Use and Land Cover* (pp. 303-324). Boca Raton, FL: CRC Press
- New Brunswick Department of Natural Resources (2013). *New Brunswick Hydrographic Network (NBHN)*. GeoNB (<http://www.snb.ca/geonb1/e/index-E.asp>): Service New Brunswick
- Rienecker, M.M., Suarez, M.J., Gelaro, R., Todling, R., Bacmeister, J., Liu, E., Bosilovich, M.G., Schubert, S.D., Takacs, L., Kim, et al. (2011). MERRA: NASA's Modern-Era Retrospective Analysis for Research and Applications. *Journal of Climate*, 24, 3624-3648
- Simley, J., & Carswell, W. (2009). *The National Map—Hydrography: U.S. Geological Survey Fact Sheet 2009-3054*. United States Geological Service: National Geospatial Program Office, 4 p
- St-Hilaire, A., Morin, G., El-Jabi, N., & Caissie, D. (2000). Water temperature modelling in a small forested stream: implication of forest canopy and soil temperature. *Canadian Journal of Civil Engineering*, 27, 1095-1108
- Tiner, R. (2009). *Status Report for the National Wetlands Inventory Program: 2009*. Arlington, VA: U.S. Fish and Wildlife Service, Division of Habitat and Resource Conservation, Branch of Resource and Mapping Support, 48 p

9. Appendix



Figure A1. Location of meteorological stations used to run model.

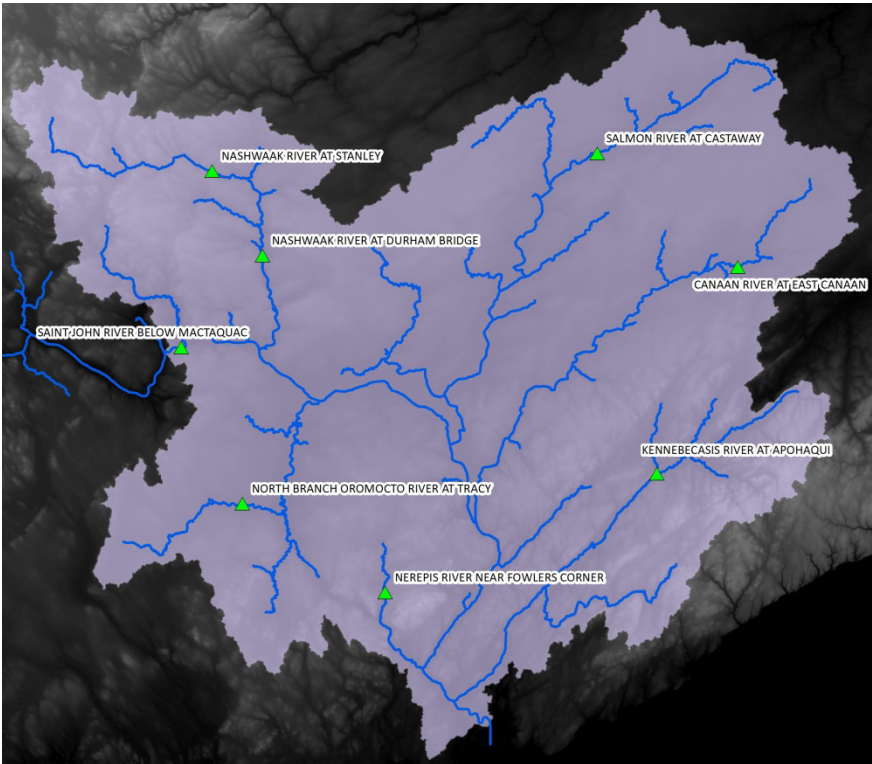


Figure A2. Location of hydrometric station used to calibrate CEQUEAU hydrological model component. Note that the station directly downstream of the Mactaquac headpond is not used for calibration purposes as it is dominated by the flow imposed into the model at the Mactaquac dam. Rather, it is used to ensure that the model is correctly functioning.

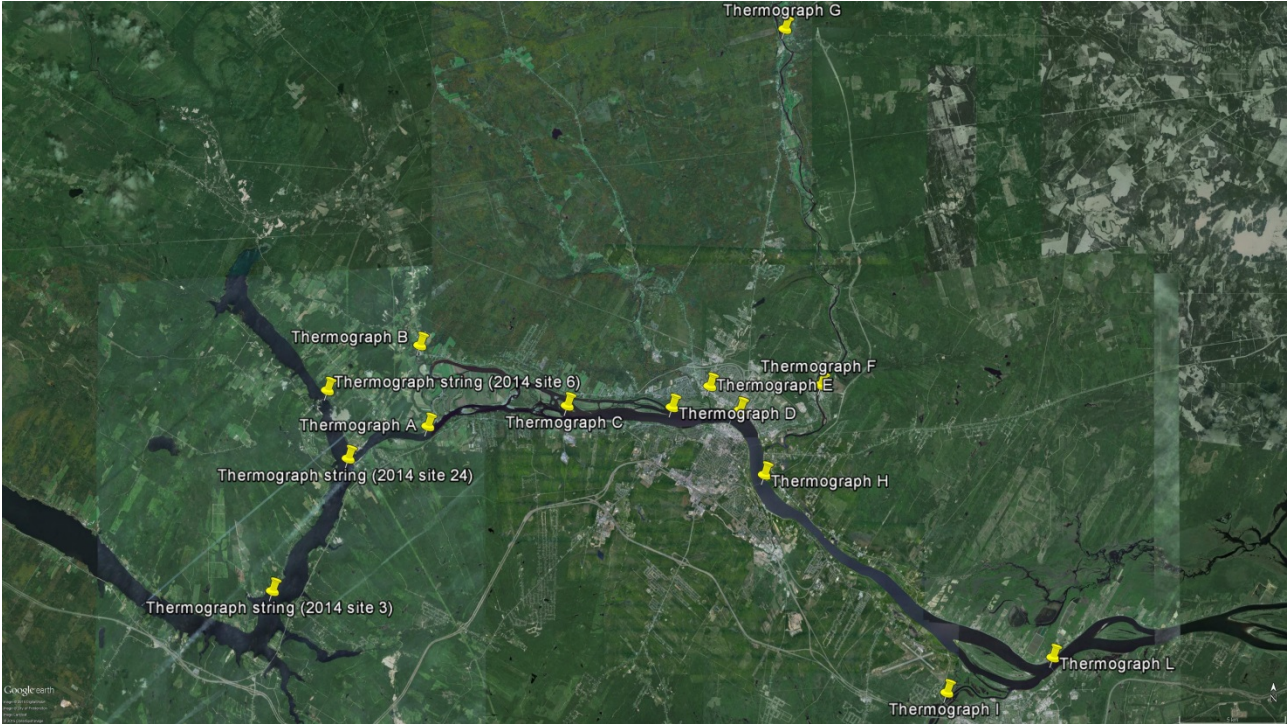


Figure A3. Location of temperature logger strings deployed in Mactaquac headpond used to establish outflow temperature and temperature loggers deployed downstream of the Mactaquac dam used to calibrate/validate CEQUEAU temperature model component.

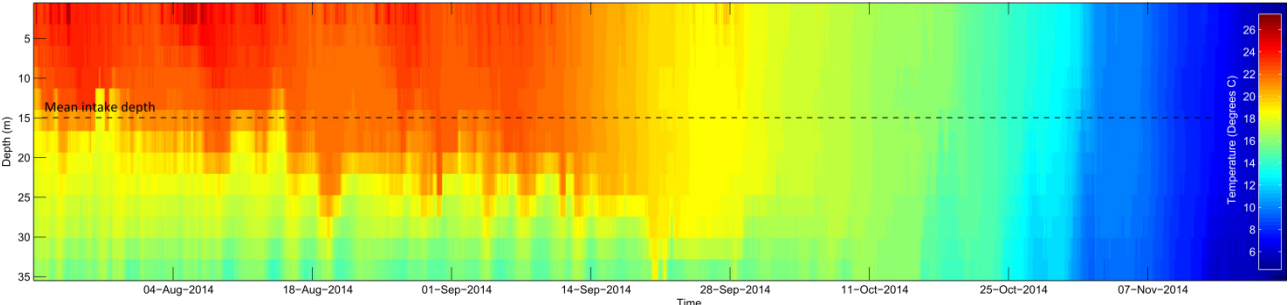


Figure A4. Temperatures recorded at thermograph string 24 (string located nearest to Mactaquac dam intake) during summer/autumn 2014