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METHODS PAPER: Implementation of a Temperature Model for the Saint John River

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DISCLAIMER

Intended use and technical limitations of the report, "Implementation of a Temperature Model for the Saint John River". This interim report describes the initial stages in the development of a deterministic temperature model for the Saint John River. The CRI doesn't assume liability for any use of the included data and analyses outside the stated scope.

NB Power Deliverable, 1.3.5-Modeling Thermal Regime Downstream: An Interim Report (models of downstream thermal regime for release scenarios)

Implementation of a Temperature Model for the Saint John River

Context

One of the potential impacts associated with NB Power's envisaged scenario regarding the Mactaquac Headpond is a modification of the thermal regime in the reaches located downstream of the current dam structure. It is therefore necessary to calibrate a temperature model for the Saint John River capable of predicting water temperatures under a range of possible future flow scenarios. Deterministic temperature models, while generally more complex than statistical models (Morin and Couillard, 1990; Benyahya et al., 2007), are well suited to application in heavily modified watersheds (Morin and Couillard, 1990; Caissie et al., 2007) and offer a greater capacity to model the complex impacts of reservoirs and dams in large river basins (Morin and Couillard, 1990; Caissie, 2006; Caissie et al., 2007). A deterministic approach is therefore preferable for the modelling of water temperatures in the Saint John River. Because a deterministic approach necessitates information concerning river flow, a hydrological model must be adjusted prior to the estimation of water temperatures. We will therefore use CEQUEAU (Charbonneau et al., 1977; Morin and Couillard, 1990; St-Hilaire et al., 2000), a coupled hydrologic – water temperature 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 at any location in the watershed. The CEQUEAU model is capable of predicting flows in impounded water courses when incorporating appropriate data concerning reservoir/dam flow regimes (Morin and Couillard, 1990). It is therefore well suited to the Saint 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 CEQEAU, giving it an upstream boundary condition to simulate the thermal regime downstream of the structure.

Hydrological model

The first stage of model implementation involves the calibration of the hydrological component of the CEQUEAU model. CEQUEAU calculates discharge at discrete points throughout a watershed by first calculating a water budget on each elementary hydrological area and by subsequently simulating the downstream transfer of water across the grid of square cells into which a watershed is divided (Morin and Couillard, 1990). These whole square cells form the basis of the CEQUEAU model, and are referred to as elementary representative areas (ERAs). As inputs, the hydrological model requires information concerning the physiographic characteristics of each ERA in terms of their altitude, wetland cover, lake cover and forest cover (Morin and Couillard, 1990). These data will be assembled from a variety of sources: Elevation data from a ~25 m SRTM DEM of the watershed, wetland and lake cover from the National Hydrographic Dataset (NHD; United States) and National Hydrographic Network (NHN; Canada) GIS databases (harmonised under the International Watersheds Initiative) and forest cover from the North American Land Cover Monitoring System project. The ERA grid is subsequently divided into a series of partial squares created through intersecting the ERAs with watershed sub-basin drainage divides. These are used to determine the routing of flow in a downstream direction from each partial square to the next. In a complex watershed such as the Saint John, the division of the watershed/ERA grid into partial squares and subsequent flow routing is best achieved using a semi-automated technique. The ESRI ArcHydro Tools suite (Maidment, 2002) will be therefore be used to delineate drainage sub-basins and a Matlab algorithm developed to automate flow routing between the partial squares. Dam conditions simulating the Mactaquac, Beechwood and Grand Falls impoundments will be imposed at the relevant points within the partial squares, allowing the model to account for regulated flow releases at these locations.

The hydrometeorological data necessary to run the hydrological simulations are available from federal repositories (Environment Canada, NOAA) but will be supplemented with data from the New Brunswick Fire Weather Network if available. Daily observations from these stations (total precipitation, maximum temperature and minimum temperature) will be interpolated across the watershed at the resolution of the ERA grid and provide the basis for the model's water balance calculations. Simulated discharge series from given points within the watershed will be compared to observed flows taken from hydrometric stations in the portion of the Saint John watershed downstream of the Mactaquac dam (available from Environment Canada) in order to calibrate the model. Because most gauging stations in this portion of the main stem Saint John River only record water levels, we intend to calibrate the model using discharge data available from gauging stations in major tributaries of the Saint John River (eg. Oromocto River, Nashwaak River, Kennebecasis River). However, should this prove infeasible, we will attempt to use discharge series reconstructed from water level records in the main stem Saint John. Model calibration is achieved largely through the adjustment of parameters governing the model's production function (Morin and Couillard, 1990). This function quantifies the vertical movement of water through the ERA after it arrives as precipitation between a series of interconnected components (snowpack formation/melt, evapotranspiration, runoff, movement of water in the saturated and unsaturated zones and through lakes and marshes). An initial calibration phase will therefore consist of manually modifying the production function parameters until the model yields a reasonable estimate of discharge observations. Parameter optimisation techniques (eg. Zheng and Wang, 1996; Arsenault et al., 2014) will be evaluated and the most appropriate subsequently used to further improve the calibration. Model power will be assessed using the Nash-Sutcliffe coefficient (Nash and Sutcliffe, 1970) in combination with other common performance measures (eg. Janssen and Heuberger, 1995), with an emphasis on adequate low flow simulations, given their importance for the subsequent water temperature simulations.

Temperature model

The second stage of model implementation consists of estimating river temperatures under a range of flow scenarios predicted by the hydrological model. This will be achieved using the water temperature component of CEQUEAU. The water temperature model is an energy budget model that calculates 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. Notwithstanding the inputs 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 of the river at the downstream end of the partial square and the altitude at its downstream end (Morin and Couillard, 1990). As with the hydrological model, these data will be assembled from the National Hydrographic Dataset (NHD; United States) and National Hydrographic Network (NHN; Canada) GIS databases.

The temperature model also requires observations of solar radiation, vapour pressure, cloud cover and wind direction (Morin and Couillard, 1990). These data will again be acquired from Environment Canada/NOAA meteorological stations, supplemented by observations from a station recently deployed immediately downstream of the Mactaquac dam.

Owing to the size and depth of the Mactaquac Headpond, it may be necessary to account for vertical thermal stratification using a one-dimensional reservoir temperature model. A 1D model should allow for fast and relatively simple integration into the larger CEQUEAU model (eg. MacKay et al., 2009). In its simplest form, this may consist of an empirical function relating vertical water temperature to depth, fetch and prevailing meteorological conditions (eg. Morin and Couillard, 1990). However, it will be necessary to account for the impact of multiple reservoir inflows and outflows on advective flux. To this end, we will evaluate a range of 1D vertical temperature models (eg. Riley and Stefan, 1988; Reichert, 1994; Bonnet et al., 2000; Blenckner et al., 2002; Saloranta and Andersen, 2007) and subsequently apply the one deemed the most appropriate for the prediction of water temperatures at the Mactaquac dam intake. Inputs to such models typically include meteorological data (eg. Net radiation, temperature, wind speed/direction; Riley and Stefan, 1988; Karagounis et al., 1993; Saloranta and Andersen, 2007) and reservoir characteristics (surface area, depth, bathymetry; Reichert, 1994; Blenckner et al., 2002). Depending on the chosen model, input data will be assembled from publically available meteorological records (eg. Environment Canada) and GIS sources used for the calibration of the hydrological model. If necessary, further data (eg. reservoir bathymetry) will be made available from other sub-projects carried out under the MAES programme. The chosen reservoir temperature model will be calibrated by means of vertical strings of temperature loggers (Onset HOBO UA-002-64 loggers attached at 2 m or 5 m intervals) installed in the Mactaquac Headpond in order to record thermocline evolution. Water temperature data collection in the reservoir was initiated during the summer of 2014 and will continue in 2015.

Following the integration of the reservoir temperature model into the main CEQUEAU model, temperature loggers installed at a range of locations downstream of the Mactaquac dam (in both the main stem Saint John River and its tributaries) will be used to calibrate the CEQUEAU temperature model. Model adjustment is achieved through the modification of a number of physical (average basin water depth, groundwater temperature, initial water temperature) and non-dimensional fitting parameters (solar radiation coefficient, convection coefficient, evaporation coefficient, thaw parameter). Model power will again be assessed using the Nash-Sutcliffe coefficient, in addition to other common performance measures, including the Root Mean Square Error (RMSE), often used to evaluate water temperature models.

Scenario development

Once calibrated, CEQUEAU will be used to simulate water temperatures under a range of different dam configuration scenarios (eg. replacement of spillway/powerhouse, maintenance of earthen dam and spillway, restoration to natural flow conditions) and hydrometeorological conditions. The model will also be paired with downscaled climate change predictions (eg. Music and Caya, 2007) in order to examine potential future modifications to the thermal regime of the Saint John River and its spatio-temporal water temperature dynamics. These data will subsequently be used by other MAES project components to assess the implications of dam configuration/hydroclimatic changes to the Saint John River ecosystem.

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