Impact of future climate change on water temperature and thermal habitat for keystone fishes in the lower Saint John River, Canada

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Abstract

Water temperature is a key determinant of biological processes in rivers. Temperature in northern latitude rivers is expected to increase under climate change, with potentially adverse consequences for cold water-adapted species. In Canada, little is currently known about the timescales or magnitude of river temperature change, particularly in large ($\geq 10^4$ km^2) watersheds. However, because Canadian watersheds are home to a large number of temperature-sensitive organisms, there is a pressing need to understand the potential impacts of climate change on thermal habitats. This paper presents the results of a study to simulate the effects of climate change on the thermal regime of the lower Saint John River (SJR), a large, heavily impounded, socio-economically important watershed in eastern Canada. The CEQUEAU hydrological-water temperature model was calibrated against river temperature observations and driven using meteorological projections from a series of regional climate models. Changes in water temperature were assessed for three future periods (2030-2034, 2070-2074 and 2095-2099). Results show that mean water temperature in the SJR will increase by approximately ~1 °C by 2070-2074 and a further ~1 °C by 2095-2099, with similar findings for the maximum, minimum and standard deviation. We calculated a range of temperature metrics pertaining to the Atlantic Salmon and Striped Bass, key species within the SJR. Results show that while the SJR will become increasingly thermally-limiting for Atlantic Salmon, the Striped Bass growth season may actually lengthen under climate change. These results provide an insight into how climate change may affect thermal habitats for fish in eastern Canadian rivers.

1. Introduction

Water temperature influences biotic and abiotic river processes (Caissie, 2006; Webb et al., 2008; Hannah and Garner, 2015), governing rates of dissolved substances (Finlay, 2003; Ficklin et al., 2013), organic and inorganic pollutants (Bloomfield et al., 2006; van Vliet and Zwolsman, 2008), nutrient and microbacterial concentrations (Delpla et al., 2009) and fish and invertebrate behaviour (Daufresne et al., 2004; Dugdale et al., 2016). River temperature in most northern and temperature regions is expected to increase as a result of climate change (Isaak and Rieman, 2013; van Vliet et al., 2013a; Hill et al., 2014), and there is therefore widespread concern that climate change could result in substantive changes in river water quality (e.g. Whitehead et al., 2009; Kaushal et al., 2010) and ecosystem dynamics (e.g. Filipe et al., 2013; Roberts et al., 2013; Justice et al., 2017). Indeed, research indicates that reductions in river water quality driven by climate change may impact the provision of safe drinking water (Delpla et al., 2009; El-Jabi et al., 2014) while the increased occurrence of high river temperatures could initiate population declines and geographic range shifts of temperature-sensitive aquatic species (Hari et al., 2006; Clews et al., 2010; Wedekind and Küng, 2010). Given these largely negative projected consequences of climate change, there is a critical need to better understand the nature of future river temperature variability in order to develop appropriate adaptation or mitigation strategies.

In eastern Canada, particular importance is placed on understanding both the driving mechanisms of river temperature and the potential for future alterations to river temperature regimes because of the high socio-economic importance of coldwater fish species such as salmonids (FOPO, 2017). Summer water temperature in many eastern Canadian rivers regularly approaches or exceeds thermal maxima for a range of coldwater species (e.g. Mather et al., 2008; Jeong et al., 2013; Daigle et al., 2015), and temperature-related salmonid mortality events are already being observed across rivers in Québec and New Brunswick (e.g. Breau, 2013). River scientists have therefore started to use temperature models (e.g. St-Hilaire et al., 2000; St-Hilaire et al., 2003; Caissie et al., 2005; Ahmadi-Nedushan et al., 2007; Caissie et al., 2007; Hebert et al., 2011) to predict the occurrence and magnitude of high temperature events likely to expose aquatic fauna to heat stress. Such models are useful both for exploring the drivers of river temperature processes (e.g. Caissie and Luce, 2017; Garner et al., 2017) and for aiding river managers to make informed decisions regarding strategies to reduce or mitigate the impacts of heat stress events (e.g. Caissie et al., 2012; Breau, 2013; Jackson et al., 2018). However, most previous applications of temperature models to Canadian rivers have been conducted in a short term context, and there remains a relative lack of long-term evidence documenting how river temperature regimes in eastern Canada will change under future climatic variability (particularly towards the end of the 21st century). Furthermore, the longer-term investigations that do exist (e.g. Jeong et al., 2013; Caissie et al., 2014; Brodeur et al., 2015; Daigle et al., 2015; Kwak et al., 2017) generally focus on relatively small, un-modified water courses, and there is a paucity of information regarding how water temperature in eastern Canada's larger (and often, more heavily-modified) river systems (i.e. drainage basin area $\geq 10^4$ km^2) will respond to climate change.

This paper documents the use of a process-based river temperature model (CEQUEAU; Morin and Couillard, 1990) to simulate the impacts of future climate change on the thermal regime of the lower

Saint John River (hereafter referred to as SJR), a large socio-economically important watershed located in the Canadian provinces of New Brunswick and Québec and the US state of Maine (Kidd et al. 2011). The SJR contains a relatively rich assemblage of fish species with five listed as species at risk (e.g. Curry and Gautreau 2010). The Atlantic Salmon (*Salmo salar*) is listed as endangered and the Striped Bass (*Morone saxatilis*) as threatened. They are both important ecologically, socially, and economically (e.g., Andrews et al. 2017; Gardner Pinfold, 2011). The Atlantic Salmon is a culturally significant species in the SJR, but has declined substantially leading to closure of the fisheries. Projected global temperature increase is likely to drive further population decline (eg. Jonsson & Jonsson, 2009; Mills et al., 2013). The SJR Striped Bass population was once vibrant but has declined since the 1970s (although it still supports a recreational fishery; Andrews et al., 2017). A better understanding of the future thermal regime of the SJR would shed light on the potential response of these fishes to a changing climate and thus inform river conservation planning and management.

Our specific objectives were : 1) Implement a process-based temperature model for the lower SJR basin capable of predicting summer water temperature with a reasonable degree of accuracy; 2) Use the model to characterise the river's current baseline temperature regime by calculating a series of thermal and ecological metrics based on present-day temperature patterns; and 3) Assess how these metrics will change as a result of future climatic warming for three reference periods (2030-2034, 2070-2074, 2095-2099) by driving the model using downscaled regional climate projections from a series of global circulation models. This article documents one of the first instances of the use of a process-based river temperature model to examine the effects of climate change on a large eastern Canadian river and will allow a valuable insight into how water temperature regimes will change under a range of different climate scenarios.

2. Method

2.1 The CEQUEAU model

CEQUEAU is a coupled process-based hydrological and water temperature model capable of simulating river flows and temperatures across a user-defined grid superimposed over a watershed (Morin and Couillard, 1990; St-Hilaire et al., 2000). The hydrological model component calculates a hydrological budget for each grid square at each timestep; the water volume for each grid square is thus calculated as a function of watershed physiography (altitude, % forest cover, % bare soil, % waterbody and %wetland) and the meteorological conditions (air temperature, precipitation) at each timestep. The volume of water computed is subsequently transferred to its downstream neighbour as streamflow based on a series of coefficients representing the storage of water within each grid square and the movement of water at the surface and in the unsaturated and saturated soil layers. Because a more detailed discussion of CEQUEAU's hydrological model component is beyond the remit of this paper, the author is referred to Morin and Couillard (1990) and Dugdale et al. (2017a) for further information.

The water temperature model component of CEQUEAU uses the output of the hydrological model by computing an energy budget for the volume of water associated with the simulated discharge on each grid square based on heat gain or loss from energy transfers into or out of the grid square. Water temperature is thus calculated as a function of the enthalpy for each grid square and the specific heat capacity of water:

(1) $$T_{w_{t,i}} = \frac{Q_{t,i}}{V_{t,i} \cdot \Theta}$$

where T_w is the water temperature (° C), Q is the enthalpy (MJ) and V is the water volume (m^3; computed by CEQUEAU's hydrological component) for grid square i at model time step t. Θ is the specific heat capacity of water (4.187 MJ m^3 K^{-1}).

The enthalpy of each grid square is calculated as the net sum of solar shortwave radiation, longwave radiation, latent, sensible and advective heat fluxes using the equation:

(2) $$Q_{t,i} = Q_{sw_{t,i}} + Q_{lw_{t,i}} + Q_{e_{t,i}} + Q_{s_{t,i}} + Q_{a_{t,i}}$$

where Q_{sw} is the incoming solar shortwave flux, Q_{lw} is the longwave radiative flux, Q_e is the energy gain or loss from latent heat transfer, Q_s represents sensible heat transfer (gain or loss) and Q_a is the advective heat transfer from upstream grid squares (MJ m^{-2}). Solar shortwave flux is derived from actual solar radiation values entered into the model, while the remaining heat flux terms are computed using a series of equations, as follows:

Longwave radiation for each grid cell is given by the equation:

(3) $$Q_{lw_{t,i}} = \sigma \cdot \beta \cdot ({T_a}^4{}_{t,i} - {T_w}^4{}_{t,i})$$

where σ is the Stefan-Boltzman constant (4.9 x 10^{-9} MJ m^{-2} K^{-4}), β is the atmospheric emissivity and *Ta* is the ambient air temperature. Atmospheric emissivity is given by the equation:

(4) $$\beta = (0.74 + 0.0065 p_{t,i}) \cdot (1 + 0.17 {c^2}_{t,i})$$

where *p* is actual vapour pressure (mm Hg) and *c* is cloud cover (0 – 1).

Latent heat flux is given by:

(5) $$Q_{e_{t,i}} = l_{e_{t,i}} \cdot H$$

where l_e is the volume of water (m^3) evaporated (as computed by CEQUEAU's hydrological model component using a Thornthwaite-type approach based on air temperature (see Morin and Couillard, 1990) and *H* is the latent heat of evaporation (2480 MJ m^{-3}).

Sensible heat flux is determined by the equation:

(6) $$Q_{h_{t,i}} = 0.2 \cdot W_{t,i} \cdot (T_{a_{t,i}} - T_{w_{t,i}})$$

where W is wind speed (km h^{-1}).

Advective heat flux is derived as a function of the temperature and volume of water flowing into the grid square from its upstream neighbours (in terms both of streamflow and of subsurface flow as computed with CEQUEAU's hydrological model component), allowing for total heat loss or gain to be calculated for each grid square using Eq. 2. Eq. 1 is then used to compute the net effect of this heat gain or loss on the temperature of streamflow within each grid square.

2.2 Study area

The SJR basin drains a 55,110 km^2 area of south-eastern Canada and north-eastern USA into the Bay of Fundy at the city of Saint John, New Brunswick (45.258, -66.088; Figure 1). The river is impounded at numerous locations, most notably by three large hydroelectric facilities (Grand Falls Dam, Beechwood Dam and Mactaquac Dam) situated in the middle reaches of the river. These facilities have driven alterations in the flow and temperature dynamics of the SJR (e.g. Hare et al., 1997) and led to large-scale changes in function and structure of the fluvial ecosystem (Dominy, 1973). The Mactaquac Dam, a 670 MW run-of-the-river facility situated ~18 km west of Fredericton, New Brunswick (45.952, -66.872), is the largest of these three impoundments. It has a mean daily outflow of 745.5 m^3s^{-1} and dominates the hydrological and thermal regime of the lower SJR. The dam is currently undergoing an alkali-aggregate reaction which is causing expansion of its concrete structure (Hayman et al. 2010). As a result, research is currently focused on understanding how dam renewal will impact ecosystem dynamics and the physico-chemical regimes of the lower SJR (see Dugdale et al., 2017b). One such component of this work is the need to quantify both the current and future thermal regime of the lower SJR with a view to understand how prevailing river temperature patterns may respond to climate change. Such data will help to inform both dam renewal strategies and climate change mitigation policies, with a view to protecting this already sensitive and heavily-impacted ecosystem.

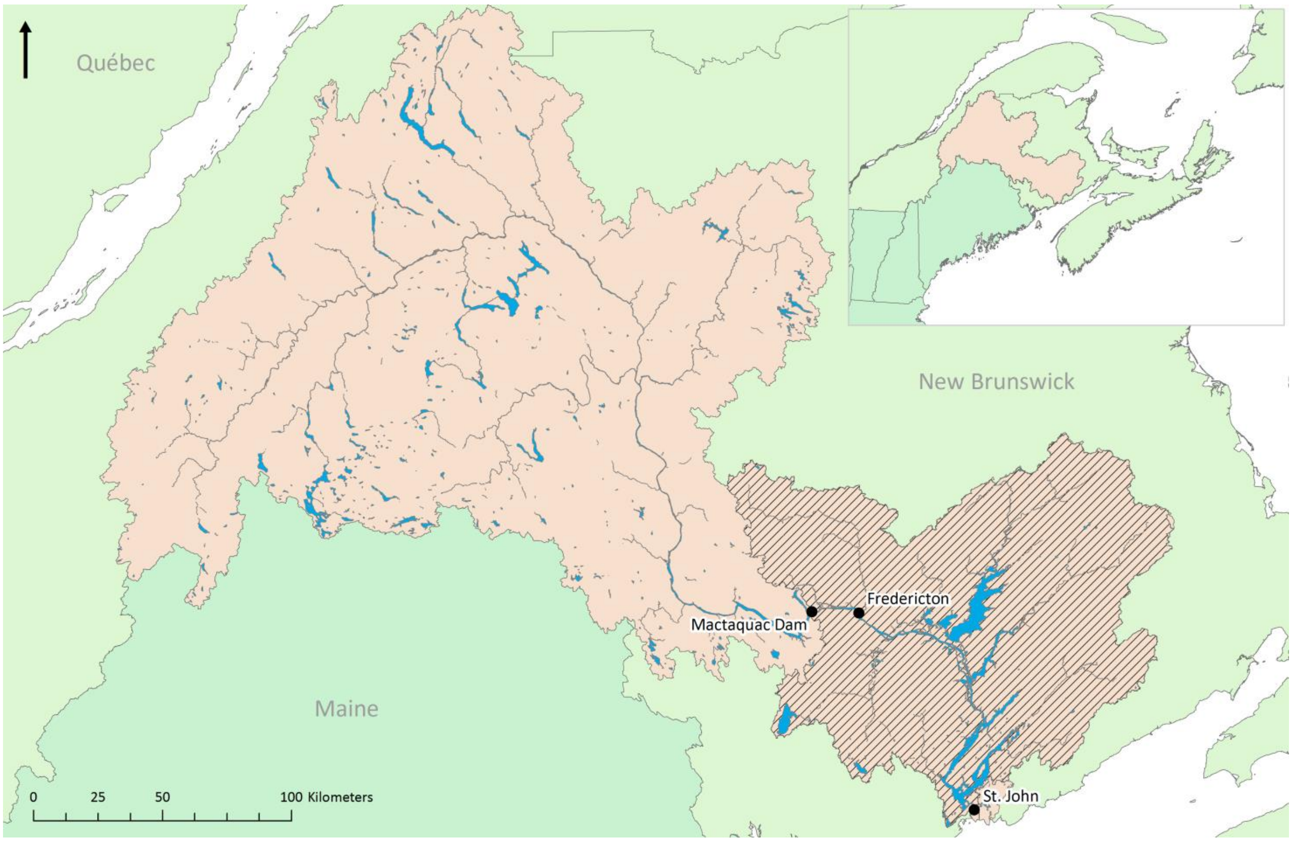

Figure 1. Saint John River watershed showing location of major water courses. Shaded region corresponds to section of watershed downstream of the Mactaquac Dam on which CEQUEAU was implemented

2.3 Model implementation

2.3.1 Model grid layout and physiographic data inputs

CEQUEAU was used to model flows and temperature in the portion of the Saint John watershed downstream of the Mactaquac Dam (approximately 14,990 km^2; Figure 1). Model implementation was conducted following the approach of Dugdale et al (2017a), using a 5 x 5 km grid consisting of 689 grid squares. Sensitivity analysis indicated that there was little difference in simulation quality for grid sizes of up to 20 x 20 km (see Dugdale et al., 2017a for details), and the chosen grid resolution was selected as a compromise to maximise grid resolution and minimise model runtime. Physiographic data necessary to run CEQUEAU's hydrological model component were assembled from a range of GIS databases. Elevations were derived from a 1 arc-second (~25 m) SRTM digital elevation model (Farr et al., 2007), while raster land use data used to compute forest and bare soil cover were obtained from the North American Land-Change Monitoring System (Latifovic et al., 2012). Percentage cover of waterbodies and wetlands were obtained from vector shapefiles downloaded from the Government of New Brunswick's GeoNB geospatial data portal (http://www.snb.ca/geonb1/e/index-E.asp). CEQUEAU's temperature model component also requires information concerning the length of the main river stem within each grid square, the width and depth of the river at the downstream end of the grid square and the channel altitude and slope (Morin and Couillard, 1990). These data were assembled using a downstream hydraulic geometry approach (see equations in Morin and Paquet, 2007) to estimate these values for each grid square as a function of the square's location within the watershed; these parameters were further refined during model calibration.

2.3.2 Meteorological data

Daily precipitation, minimum temperature and maximum temperature data necessary for calibration/validation of the hydrological component of CEQUEAU were assembled from 27 Environment Canada meteorological stations in or near the lower SJR basin (Figure 2a). CEQUEAU's temperature model component additionally requires observations of solar radiation, vapour pressure, cloud cover and wind speed as inputs to equations 3-6. Vapour pressure and wind speed records were assembled from the Fredericton Airport (climate ID 8101500/8101505), Fredericton CDA (810600), Saint John Airport (climate ID 8104900/8104901), Gagetown A (climate ID 8101792), Doaktown (climate ID 8101201) and Mechanic Settlement (climate ID 8102848) Environment Canada meteorological stations. Cloud cover data were available for Fredericton Airport, Fredericton CDA, Saint John Airport and Gagetown A. Solar radiation data were obtained from Environment Canada's Fredericton Airport meteorological station but also supplemented by observations from the Fredericton CDA and Saint John Airport meteorological stations obtained under the Atlantic Zone Monitoring Program (AZMP; Pepin et al., 2005) and the Canadian Weather Energy and Engineering Dataset (CWEEDS; Kleissl, 2013). Data gaps at each station (owing to temporary periods of station downtime) were filled using meteorological reanalysis hindcasts from NASA's MERRA programme (Rienecker et al., 2011). These were further supplemented with observations from an automated meteorological station (referred to as CRI/INRS met. station) deployed immediately downstream of the Mactaquac Dam. Although meteorological data required for the water temperature model were available for the period 1968-2015 at certain locations (Fredericton CDA/Saint John Airport), the largest concomitant dataset was available for the period 2010-2014. This period was therefore used for calibration/validation in order to ensure maximum model quality.

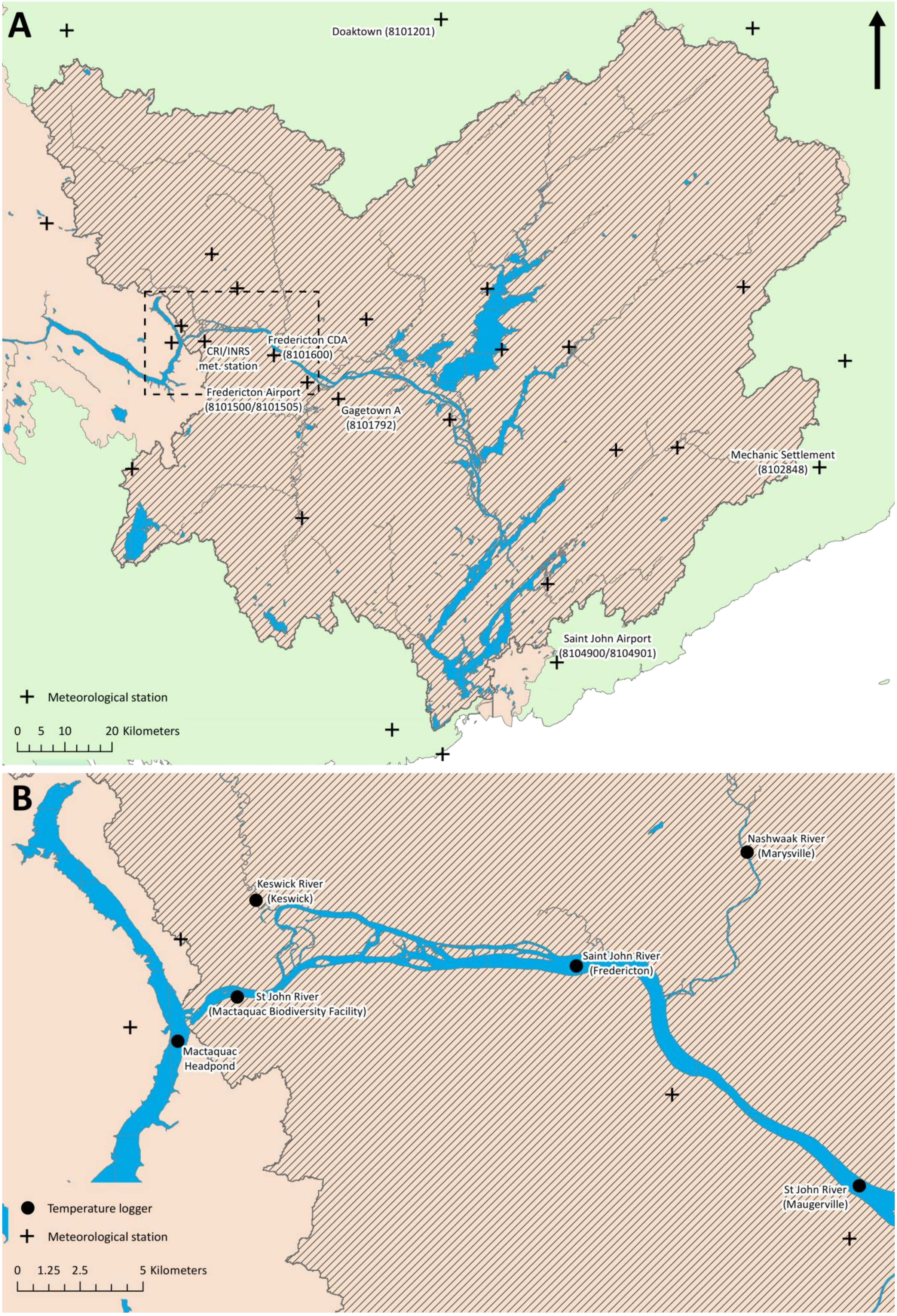

Figure 2 (A). Location of meteorological stations used to drive CEQUEAU model of lower SJR watershed. Meteorological stations with additional observations used for water temperature simulation are labelled. (B) Location of temperature loggers used for temperature model calibration/validation (extent of panel B given by dashed box in panel A).

2.3.3 Upstream boundary conditions

Flow and temperature boundary conditions were input to the model at the upstream-most grid square coinciding with the outflow of the Mactaquac Dam. In terms of flow, the observed daily discharge from the Mactaquac Dam was used as the boundary condition during model calibration/validation. However, when the model was run in a forecasting capacity, it was not possible to use these observed values. Instead, a boundary condition was assigned by choosing a representative flow series from historical Mactaquac outflow records. Historical daily outflow data from the period 1969-2014 was therefore inspected to determine the annual discharge series that was most representative of past outflows from the dam in terms of their magnitude and variance. This was accomplished by computing the Q5, Q25, Q50, Q75 and Q95 values as well as the variance and Julian date of maximum peak flow for all Mactaquac outflow discharges between 1969 and 2015 and then for each year within this period. Each year was subsequently ranked by the similarity between its annual metrics and those computed for the entire period. The year which scored the highest combined rank (2007) was determined to be the most representative of past Mactaquac outflows, and was thus selected as the upstream discharge boundary condition when the model was run in a forecasting capacity.

In terms of temperature, the boundary condition used for model calibration/validation and calculation of baseline data was obtained from temperature loggers installed within the Mactaquac Dam reservoir (hereafter referred to as the 'Mactaquac headpond'; Figure 2b). A string of temperature loggers (with a vertical resolution of 2 - 5 m) was installed in the Mactaquac headpond and supplemented with data from an additional logger situated below the Mactaquac Dam outflow at the Mactaquac Biodiversity Facility (Figure 2b). From these data, it was determined that the temperature of the Mactaquac Dam outflow was best approximated by the temperature of the Mactaquac headpond at a depth equal to 7 m. Because it is not possible to use these observed data as a boundary condition when running the model in a forecasting capacity, it was necessary to develop a predictive function to calculate the

Mactaquac headpond outflow water temperature as a function of air temperature. A non-linear (sigmoid) function (Mohseni et al., 1998) was therefore applied to regress temperature recorded by the logger situated at 7 m against the 14-day moving average daily mean air temperature recorded by Environment Canada's Mactaquac Provincial Park weather station (climate ID 8102536). The 14-day moving average was selected amongst a series of tested moving averages of different durations as predictor. The high R^2 (0.98) and low RMSE (0.64 °C) values yielded by this non-linear regression indicated that the temperature of the Mactaquac headpond outflow could be approximated with a good degree of accuracy. These data was therefore deemed suitable for use as an upstream boundary condition when using CEQUEAU model to forecast future water temperatures.

2.4 Model calibration

2.4.1 Hydrological model calibration

CEQUEAU's hydrological model component was calibrated prior to the water temperature model. This was achieved through adjusting the various parameters governing the hydrological model component (see Morin and Couillard, 1990; Dugdale et al., 2017a) until simulated flows approximated observed data recorded at hydrometric stations located throughout the lower SJR watershed with a reasonable degree of accuracy. Simulation quality was measured using the Nash-Sutcliffe model efficiency coefficient (*NSE*) and its logarithm-transformed counterpart (log*NSE*), defined as (respectively):

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

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

where *Qobs* and *Qsim* are the observed and simulated mean discharges respectively at timestep *i* and $\bar{Q}obs$ is the mean observed discharge for the calibration period *n*. Although further details on the hydrological model calibration strategy and results are beyond the remit of this article, comprehensive details can be found in Dugdale *et al.* (2017a). However, model performance near Fredericton (the principal location of interest for temperature model simulations) was found to be good, with identically-high values achieved for both *NSE* and *logNSE* (0.86). Given the good agreement between these model performance metrics, and the fact that logNSE is more sensitive to lower discharges (e.g. Krause et al., 2005) that often occur concomitantly with elevated water temperature, this result indicates that CEQUEAU's hydrological model simulated flows with a sufficient degree of accuracy for implementation of the water temperature model.

2.4.3 Water temperature model calibration

CEQUEAU's temperature model component was calibrated using daily temperature observations recorded by a temperature logger installed in the main stem SJR near Maugerville (45.886° N, 66.527 W; Figure 2b) between 2011 and 2012. The model was subsequently validated against records from another logger installed in the SJR near Fredericton (45.968° N, 66.670 W) during 2014. Because the SJR near Fredericton is the main site of interest for current and future temperature simulations in relation to the Mactaquac dam renewal, this model calibration/validation strategy was deemed acceptable. The optimal calibration was used to simulate temperature in two other nearby tributaries in which loggers were also installed (Keswick River at 45.995° N, 66.833 W and Nashwaak River at 46.007° N, 66.580 W) to ensure that the model was also capable of reproducing reasonable temperature estimates in smaller tributary environments.

Model calibration was conducted following a two-stage process. First, the various model parameters (see Morin and Couillard (1990 for further information) were adjusted manually to ensure that the modelled heat flux terms (e.g. energy gain from solar radiation, energy loss from evaporation) stayed within real-world limits. Following this manual calibration phase, the Tabu Search optimisation algorithm (Zheng and Wang, 1996) was used to further refine the model parameters. Simulation quality was assessed using the model's root mean-squared error (RMSE; eq. 9):

$$(9) \qquad RMSE = \left(\frac{1}{n}\sum_{i=1}^{n}\left(T_{obs_{i,t}} - T_{sim_{i,t}}\right)^{2}\right)^{0.5}$$

where T_{obs} and T_{sim} are the observed and simulated mean temperatures respectively at model timestep t and for grid square i.

Calibration/validation results show that the CEQUEAU temperature model is able to predict water temperature in the lower SJR in the vicinity of Fredericton with a good degree of accuracy (Table 1; Figure 3). Validation against temperature loggers installed at Maugerville/Fredericton shows that the model is especially good at predicting temperature in the main stem SJR, yielding low summer (June – September) RMSE values (0.74 °C).

Table 1. Model RMSE for four temperature calibration/validation sites within the lower SJR watershed

Location	No. obs	Summer RMSE (°C)	Annual RMSE (°C)
SJR at Maugerville (calibration)	252	0.98	1.19
SJR at Fredericton (validation)	129	0.74	0.97
Keswick River at Keswick (secondary validation)	103	1.32	1.27
Nashwaak River at Marysville (secondary validation)	162	1.39	1.12

The validation results also show that the model can produce reasonable simulations of water temperature in lower-order rivers (e.g. Keswick, Nashwaak), although the simulation quality is somewhat reduced (summer RMSE ≈ 1.2 °C). This is presumably due to the fact that the magnitude of energy exchange processes in lower order streams is substantially different than in large rivers (e.g. lower evaporation rates). Furthermore, CEQUEAU is currently unable to model the effects of riparian shading on solar shortwave heat fluxes, which has an inherently larger impact on temperature processes in smaller water courses. Nevertheless, the results show that the CEQUEAU model can produce acceptable (RMSE < 1.5 °C) simulations of water temperature even in the smaller tributaries of the lower SJR basin.

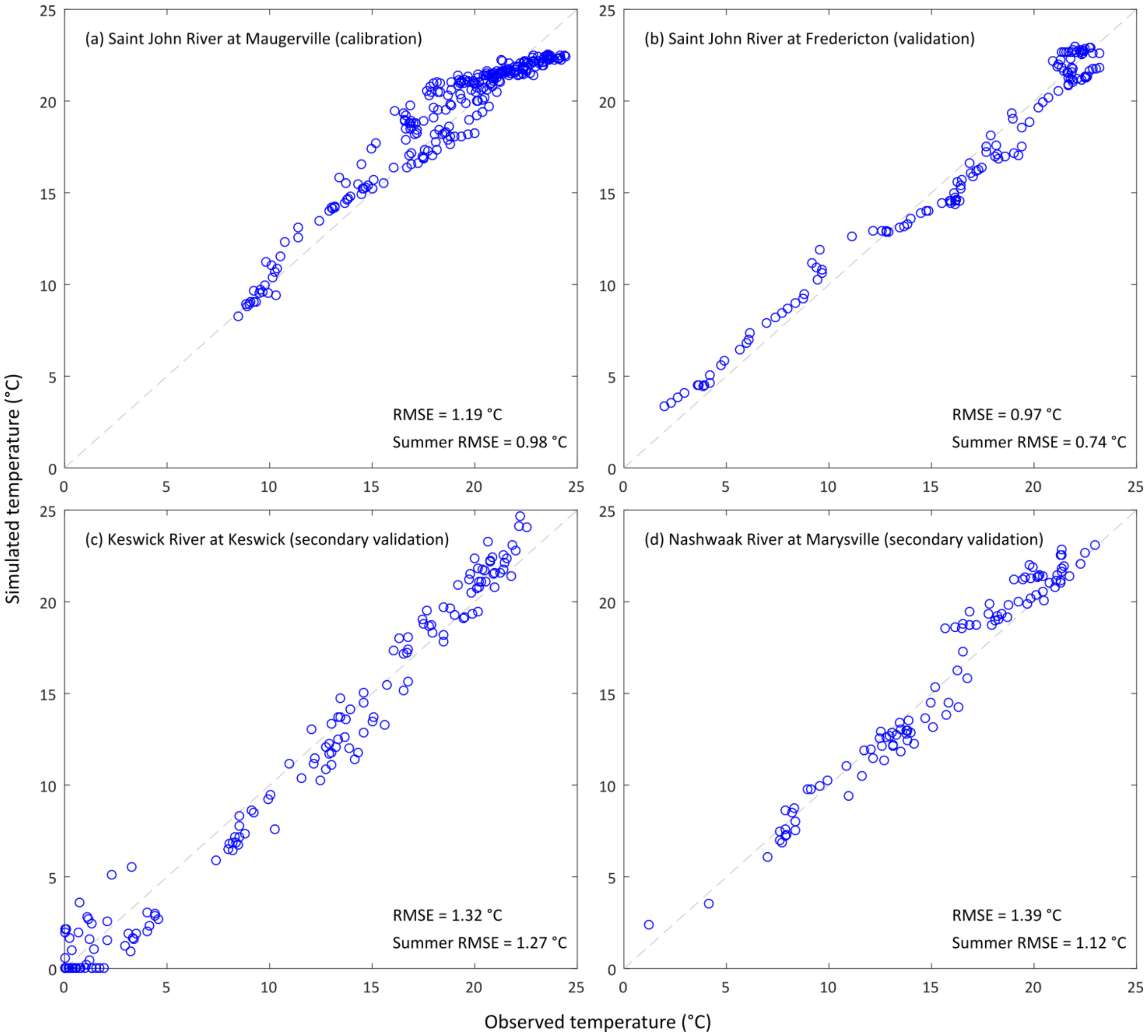

Figure 3. Observed and simulated temperatures at (a) Saint John River at Maugerville (calibration site), (b) Saint John River at Fredericton (primary validation site), (c) Keswick River at Keswick and (d) Nashwaak River at Marysville (both secondary calibration sites)

2.5 Baseline river temperature characterisation

Following calibration, the CEQUEAU temperature model was used to simulate water temperature in the SJR for the period 2010-2014 in order to compute a current-day river temperature baseline and provide a comparative context for future river temperature change due to projected climate change. Mean annual air temperature (6.6 ± 10.6 °C) during the baseline period was found to be slightly higher than the preceding 30-year mean (5.8 ± 10.9°C; 1980-2009). However, this difference is largely a function of warmer winters during the baseline period rather than increased summer temperatures. Indeed, the difference in non-negative air temperature between the baseline period and the 30-year mean was much smaller (11.9 ± 6.8 °C vs 11.7 ± 6.7 °C respectively). Total annual precipitation (1234.7 ± 143.4 mm at Fredericton) was higher than the 30-year mean (1085.4 ± 154.3 mm; 1980-2009), but this was largely due to the existence of several extremely low precipitation years in the 2000s. Given that both air temperature and precipitation during 2010-2014 were within one standard deviation of the 30-year mean and that this period comprised the largest concomitant meteorological dataset, 2010-2014 was deemed appropriate for the calculation of a baseline river temperature series. River temperature was subsequently simulated for the model grid square corresponding to the SJR immediately upstream of Fredericton (45.966° N, 66.661° W; approx. 16 km downstream from the Mactaquac Dam) and is hence unaffected by major tributaries (i.e. Nashwaakis Stream, Nashwaak River, Oromocto River) which join the SJR downstream of this point. A range of metrics describing the thermal regime of the river were subsequently computed from the water temperature simulations (Table 2).

Table 2. Metrics extracted from CEQUEAU simulations of temperature in the SJR near Fredericton

Metric	Notes/definitions
Annual and seasonal metrics	
Annual mean temperature	
Annual maximum temperature	
Minimum July-August temperature	
Annual temperature standard deviation	
Degree days and temperature event timings	
Degree days above 0 °C	
Julian date of positive temperature onset	First date when temperature rises for five consecutive days
Ecologically-relevant temperature metrics	
Atlantic Salmon (Salmo salar)	
Annual number of days in optimal temperature range (8 - <19 °C)	Optimal temperature range in which growth/feeding occurs (Elliott, 1991; Elliott and Elliott, 2010; Jensen et al., 1989; Jonsson et al., 2001; Solomon and Lightfoot, 2008)
Annual number of days above critical temperature (≥23 °C)	Critical temperature threshold above which behavioural thermoregulation occurs (Breau et al., 2007; 2011; Dugdale et al., 2016; Mather et al., 2008)
Striped Bass (Morone saxatilis)	
Julian date of first day on which 16 °C occurs	Possible spawning trigger for Striped Bass (Coutant, 1990; Greene et al., 2009; Rulifson & Dadswell, 1995; Westin & Rogers, 1978)
Annual length of young-of-the-year growth period	Defined as the no. of days post spawning (>16 °C) until the temperature drops below 10 °C prior to winter (Koo and Richie 1973; COSEWIC, 2012, DFO, 2011)

Temperature metrics relating to Atlantic Salmon and Striped Bass were extracted to demonstrate changes to the SJR's temperature regime in an ecological context (Table 2). These metrics represent a conservative synthesis of current knowledge regarding temperature thresholds for these species (i.e. metrics are not derived from the SJR populations and their behaviour owing to lack of data). For the Atlantic Salmon, we quantified optimal temperature for growth (8 - <19 °C) and the duration of time temperatures exceeded the upper critical temperature threshold (≥23 °C). Our chosen optimal temperature range was synthesized from numerous studies (see Elliott, 1991; Elliott and Elliott, 2010; Jensen et al., 1989; Jonsson et al., 2001; Solomon and Lightfoot, 2008), and represents a generalized temperature window in which growth occurs. However the 'growth' window can extend beyond these boundaries at certain life stages (see Elliott, 2001). The chosen critical temperature threshold represents the most frequently-cited temperature at which behavioural thermoregulation begins (see Breau et al., 2007; 2011; Dugdale et al., 2016; Mather et al., 2008).

The native SJR Striped Bass population is currently designated as extirpated (COSEWIC 2012; see Andrews et al. 2017 for full review), although large Striped Bass (presumably from other rivers) are numerous in the SJR. We therefore chose two metrics pertaining to the possible reestablishment of a native population in the SJR. The first metric, the Julian date when 16 °C first occurs, represents a general spawning trigger for Striped Bass populations native to eastern Canada and the Gulf of Maine (e.g. Coutant, 1990; Greene et al., 2009; Rulifson & Dadswell, 1995; Westin & Rogers, 1978). The second metric, the annual length of the growing period for young-of-the-year (YoY) bass, was defined as the length of time (days) between the occurrence of the 16 °C spawning threshold and the date on which temperatures drop below 10 °C during the onset of autumn/winter (i.e. when juveniles cease feeding and move into overwintering habitat; e.g. Koo and Richie 1973; COSEWIC, 2012; DFO, 2011).

2.6 Future river temperature projections

Following the simulation and extraction of baseline temperature metrics, CEQUEAU was used to simulate water temperature for the SJR near Fredericton under a range of future climate scenarios. Future meteorological projections necessary to run CEQUEAU in a forecasting capacity were generated by the Ouranos Consortium on Regional Climatology and Adaptation to Climate Change (Gauvin St-Denis and Huard, 2015). First, a series of regional climate models (RCM) driven by downscaled general circulation model (GCM) outputs were used to assess future changes in precipitation and air temperature over the SJR basin under a range of different emissions scenarios. From the range of available scenarios, 11 RCMs (Table 3) were selected with a view to encompassing the range of variability in projected temperature and precipitation change (Figure 4).

Table 3. List of selected future climate simulations. Source: Gauvin St-Denis & Huard (2015)

Ensemble	RCM	GCM	GHG scenario	Member	Simulation period
CCCMA (CORDEX)	CanRCM4	CANESM2	RCP 4.5	r1i1p1	1950 - 2100
CCCMA (CORDEX)	CanRCM4	CANESM2	RCP 8.5	r1i1p1	1950 - 2100
Ouranos	CRCM4	CGCM3	SRES A2	r4i1p1	1961 - 2100
Ouranos	CRCM4	CGCM3	SRES A2	r5i1p1	1971 - 2100
Ouranos	CRCM4	ECHAM5	SRES A2	r1i1p1	1971 - 2100
Ouranos	CRCM4	ECHAM5	SRES A2	r3i1p1	1971 - 2100
SMHI (CORDEX)	RCA4	CANESM2	RCP 4.5	r1i1p1	1951 - 2100
SMHI (CORDEX)	RCA4	CANESM2	RCP 8.5	r1i1p1	1951 - 2100
SMHI (CORDEX)	RCA4	EC-EARTH	RCP 2.6	r1i1p1	1951 - 2100
SMHI (CORDEX)	RCA4	EC-EARTH	RCP 4.5	r1i1p1	1951 - 2100
SMHI (CORDEX)	RCA4	EC-EARTH	RCP 8.5	r1i1p1	1951 - 2100

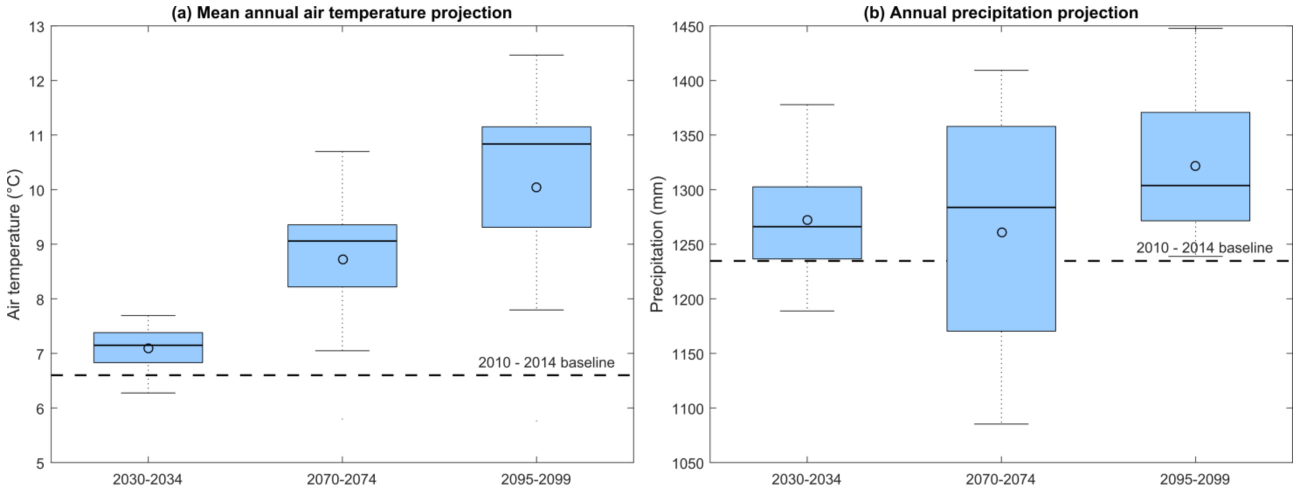

Figure 4. Range of variability in (a) projected mean annual air temperature and (b) precipitation under selected future climate scenarios. Median value given by line, mean by circle. Upper and lower limits of boxes show 25th and 75th percentiles, whiskers show outliers within 1 IQR of mean. 2010-2014 baseline value denoted by horizontal dashed line.

The selected models were subsequently used to generate daily meteorological time series (daily minimum/maximum temperature, precipitation, wind speed, cloud cover, actual vapour pressure and incoming solar shortwave radiation); meteorological data were bias-corrected by comparing meteorological hindcasts generated by the models to observed data recorded by the meteorological stations detailed in 2.3.2. Bias correction was achieved using the quantile-mapping methodology of

Gennaretti et al. (2015). First, a fourth-order polynomial was fitted to the observed and simulated (hindcast) time series and used to subtract long-term trends. The residuals of each time series were then binned into 50 quantiles and each quantile (observed vs. simulated) compared, yielding 50 correction factors. The correction factors were applied to the simulated data (either multiplicatively or additively depending upon each variable), and the long-term trend added back in to generate bias-corrected simulations. Finally, the bias-corrected meteorological projections were applied to CEQUEAU, and the model was run for the periods 2030-2034, 2070-2074 and 2095-2099 to generate future water temperature projections for the SJR.

3. Results

3.1 Baseline river temperature characterisation

Results of the baseline river temperature simulations show that mean daily temperature in the SJR (near Fredericton) during the period 2010 - 2014 was 10.9 °C, with a mean annual maximum temperature of 22.8 °C attained during the warmest part of the summer (Table 4). Mean minimum July – August temperature (a particularly important metric for temperature-sensitive aquatic species (e.g. Caissie et al., 2012; Breau, 2013) was 20.1 °C. 2010 and 2012 yielded the highest degree days statistics within the period, unsurprising given that these periods are widely acknowledged as years of above-average air temperature for the region (e.g. Jeong et al., 2013; Dugdale et al., 2016). While 2014 exhibited the lowest number of degree days, it was also the only year during the baseline simulation period in which water temperature exceeded 23 °C (Table 5). The post-winter warming onset started particularly early in 2014 (11^{th} day of year compared to mean DOY of 52.6). However, this date may simply reflect the choice of indicator for this metric (i.e. warming onset was defined as the first date each year upon which temperature rises for five consecutive days).

Table 4. Water temperature metrics for the SJR near Fredericton for the period 2010-2014

Year	Annual mean temperature (°C)	Annual max temperature (°C)	Minimum July – August temperature (°C)	Standard deviation (°C)	Degree days (>0 °C)	Julian date of positive temperature onset
2010	11.2	23.0	18.9	7.9	4085.5	46
2011	11.0	22.4	20.1	8.3	4007.6	70
2012	11.1	22.8	21.3	8.4	4051.2	75
2013	10.7	22.9	19.6	8.5	3901.2	61
2014	10.5	23.0	20.7	8.7	3820.1	11
Mean	*10.9*	*22.8*	*20.1*	*8.4*	*3973.1*	*52.6*

In terms of temperature metrics pertaining to Atlantic Salmon and Striped Bass, temperature fell within the optimal range for Atlantic Salmon for an average of 124.6 days (Table 5). Temperature only exceeded the critical threshold once during the 2010-2014 baseline period. For Striped Bass, the 16 °C spawning trigger was reached by the 149.6th day of the year on average (30th May; Table 5). Furthermore, the annual growth period for YoY Striped Bass averaged 161 days during the baseline period.

Table 5. Ecologically relevant water temperature metrics for the Atlantic Salmon and Striped Bass computed for the period 2010-2014

	Atlantic Salmon		Striped Bass	
Year	Days in optimal temperature window (8 - <19 °C)	Days above critical temperature (≥23 °C)	Julian date of 1st day on which 16 °C occurred	Annual length of young-of-the-year growth period (no. days)
2010	152	0	150	154
2011	106	0	152	160
2012	136	0	143	172
2013	108	0	152	158
2014	121	1	151	161
Mean	*124.6*	*0.2*	*149.6*	*161*

3.2 Future river temperature projections

Synthesis of the climate simulations indicates a general trend of increasing water temperature within the SJR near Fredericton by the year 2099 (Figure 5). The relative similarity and low range of variability in river temperature metrics produced by the various simulations (generally within the model calibration RMSE) highlights a reasonable degree of agreement between the different climate models, in spite of the differences in GCM/RCM and greenhouse gas scenarios.

3.2.1 Annual and seasonal temperature metrics

Taking the mean of all river temperature simulations generated by the various future climate scenarios (Table 3), water temperature in the SJR near Fredericton is projected to be marginally lower in for the period 2030-2034 (10.8 °C) than that yielded by the baseline temperature simulation (10.9 °C; section 3.1). This result is presumably due to the relatively small difference in air temperature and precipitation between the baseline period and 2030-2034 (see figure 4), which, given the model's calibration RMSE, means that any increase in mean annual water temperature between the present and 2030-2034 is likely to be negligible. However, higher mean annual temperature *is* projected for the periods 2070-2074 and 2095-2099 (11.9° C and 12.8° C respectively; Figure 5a), representing an increase in temperature of approximately 1 °C for each ~30 year period. Despite the fact that mean annual river temperature is not projected to rise by 2030-2034, maximum water temperature metrics show a clear increase in comparison to the 2010-2014 baseline (22.8 °C), rising to 24.2 °C by 2030-2034. Further increases in annual maximum water temperature (to 25.3 °C and 26.4 °C for the periods 2070-2074 and 2095-2099 respectively) demonstrates that the rate of maximum temperature increase may outstrip that of mean temperature (Figure 5b). Minimum August/July temperature is also projected to increase towards 2099. Although the minimum August/July temperature projected for 2030-2034 is actually marginally lower than the baseline value of 20.1°C (although again within the model RMSE), higher minimum August/July temperature (20.7 °C and 21.8 °C respectively) *is* projected for the more distant simulation periods (2070-2074, 2095-2099; Figure 5c). While daily standard deviation of temperature does increase very slightly for each simulation period (Figure 5d), the difference is small (within the model calibration RMSE), and it is therefore likely that the range of temperature variability will stay relatively constant.

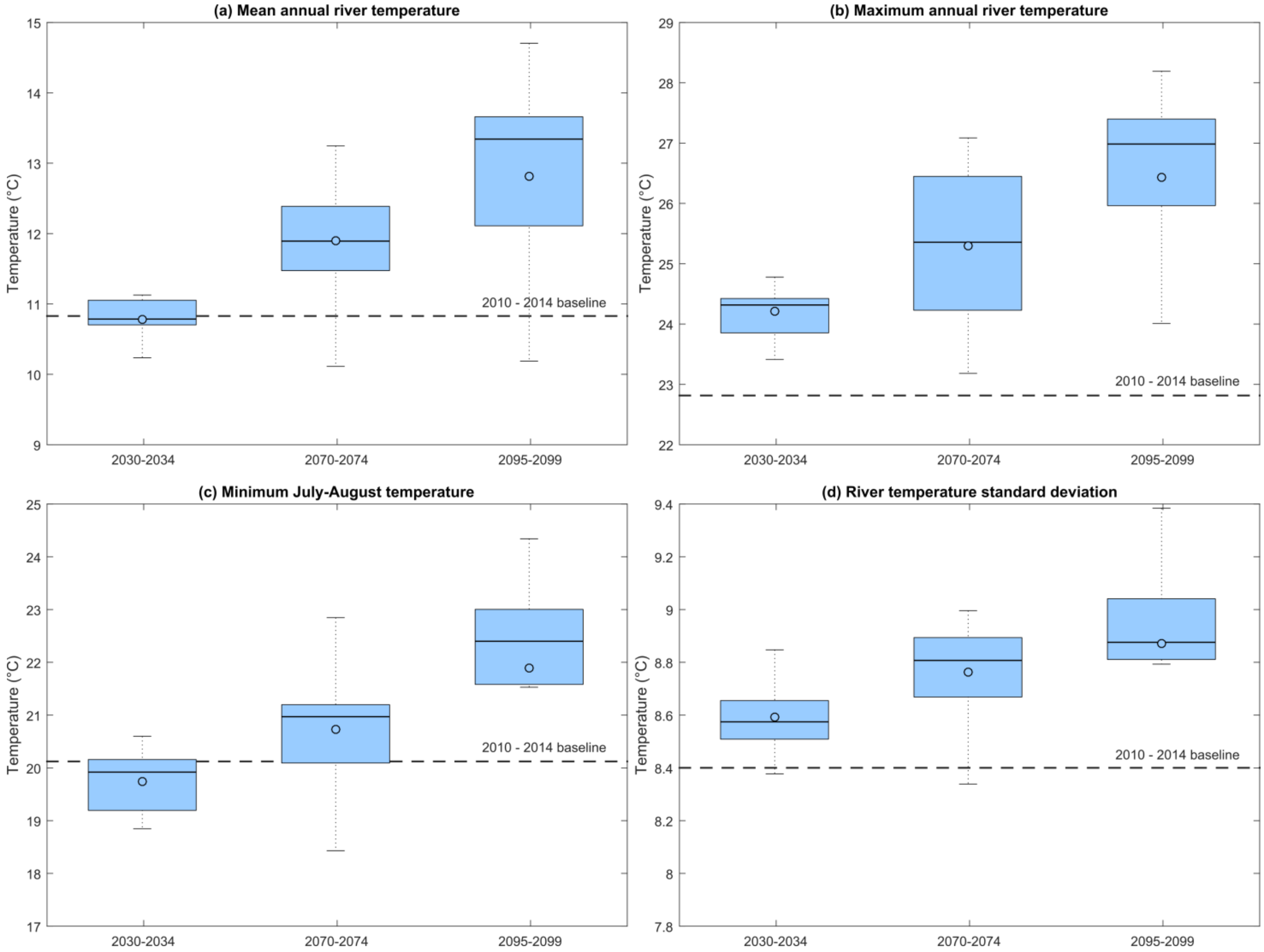

Figure 5. Annual and seasonal river temperature metrics for future climate periods 2030-2034, 2070-2074 and 2095-2099. Boxplots show range of variability yielded by different future climate scenarios. Median value given by line, mean by circle. Upper and lower limits of boxes show 25th and 75th percentiles, whiskers show outliers within 1 IQR of mean. 2010-2014 baseline value denoted by horizontal dashed line.

3.2.2 Degree days and annual temperature onset

Results of the degree days and annual temperature onset metrics (Figure 6) show similar trends to the annual and seasonal temperature metrics. In terms of degree days (Figure 6a), while the 2030-2034 projection actually shows a slight decrease compared to the 2010-2014 baseline, this decrease is negligible and within the standard deviation of values produced by the baseline dataset. Conversely, the periods 2070-2074 and 2095-2099 are associated with large increases (4344.5 and 4678.6) in comparison to the 2010-2014 baseline that are substantially outside the current range of variability. In terms of projected changes in the date of annual temperature onset (defined as the first day of the year on which temperature has risen for five consecutive days; Figure 6b), the annual temperature warming onset is projected to occur on or around the 62nd day of the year (March 3rd) in the period 2030-2034. This is substantially later than that calculated for the current-day baseline (52nd day of year), and is likely due to the anomalously early temperature onset observed in 2014. However, the warming onset will occur approximately 15 days earlier than the current baseline in the period 2070-2074 (47th day of the year; February 16th) and a further ~10 days earlier by 2095-2099 (37th day of the year; February 6th). Together, these results highlight a shift in seasonality within the SJR, with a substantially longer ice-free period becoming the norm.

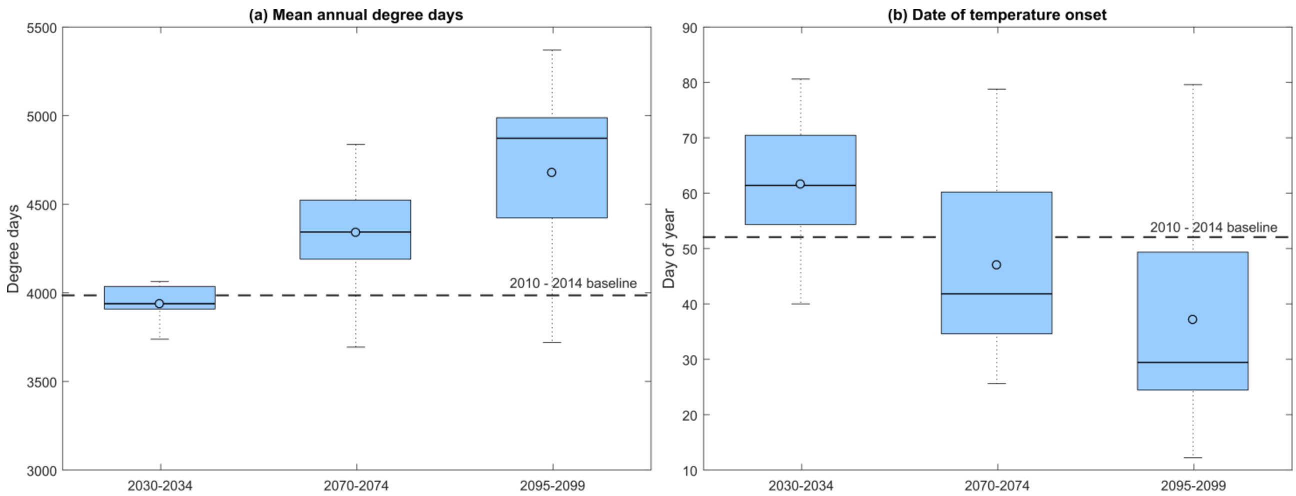

Figure 6. (A) Projected changes in annual degree days and (B) date of annual warming onset for future climate periods 2030-2034, 2070-2074 and 2095-2099. Boxplots show range of variability yielded by different future climate scenarios. Median value given by line, mean by circle. Upper and lower limits of boxes show 25th and 75th percentiles, whiskers show outliers within 1 IQR of mean. 2010-2014 baseline value denoted by horizontal dashed line.

3.2.3 Ecologically relevant temperature metrics

Metrics relating to the temperature requirements of Atlantic Salmon highlight a trend towards a decreasing amount of time during which river temperature is within the optimal range for Atlantic Salmon (8 – 19 °C) as a function of distance into the future (112.9, 108.1, and 103.6 days annually respectively for 2030-2034, 2070-2074 and 2095-2099; Figure 7) in comparison to the 2010-2014 baseline (124.6 days). In tandem with this, future climate scenarios also indicate a potentially substantial increase in the number of days during which mean river temperature is above the upper critical threshold for Atlantic Salmon (13.3, 41.1 and 58.6 days per year respectively for 2030-2034, 2070-2074 and 2095-2099) in comparison to the current baseline of 0.2 days.

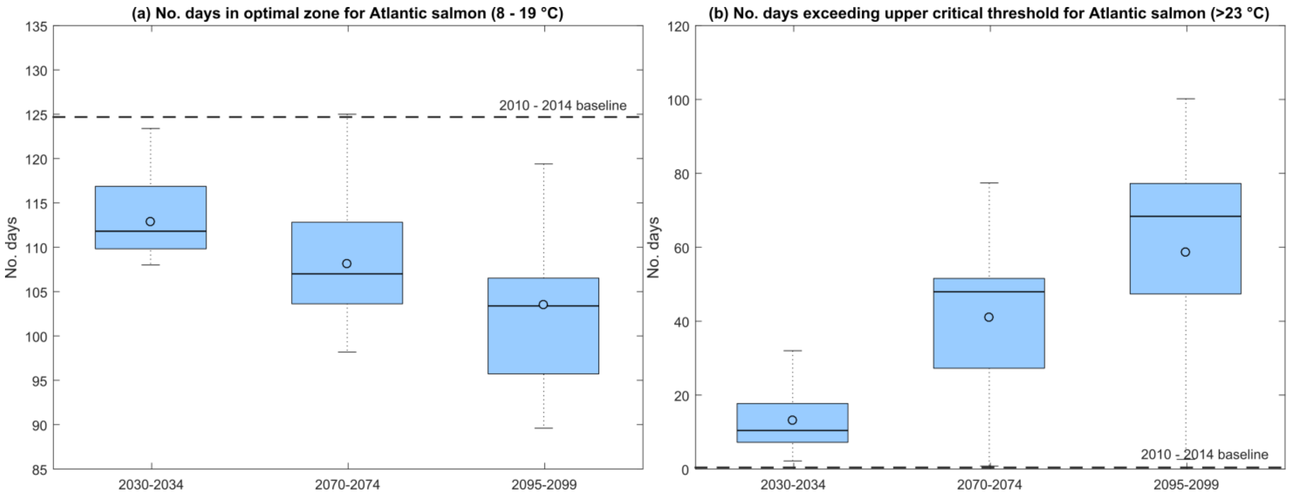

Figure 7. Projected changes in annual number of days on which temperature (A) is within the optimal temperature zone for the Atlantic Salmon (8 - 19 °C) and (B) exceeds the upper critical limit (23 °C). Note: This is not the same as the upper incipient lethal limit (~28 °C), above which salmon populations are likely to become extirpated. Boxplots show range of variability yielded by different future climate scenarios. Median value given by line, mean by circle. Upper and lower limits of boxes show 25th and 75th percentiles, whiskers show outliers within 1 IQR of mean. 2010-2014 baseline value denoted by horizontal dashed line.

Metrics relating to the Striped Bass indicate that the ~16 °C spawning cue will occur progressively earlier (150th, 141st and 136th day of year for the periods 2030-2034, 2070-2074 and 2095-2099 respectively; Figure 8). This represents an advance of 9, 14 and 23 days respectively compared to the current baseline. In tandem, the length of the Striped Bass YoY growing season is projected to increase in comparison to its baseline of 161 days (171, 183 and 195 days respectively for the periods 2030-2034, 2070-2074 and 2095-2099). This represents a 21% increase in the length of the growth season by the year 2099.

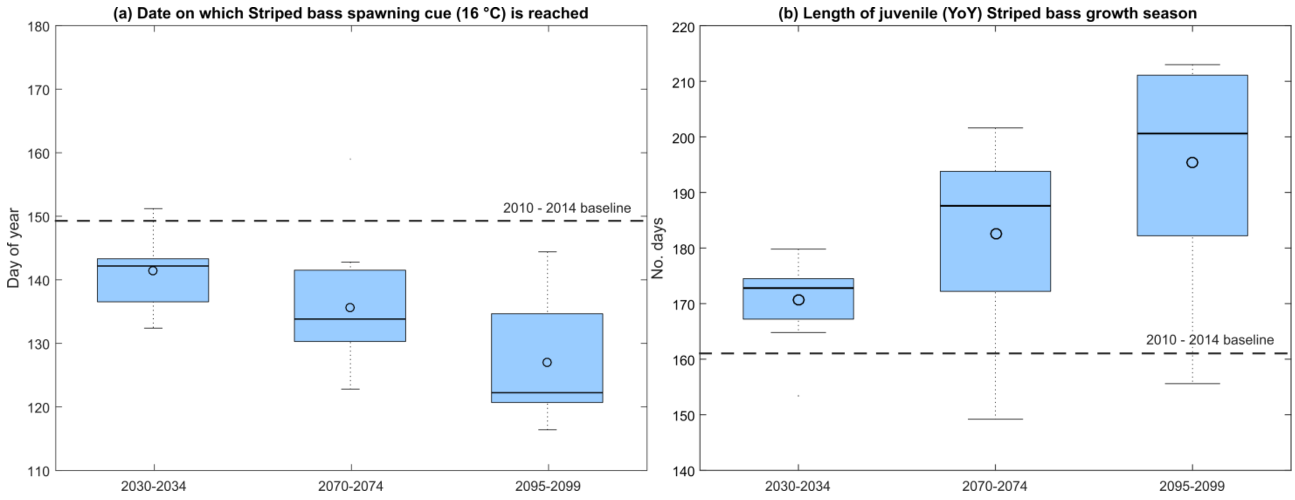

Figure 8. Projected changes in temperature metrics relating to Striped Bass under future climate scenarios. (A) Date on which river temperature first reaches 16 °C, a spawning trigger for Striped Bass. (B) Length of YoY growing season (defined as period between 16 °C and point at which temperature falls below 10 °C with the onset of the following autumn). 2010-2014 baseline value denoted by horizontal dashed line.

4. Discussion

4.1 Impacts of climate change on the thermal regime of the SJR

Results of the CEQUEAU simulations using climate change scenarios as inputs indicate that mean annual river temperature in the SJR will increase by ~1 °C by 2070-2074 and a further ~1 °C by 2095-2099. We make no assertions as to the most likely/appropriate climate model or greenhouse gas concentration pathway, preferring instead to report mean syntheses of all future climate scenarios owing to the relatively small range of values of temperature increase generated by the various climate projections (generally ≲ 1.5 °C) for each simulation period. The magnitude of annual mean river temperature warming is generally situated towards the middle of values reported by other studies from eastern Canada (e.g. 3.2 °C by 2100; Brodeur et al., 2015; 2.1 – 3.7 °C by 2100; Caissie et al., 2014; 0.2 – 2.5 °C by 2065; Jeong et al., 2013), presumably because these later studies focus on smaller watersheds than the SJR (10^2 or 10^3 km^2 rather than 10^4 km^2) which are more susceptible to extremes, whereas the thermal inertia of larger river systems will likely will act to buffer the incidence of very high or low temperature events. Nonetheless, the temperature increases reported in this study are broadly in line with projections for the region from larger-scale global water temperature modelling efforts (e.g. van Vliet et al., 2013a; van Vliet et al., 2013b).

Although Kwak et al. (2017) reported a relatively small increase in median June temperature (0.2 – 0.7 °C increase in mean June temperature by 2096), the results of our study are broadly consistent with the findings of Daigle et al. (2015; 0.7-2.7 °C increase in seven-day maximum temperature by 2065), thus adding credence to our projected increase in annual maximum and summer minimum river temperature towards 2100. However, both Kwak et al. (2017) and Daigle et al. (2015) were conducted in substantially smaller watersheds than the SJR, so limited inferences can be drawn as to their comparability.

Results of the degree days and positive temperature onset metrics highlight a trend towards a seasonal shift in the SJR's thermal regime under a warming future climate, with warmer river temperatures occurring earlier in the year and enduring longer into the autumn/winter months. Although the precise definition of what constitutes a 'positive temperature onset' varies between studies (e.g. Daigle et al., 2009), similar seasonal modifications in temperature amplitude have been attributed to climate change-driven alterations to river flow regimes (e.g. van Vliet et al., 2011). Taken together, this combination of increased mean and maximum temperature, a longer duration ice-free period and the earlier onset of post-winter river temperature warming will likely have substantial impacts on the biotic components of the SJR's ecosystem (eg. Daufresne et al., 2004; van Vliet et al., 2013b).

4.2 Ecological implications of SJR temperature warming

In general terms, the shift in isotherms (e.g. Isaak and Rieman, 2013) projected for the SJR will result in habitat changes for a range of river biota. Although uncertainty prevails regarding the exact thresholds that define 'critical' temperatures for Atlantic Salmon (e.g. Ficke et al., 2007), our results highlight a generally negative future for thermal habitats of the Atlantic Salmon. Results show a reduction in the number of days during which temperature is optimal for feeding and growth and a substantial increase in the amount of time during which temperature exceeds the upper critical limit (~23 °C). This change is particularly pronounced during the 2095-2099 simulation period (similar to projections reported by Brodeur et al., 2015). For the SJR, even the 2030-2034 simulation yielded a substantial increase in the number of days during which temperature exceeded the upper critical threshold in comparison to current baseline conditions. Similarly large increases in the number of days exceeding the critical temperature threshold for Atlantic Salmon have been reported by Caissie et al. (2014) and Daigle et al. (2015) in smaller river systems proximal to the SJR, indicating that this trend is likely to predominate across eastern Canada. Our results also indicate that the minimum July-August temperature will increasingly stay above 20 °C, a threshold often cited as a minimum temperature necessary to allow post-heat stress recovery (e.g. Caissie et al., 2012; Breau, 2013). Together, these results project an increased incidence of heat stress events, a reduction in the length of the recovery temperature period, and thus an increasing probability of mortality and ultimately population scale declines. This adds credence to calls for improved river management strategies in order to preserve cool water habitats and reduce the incidence of anthropogenically-driven stressors on salmon fisheries (e.g. Breau, 2013; Brodeur et al., 2015; Kurylyk, 2015). Given that dams can be used as effective tools for managing river temperature regimes and moderating thermal extremes by releasing hypolimnetic water to downstream reaches (eg. Olden et al. 2010; Null et al. 2013), the alteration of outflow regimes and/or intake depths at impoundments such as the Mactaquac dam may present one such strategy for mitigating the projected climate change impacts on the SJR.

For Striped Bass, the ~16 °C spawning cue is projected to occur earlier in the year in comparison to the 2010-2014 baseline. Although the native SJR Striped Bass population was thought to have been extirpated post-1975 (Dadswell 1976), the river is currently frequented by migrant fish from the coastal USA and Nova Scotia, and the presence of juveniles indicates that there may be intermittent spawning events in the SJR (Andrews et al. 2017). This intermittent spawning may be related to flow management at the Mactaquac Dam and the consequential impact on the river's thermal regime at the time of spawning. Our model assumes that flow management will remain similar over time and in this scenario, the spawning period could therefore begin earlier. This, coupled with the longer growing period for YoY, suggests that the warming climate may have a positive effect on YoY growth and therefore survival for Striped Bass that are reproducing in the SJR (e.g. Hurst et al. 2003). The projected shortening of the winter period may also decrease winter mortality of juveniles (e.g., Hurst and Conover 2002). Taken together, the projections for Striped Bass suggest that thermal habitats will improve with a warming climate in the SJR and other rivers located at the northern limit of the species' range.

Our projected changes to the thermal regime of the SJR and extrapolation of these results onto the biology of fishes in the SJR come with a range of assumptions. The most significant outcome from our findings is that the river's ecosystem will respond in diverse ways as the river continues to warm over future years. The more complex matrix of responses to temperature changes has yet to be examined and thus we cannot presently predict the future state of the SJR or similar ecosystems. For example, our model is incapable of simulating either finer-scale variations in thermal habitat (e.g. thermal refuges resulting from tributaries or groundwater), or the impacts of climate change thereon (eg. Kurylyk et al. 2014). Given that salmonids and other species in warmer rivers in Eastern Canada are known to use thermal refuges to avoid heat stress (e.g. Dugdale et al. 2016), it is possible that the presence of thermal refuges may mitigate the impact of projected temperature rises on Atlantic Salmon (for example). However, information on thermal microhabitat within the SJR and its use by salmonids for thermoregulation is lacking. Further research is therefore essential in order to better understand the impacts of climate change on the entire SJR ecosystem.

4.3 Limitations and future work

It is important to be aware of the methodological limitations and potential sources of error inherent in the modelling approaches used to simulate the temperature data detailed here. Aside from obvious uncertainty regarding future climate scenarios, error is also inherent in the CEQUEAU model itself. One key source of error arises from the relatively limited number of water temperature observations that were available for model calibration. No long-term water temperature series exist for the SJR because of the difficulty of installing temperature loggers in a large river prone to severe flooding and ice-scour events. It was therefore necessary to calibrate/validate CEQUEAU on a relatively small number of temperature observations (252 days for calibration, 129 for validation on the main SJR plus 103 and 162 days' additional data for two tributaries) acquired over a short period of time. Although the resulting model validation RMSE was reasonable (RMSE = 0.97; summer RMSE = 0.74 °C for simulations near Fredericton), uncertainty remains concerning how the model will perform against longer multi-year temperature series or at other locations for which validation data is unavailable. Because the short time series used for model calibration do not capture temperature variability over a longer period (i.e. several years) or during winter, it is difficult to determine the level to which the model yields realistic water temperature predictions during other parts of the year. However, considering that the principal focus of this investigation was the modelling of summer water temperature with a view to understanding the impact of temperature increase on the SJR's fluvial biota, we feel that the model calibration achieved here was acceptable for this purpose. Furthermore, given the almost complete absence of other temperature data for the SJR, this data at provides an initial insight into the impacts of climate change on a region for which there would otherwise be no information available. Nevertheless, we advocate the continued acquisition of water temperature data for the SJR with a view to improving model calibration and reducing uncertainty.

CEQUEAU's use of the Thornthwaite equation (Thornthwaite, 1948) to calculate evaporative heat flux is another potential source of uncertainty in water temperature projections. Recent research (e.g. Sheffield et al., 2012) indicates that the use of the Thornwhaite equation generates positively-biased (ie. too high) evaporation rates when applied to future climate models. In the context of the

CEQUEAU model, this may mean that computed evaporative heat losses are slightly high, and future river temperature may in fact be marginally warmer than those projected here. However, given that evaporative heat losses are accompanied by an associated decrease in water volume, any erroneously high evaporative cooling may be balanced by an associated decrease in water volume which will act to maintain river temperature. This means that biases resulting from the use of the Thornthwaite equation are likely to be relatively small, and the overall trends presented in this paper are still relevant. Furthermore, recent efforts to update CEQUEAU (e.g. St-Hilaire et al, 2015) are focusing on the implementation of alternative methods for calculating evapotranspiration (e.g. Penman, 1948; Priestly & Taylor, 1972), potentially allowing for the future refinement of water temperature simulations.

In addition to error associated with the CEQUEAU model itself, the sigmoid function used to compute the temperature of the Mactaquac headpond outflow is likely a further source of error. This results in part from the use of the 14-day moving average of mean air temperature to predict outflow water temperature which has the effect of dampening variability in the temperature series. This means that extreme temperature events are likely to be missed in the model simulations and as such, the model results likely underrepresent 'real' natural temperature variability. Similarly, it is also important to note that any temperature simulations for the lower SJR using the current CEQUEAU implementation will partially reflect water temperature within the Mactaquac headpond. This is particularly apparent with regards to the temperature metrics extracted for 2010 and 2012. Despite the fact that these two years yielded notably high summer air temperature in comparison to other years in the period 2010-2014, many of the water temperature metrics extracted in this study (e.g. annual maximum temperature, minimum July – August temperature, no. of days > 23 °C) do not highlight these two years as being anomalously warm. Indeed, the opposite appears to be the case, with 2014 (a notably cooler year when examining annual air temperature statistics) showing higher temperatures. This is presumably due to the temperature and flow regime of the Mactaquac headpond, which acts to buffer downstream temperature, dampening the occurrence of high temperature events such as those in 2010 and 2012. However, temperature simulated for the Nashwaak River (a natural river unimpeded by a significant thermal mass such as the Mactaquac headpond), were indeed warmer in 2010 and 2012 than in 2014. This indicates that the CEQUEAU model is functioning correctly and the lower-than-expected temperature in 2010 and 2012 are simply a reflection of the Mactaquac headpond's influence on temperature in the lower SJR.

Another limitation inherent in the future climate simulations concerns the use of historical hydrometric data to represent the Mactaquac dam outflow when running CEQUEAU in a forecasting capacity (see section 2.3.3). Although efforts were made to ensure that the chosen discharge series imposed at the model square corresponding to the Mactaquac dam outflow was representative of past discharges, it is possible that the outflow regime of the Mactaquac headpond will also change under future climate conditions. Thus, the outflow discharges used to run the model may not necessarily represent those that will occur under future climate conditions. However, given that outflows from the Mactaquac dam are presently managed to maintain discharge between certain thresholds and this practise will likely continue into the future, our use of past hydrometric data to simulate future dam outflows should not unduly alter the projections documented here.

While we are confident that the results of our simulations/projections are representative of the reaches of the lower SJR in the vicinity of Fredericton, it is less likely that they reflect the true thermal regime of the lacustrine or tidal portions of river further downstream, towards the Bay of Fundy due to the fundamentally difference thermal processes that likely occur within these reaches. In terms of the applicability of our findings to smaller tributaries, flow and temperature simulations were well conditioned in the tributaries closer to Fredericton (e.g. Keswick and Nashwaak rivers; see figure 3). Simulated flows in more distant tributaries were less accurate (although generally still reasonable; see Dugdale et al. 2017 for further details), meaning that the resulting temperature simulations may also suffer from lower accuracy. However, the absence of temperature records for these more distant locations means that validation at these sites is not currently possible. Future work should therefore focus on the acquisition of temperature data for more distant tributaries or reaches of the SJR closer to the Bay of Fundy with a view to better understanding the quality of temperature simulations (and hence, applicability of our future temperature projections) to these locations. Nevertheless, we feel that given the complete lack of existing water temperature projections for the Saint John River, our study provides a useful initial point of reference with regards to the impacts of climate change on the SJR and other similarly-sized watersheds in the region.

5. Conclusion

Given the general lack of information regarding the impacts of climate change on river systems in eastern Canada, the results of this investigation provide a first insight into how the thermal regime of a large eastern Canadian river may change in response to future climatic warming. While methodological limitations mean that further research is needed, the results of this study provide a basis upon which more detailed studies into the impacts of climate change on the SJR and its ecosystem can be conducted. Results of the future climate simulations present a picture of generally elevated temperature with a shift towards increased incidence of high temperature events and an elongation of the period during which water temperature is above zero. These results mirror those of other climate change simulations conducted in Québec and New Brunswick, and present a troubling picture with regards to the continued survival of temperature-sensitive fish species native to the region (e.g. Atlantic Salmon, Brook Trout, Slimy Sculpin). Although considerable further research is required, it is hoped that the improved evidence base for river temperature warming in the Saint John River that this study provides will spur improved river management strategies with regards to conserving the populations of native cold water fishes, for example, through conservation of critical thermal habitats, the reduction of anthropogenic stressors, or the implementation of appropriate environmental flow management plans.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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