STREAM WATER TEMPERATURE MODELING UNDER CLIMATE CHANGE SCENARIOS

PHASE II: STUDY OF STREAM WATER TEMPERATURES UNDER CLIMATE CHANGE SCENARIOS B1 & A2

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20C3M	Observed 20th century scenario
A2, B1	Climate scenarios
CCCma	Canadian Centre for Climate modeling and analysis
CGCM	Coupled General Climate Model
GMDH	Group Method of Data Handling
IDW	Inverse Distance Weighting
IPCC	Intergovernmental Panel on Climate Change
LSWM	Little Southwest Miramichi
PNN	Polynomial Neural Network
RMSE	Root Mean Square Error
SRES	Special Report on Emission Scenarios
WMO	World Meteorological Organization
T	Mean air temperature
$\bar{T}$	Mean air temperature
T_{Δ}	Air temperature input for scenario simulation
T_{max}	Maximum air temperature
T_{min}	Minimum air temperature
T_{OBS}	Observed air temperature
T_{W}	Mean water temperature
T_{W}^{max}	Maximum water temperature
T_{W}^{min}	Minimum water temperature
Δ_{T}	Change in air temperature

ABSTRACT / RÉSUMÉ

Abstract: Stream water temperature is a very important parameter when assessing water quality and aquatic ecosystem dynamics. For instance, cold-water fishes such as salmon can be adversely affected by maximum summer temperatures or by those exaggerated by land-use activities such as deforestation. The present study deals with the modelling of stream water temperatures under climate change scenarios by means of polynomial neural networks (PNN) to relate air and water temperatures in Little Southwest Miramichi River (LSWM), a river in New Brunswick. Future climate data were extracted from the Canadian Coupled General Climate Model (CGCM 3.1/T63) under the greenhouse emission scenarios B1 and A2 defined by the Intergovernmental Panel on Climate Change (IPCC). The climate air temperatures were downscaled using the delta change approach. The study predicts an increase in stream water temperature of between 2.1 ºC to 3.7 ºC, at the end of this century.

Résumé : La température des cours d’eau est un paramètre fort important lors de l’évaluation de la dynamique des écosystèmes aquatiques. Par exemple, les poissons d’eau froide, tel que le saumon, peuvent être défavorablement affectés par les températures maximales estivales ou par celles amplifiées par les activités d’utilisation des sols, telle que la déforestation. La présente étude se concentre sur la modélisation des températures des cours d’eau sous changements climatiques en utilisant les réseaux de neurones polynomiaux (RNP) afin d’associer les températures de l’eau et de l’air. Les données climatiques, provenant d’une simulation de la troisième génération du modèle couplé climatique global (MCCG3.1/T63), ont été utilisées avec les RNP pour estimer les températures de l’eau au cours d’eau Little Southwest Miramichi (LSWM) dans le contexte actuel et dans le contexte climatique sous les familles de scénarios B1 et A2. La régionalisation des températures de l’air a été accomplie en utilisant la méthode des deltas. Les résultats montrent que vers la fin du siècle la température de l’eau subira une augmentation de 2.1 ºC à 3.7 ºC.

1. INTRODUCTION

Climate change impacts on river systems includes changes in runoff, river flow and groundwater storage. To these quantitatively aspects, some water quality aspects have to be assessed through its many physical and biogeochemical facets. With respect to this biogeochemical water quality, most climate change impacts can be attributed to changes in stream water temperature. When water temperature increases, dissolved oxygen decrease, and biological activities is enhanced, with consequences on nutrients, organic matter and biomass in general. Also, the impact of climate change on stream water temperature is heavily dependent on the future evolution of air temperature as well as other meteorological and physical parameters. As air temperature is the parameter that is expected to change most significantly under climate change; therefore, water temperature is also expected to be an extremely important parameter with significant changes.

In recent years, research on regional and global climatic changes and their impacts on water resources have received considerable attention. Higher water temperatures and greater variations in runoff associated with climate change are likely to influence physical, chemical and biological processes governing water quality that will adversely modify human water use (Dale 1997; Murdoch et al. 2000; Schindler 2001; Thorne and Fenner 2011).

The predicted impact of climate change on the hydrological cycle and streamflow have been extensively analyzed in various parts of the world based on different emission scenarios and climate models (Müller-Wohlfeil et al. 2000; Christensen and Christensen 2003; Alcamo et al. 2007; El-Jabi et al., 2009, Turkkan et al., 2011), but relatively little is known about the changes in water quality, which is largely dependent on stream water temperature.

Water temperature has both economic and ecological significance when considering issues such as water quality and biotic conditions in rivers (Caissie, 2006). The thermal regime of rivers is influenced by many factors such as atmospheric conditions, topography, riparian vegetation, stream discharge, and heat fluxes (Poole and Berman, 2001; Caissie, 2006; Caissie et al., 2005, 2006 and 2007; Webb et al., 2008).

The knowledge and ability to predict stream water temperature are essential to address thermal discharge problems, water quality and in conducting environmental impact studies. A better understanding of the natural thermal regime of a river system is also very important in the management of water supply. The first step in the overall understanding of the stream thermal regime is to be able to study and predict the natural variations in stream water temperatures.

The objective the present study is to carry out a stream temperature modeling using the most reliable climate change scenarios available (CGCM 3.1/T63, SRES 20C3M, B1, A2) in order to evaluate future river water temperatures under climate change impact. This study, will illustrate the usefulness of a Stream Water Temperature models, coupled with Climate Change Scenarios to explain the evolutions of future water temperature regimes. The knowledge gained from this study will enable engineers and water resources managers to better understand the impact of future climate on the thermal regime of rivers and its impact on water quality related to climate change impact.

2. LITERATURE REVIEW

2.1 River thermal regimes

The thermal regime of a river represents the natural variations in water temperatures for a selected period (seasonal, daily or diurnal) and watercourses. Many factors can influence the thermal regime and they can be classified using different factors. For example, Poole and Berman (2001) classified these factors in two categories: internal and external factors. The external factors consider the net energy and water inputs. Internal factors are related to the fluvial processes and river characteristics (riparian zone, surface/subsurface water interaction, etc.). Changes in these factors thus modify water temperature variability along river reaches.

River water temperatures are also influenced by factors such as atmospheric conditions, topography, stream discharge, and riverbed thermal fluxes (Caissie 2006). The atmospheric conditions characterize the most influential group. Atmospheric conditions are principally responsible for the heat exchange process at the water surface. It includes solar radiation, air temperature, humidity, wind speed as well as the type and quantity of precipitation. Topography can also influence the thermal regime of rivers and it includes factors such as latitude/longitude, riparian vegetation, geology, river aspect (orientation) and upland shading (e.g., prairie vs. mountain). Some topography factors can be influenced by human activities like timber harvesting, resulting in an increase in river water temperatures, especially for small streams. Stream discharge factors are mostly related to river hydraulic conditions (e.g. surface area, water volume, etc.). Some stream discharge factors are extremely important like the volume of water whereas other can be neglected like the slope or the presence of waterfalls. Streambed heat fluxes can also influence the thermal regime of a river depending on the exchange processes and groundwater contribution. These factors mainly include the heat conduction at riverbed and the contribution of groundwater flow.

Thermal regime of rivers has been widely studied for many years. For example, Macan (1958) studied the seasonal trends in water temperature as well as the influence of sunshine (or solar radiation) and other parameters related to water temperature. This descriptive study concluded that diurnal variation of water temperature was more significant during clear sky period. The largest diel fluctuations in water temperature were generally observed in summer while the smallest diel fluctuations were generally observed in winter, as reported in a study on the Hinau in New Zealand (Hopkins 1971). On a seasonal basis, water temperature varies from low temperature (close 0°C in northern latitude rivers) in winter and spring to maximum water temperature in mid-summer. Maximum water temperatures are followed by a cooling period in autumn prior to winter conditions (Vannote et al. 1980). This natural process of heating and cooling depends on meteorological and physical conditions of the river. This phenomenon is important for water quality parameters and ecological processes as well as for the flora and fauna of river environments (Vannote et al. 1980). Daily fluctuations can be observed on a local scale or along a reach of a stream. For example, upstream waters are generally colder due to groundwater contributions (Vannote and Sweeney 1980). Water temperature tends to be warmer in the downstream direction of a river due to a longer run and a heating exposition (Danehy et al. 2005). The diel variability is also dependent on the climate and the physical characteristics of a river. For example, the downstream section of a river is deeper and the diel variability is generally less than upstream sections. All of these seasonal or daily variations of stream water temperatures are important for aquatic resources. This concept is explained in the 'River Continuum concept' (Vannote et al. 1980).

An important research on thermal regime was conducted by Ward (1985) which included many rivers from the southern hemisphere. Ward (1985) also observed that diel fluctuations increased in the downstream direction of rivers, where water sources are less dominant by groundwater and where the stream is more exposed to meteorological conditions. This study also concluded that the difference in the thermal regime between southern and northern hemisphere rivers was mainly related to the size of rivers and not to the thermal process. Another factor making the comparison difficult was the presence of important arid and semi-arid zone in the southern hemisphere, mainly in Australia.

A study by Smith (1972) tried to categorize, without success, the thermal regime of rivers using the latitude and the altitude as the dominant factors. Due to the complex nature of the thermal process in rivers (e.g., Smith 1975; Smith and Lavis 1975), no other studies have tried to categorized the thermal regime based on geographical positions. Some studies have showed relations between different parameters of the thermal regime. For instance, Webb and Walling (1986) established a relation between mean temperature and the watershed elevation. However, it was difficult to make a 'general' relation because cold water streams were usually observed at higher altitude. The latitudinal difference in climate parameters (e.g. air temperature) may be a major influence on stream thermal regime (Liu et al. 2005). Another study investigated the daily and seasonal water temperature to show a relation between water temperature and other parameters such as the stream order, groundwater contribution and cold-water tributaries (Arscott et al. 2001). The temperature variability of a stream is also highly related to the dynamic and proximity of the water source and pathway contributions as well as the hydroclimatological conditions, streamflow volume and basin characteristics as reported in Brown et al. (2005) and Cadbury et al. (2008).

Using multiple linear regressions, the elevation and azimuth were found to be important variables explaining most of the average daily temperature patterns (Brown and Hannah 2008). Water temperature is influenced by micro-thermal conditions, because thermal conditions can vary within only a few meters (Clark et al. 1999). Thermal regime can also depend on the type of rivers (Mosley 1983). In this study, they showed that braided rivers are subjected to high temperatures due to shallow water depth and a higher exposition to meteorological conditions.

Kobayashi et al. (1999) observed evidence of major contributions of subsurface water to stream water. Notably, stream temperature during summer rainstorm decreased gradually after streamflow peaked. Soil temperature increases with depth during the snowmelt period but decreases with depth during the summer. During storm flow recession, stream temperature related to extreme events (summer storm or snowmelt) was similar to the soil temperature at 1.8 m below the land surface, suggesting that subsurface water contributions to stream flow was derived from this depth. Regional differences in water temperatures can be explained by morphological conditions, hydrology, water used, elevation, slope, timber harvesting, but mainly latitude (Mohseni et al. 2002). Other studies have shown basin-scale stream temperatures are strongly affected by water sources, as well as basin characteristics like altitude, azimuth and stream length (Brown and Hannah 2008).

2.2 Climate change impacts on stream water temperatures

In eastern Canada, the air temperature is expected to increase by 2°C to 6°C in the next 100 years (Parks Canada 1999). Such an increase will greatly affect stream water temperatures. Higher water temperatures and changes in extreme precipitation events are projected to affect water quality from sediments, nutrients, dissolved organic carbon, pathogens, pesticides and salt, with possible negative impacts on ecosystems, human health, and water system reliability and operating costs (IPCC 2008). Awareness of climate change and concerns about its potential impacts are significantly influenced by the occurrence of extreme and challenging events (Arnell and Delaney 2006). The impacts and adaption strategies will greatly depend on local hydrological, economic, social and political conditions (Kundzewick et al. 2008). Different methods can be found in the literature to assess the impacts of climate change on hydrological responses (Rehana and Mujumdar 2011, Benyahya et al, 2009a,2009b, 2010 and 2012; Hebert et al., 2011). Methods are either using high-resolution regional climate models (Malmaeus et al. 2006), general circulation models (GCMs) through statistical downscaling techniques (Cruise et al. 1999; Burlando and Rosso 2002; Andersen et al. 2006) or hypothetical scenarios as input to hydrologic models (Arnell et al. 1996; Nimikou et al. 2000; Chang 2004).

Studies have looked at the impact of climate change on river water temperatures (Meisner 1990). However, the impact of climate change is difficult to predict (around the world) due to a lack of long-term water temperature time series (Webb 1996). For instance, Kjellström et al. (2007) have studied monthly mean water temperatures from 1901-2000 in three Austrian rivers. Water temperatures in winter are expected to decrease whereas summer temperatures are projected to increase. The significant rise in river water temperatures during the course of the 20th century was mainly driven by rising air temperatures (Kothyari et al. 1997). A rapid rise in water temperature after the 1970s reflects the global warming.

Studies conducted on Fraser River (BC) established that climate change could modify the arrival of peak flow and a rise of summer temperatures (Morrison et al. 2002). Peak flows could occur earlier in the season and this could have an impact on summer water temperatures as summer low flows would occur earlier as well. Summer water temperatures were predicted to increase by 1.9°C. Another study showed that the greater increase in water temperatures would not be in summer, as reported in most studies, but in autumn and winter (Moore et al. 1997). Results by Minns et al. (1995) showed an increase in annual maximum temperature under climate change. An increase in water temperatures combined with a predicted reduced precipitation could greatly affect water quality in streams (Nimikou et al. 2000). Morrill et al. (2005) predicted an increase of 2°C to 3°C in stream temperatures resulting from an increase of 3°C to 5°C in air temperatures. The River Dee in Scotland has experienced an increase in mean daily maximum stream temperatures in winter and spring since the 1960’s (Langan et al. 2001). Foreman et al. (2001) estimated a warming of 0.022°C per year (1953-1998) on the Fraser River (BC) due to climatic warming. Another study is showing that water temperature of Lake Tahoe (USA) is warming at 0.013°C/year (Sahoo et al. 2011).

Cooter and Cooter (1990) predicted that water temperature could increase to up to 7°C in the southern United States. Mohseni et al. (1999) studied 803 streams from the United States. Only 39 of these studies were found not to be influenced by climatic change. The other 764 streams are projected to increase their mean annual temperature by 2°C to 5°C. This study showed that for all the United States, minimum and maximum weekly temperatures are going to increase by 1°C to 3°C. The most significant changes in weekly temperatures would be in spring (March – June) whereas minimum changes would be in winter (December – January) and summer (July – August).

Under a doubling of CO_2 scenario, Pilgrim et al. (1998) estimated an average increase of 4.1°C in stream temperatures of Minnesota. Tung et al. (2006) predicted an increase of 0.5°C to 2.9°C in annual average stream temperatures of Taiwan Island. When studying forcing parameters, Mohseni and Stefan (1999) showed that water temperatures tends to level off at high temperatures due to evaporative cooling. The upper bound stream temperature represents the highest temperature that a stream can physically attaint without anthropogenic influences (Mohseni et al. 2003).

On the Colorado River, average annual stream temperature was simulated to increase by up to 2.4°C by the 2010 (Christensen et al. 2004). By 2050, George et al. (2007) predicted an increase in water temperatures of up to 1.08°C and 2.18°C for English Lake District. Leblanc et al. (1997) predicted an increase of water temperatures of almost 4°C on Morningside Creek (Ontario). Surface water temperatures are expected to increase by 3.8°C on Shimajigawa reservoir (Japan) under a GCM A2 scenario (Komatsu et al. 2007).

3. MATERIALS AND METHODS

3.1 Study area

The study site is the Little Southwest Miramichi River, which is located within the Miramichi River system. This system has an annual precipitation ranging from 860 to 1365 mm, with a long-term average of 1142 mm (Caissie and El-Jabi, 1995). On a monthly basis, precipitation was close to 100 mm per month, with values ranging between 72 mm in February and 109 mm in November. January has the coldest mean monthly air temperature with a long-term mean of -11.8 °C. July is the warmest month with a mean monthly air temperature of 18.8 °C, although August is very close (at 17.7 °C). Between these two extremes, mean monthly air temperatures vary gradually, with seven months of the year experiencing temperatures above freezing. The mean annual runoff was estimated at 714 mm for the Miramichi region with values ranging from 631 mm to 763 mm (Caissie and El-Jabi 1995). The open-water period usually extends from mid-April to late November.

The Little Southwest Miramichi River (LSWM) study site is located approximately 25 km from the river mouth (Fig. 1). Water temperature data have been collected at this site since 1992. The LSWM River is approximately 80 m in width with an average water depth of 0.55 m. The drainage basin of the LSWM River at the water temperature measurement site covers 1190 km^2. The data used in the present study were daily minimum, maximum and mean water temperatures obtained from hourly data (24 observations). Although the riparian vegetation is mature along the banks of the LSWM River, this river is nevertheless well exposed to meteorological conditions due to its relatively large width. Therefore, it can be considered as a wide and shallow river for modeling purposes. The forest along the LSWM has a canopy closure of less than 20%.

3.2 Global climate model

The climate model used in the present study was the third generation coupled global climate model (CGCM3.1). The time-slice simulations follow the Intergovernmental Panel on Climate Change (IPCC) (Alcamo et al., 1995) "observed 20th century" 20C3M scenario for years 1970-2000 and the Special Report on Emissions Scenarios (SRES) B1 and A2 (see Fig. 2) for years 2010-2100 over the Gaussian 128x64 grid (Fig. 3). The B1 storyline and scenario family describes a convergent world with low population growth and rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis of this scenario is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives. The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in high population growth. Economic development is primarily regionally oriented and per capita economic growth and technological changes are more fragmented and slower than in other storylines (CCCma). The Fig. 2 shows the time evolution of the CO_2 concentrations and globally averaged sulphate aerosol loadings scaled to year 2000 for different scenarios including the 20C3M, SRES B1 and SRES A2 and the so-called "Committed" scenario in which the greenhouse gas concentrations and aerosol loadings were held fixed at the year 2000 level.

3.3 Data collection and processing

Meteorological data were obtained from the Catamaran Brook meteorological station, which is located less than 10 km from the water temperature study sites (Fig. 1). The station is located at the center of a

400 m x 400 m clear cut area to meet Environment Canada and the World Meteorological Organization (WMO) weather station specifications (e.g., wind speed, solar radiation). Meteorological conditions measured at Catamaran Brook are reflective of conditions experienced by the LSWM River due to climate homogeneity within the region (Caissie and El-Jabi 1995). Therefore, this data base will be used for the water temperature modeling of the LSWM River. Data from Doaktown, closest meteorological station to Catamaran Brook, were obtained from Environment Canada's National Climate Data Archive and used for climate change predictions.

Simulated daily minimum, mean and maximum air temperatures for the period 1970-2100 were obtained from CCCma, Canadian Centre for Climate Modelling and Analysis. The atmosphere model output is provided on a 128 x 64 Gaussian grid (Fig. 3). Figure 4 shows the sub-region occupied by New Brunswick.

When using simulated data from the CCCma model, an inverse distance weighting (IDW) method was used to compute a value at Doaktown meteorological site. Data at that site were computed from the known values at four grid points surrounding the site (Fig. 4).

The interpolated data are then downscaled using delta change approach. For temperature the procedure is as follows:

$$T_{\Delta}(d,m) = T_{OBS}(d,m) + \Delta_T(m)$$

where T_{Δ} is temperature input for the scenario simulation, T_{OBS} is observed temperature in the historical period, (d,m) stand for day and month, and Δ_T is the change in temperature as simulated by the climate model. This value is calculated by:

$$\Delta_T(m) = \bar{T}_{scen}(m) - \bar{T}_{ctrl}(m) \quad ; \quad m = 1,2,\ldots,12$$

where $\bar{T}(m)$ is the mean daily temperature for month *m*, for all 30 years of reference period. The indices *scen* and *ctrl* stand for the scenario periods (2010-2039, 2040-69, 2070-2099) and control period (1970-1999), respectively.

3.4 Water temperature modeling

In a previous study, stream water temperature and air temperature relationships were modeled by means of a regression model and stochastic model and two intelligent algorithms: genetic programming and polynomial neural network (PNN) (El-Jabi et al., 2012). This study showed that in all modeling approaches, the root-mean-square error (RSME) was generally less than 2 ºC. The PNN model was used in the present study because it was able to closely follow the behaviour of stream water temperatures by providing simple equations which can be readily incorporated into any programming environment.

PNN is a flexible neural architecture whose topology is not predetermined but developed through learning. The design is based on Group Method of Data Handling (GMDH) which was invented by Prof. A. G. Ivankhnenko in the late 1960s (Ivankhnenko, 1971) and later enhanced by others. He developed the GMDH as a means of identifying nonlinear relations between input and output variables. The GMDH generates successive layers with complex links that are individual terms of a polynomial equation. For more details on the PNN modeling approach and performances, see El-Jabi et al. (2012).

The following PNN model was used to predict minimum, mean and maximum stream temperatures:

$$\begin{Bmatrix} t \\ T(t), T(t-1), T(t-2) \\ T_{max}(t), T_{Max}(t-1), T_{max}(t-2) \\ T_{min}(t), T_{min}(t-1), T_{min}(t-2) \end{Bmatrix} \rightarrow \begin{Bmatrix} T_W^{min} \\ T_W \\ or \\ T_W^{max} \end{Bmatrix}$$

where T_W is the stream temperature (min, mean or max), *t* is the day of year (100 … 320, July 1=182), *T, T_{max} and T_{min}* are the mean, maximum and minimum air temperatures, respectively.

For this model, the 1992-2005 data were used for training and validation (5-fold cross-validation) and the 2006-2010 data for testing. The equations obtained for minimum, mean and maximum stream temperatures were as follows:

Minimum stream temperature

$$T_W^{min} = 0.3888A + 0.5728B + 0.0609B^2 - 0.1375BC + 0.0789C^2$$

$$\begin{aligned} A = {} & -22.12 + 0.2696t - 0.0006t^2 + 0.1383T(t) + 0.0006tT(t) + 0.2578T(t-2) \\ & - 0.0004tT(t-2) + 0.0130T(t)T(t-2) - 0.0038T(t-2)^2 \end{aligned}$$

$$\begin{aligned} B = {} & -27.74 + 0.3446t - 0.0008t^2 + 0.0008tT_{min}(t) + 0.0026T_{min}(t)^2 + 0.3493T(t-1) \\ & - 0.0006tT(t-1) + 0.0060T(t-1)^2 \end{aligned}$$

$$\begin{aligned} C = {} & -31.65 + 0.3855t - 0.0009t^2 + 0.0008tT_{min}(t) + 0.0026T_{min}(t)^2 + 0.1812T_{max}(t-1) \\ & - 0.0004tT_{max}(t-1) + 0.0024T_{min}(t)T_{max}(t-1) + 0.0042T_{max}(t-1)^2 \end{aligned}$$

Mean stream temperature

$$T_W = 0.6502A + 0.4818B - 0.0212B^2 - 0.1652C + 0.0232C^2$$

$$\begin{aligned} A = {} & -26.76 + 0.3358t - 0.0008t^2 + 0.2832T(t) + 0.0025T(t)^2 + 0.1417T(t-2) \\ & + 0.0073T(t)T(t-2) \end{aligned}$$

$$\begin{aligned} B = {} & -33.96 + 0.4287t - 0.0010t^2 - 0.1391T_{min}(t) + 0.0010tT_{min}(t) + 0.4185T(t-1) \\ & - 0.0008tT(t-1) + 0.0022T_{min}(t)T(t-1) + 0.0070T(t-1)^2 \end{aligned}$$

$$\begin{aligned} C = {} & -34.69 + 0.4412t - 0.0010t^2 + 0.0024T_{max}(t-1)^2 + 0.1463T(t-1) + 0.0002tT(t-1) \\ & + 0.0075T_{max}(t-1)T(t-1) \end{aligned}$$

Maximum stream temperature

$$T_W^{max} = 0.9704A - 0.0740A^2 + 0.3642B + 0.1138AB - 0.0382B^2 + 0.3683C$$

$$\begin{aligned} A = {} & -33.33 + 0.4228t - 0.0010t^2 + 0.2095T(t) + 0.0162T(t)^2 + 0.1881T(t-1) \\ & - 0.0191T(t)T(t-1) + 0.0128T(t-1)^2 \end{aligned}$$

$$\begin{aligned} B = {} & -38.95 + 0.4984t - 0.0012t^2 + 0.0473T_{max}(t) + 0.0116T_{max}(t)^2 + 0.0002tT_{max}(t-1) \\ & - 0.0118T_{max}(t)T_{max}(t-1) + 0.0117T_{max}(t-1)^2 \end{aligned}$$

$$\begin{aligned} C = {} & -33.39 + 0.4266t - 0.0010t^2 + 0.1771T(t-2) - 0.0002tT(t-2) + 0.0033T(t-2)^2 \\ & + 0.0792T_{max}(t) + 0.0002tT_{max}(t) + 0.0029T(t-2)T_{max}(t) + 0.0059T_{max}(t)^2 \end{aligned}$$

The RMSE was used to compare the relative performance among models:

$$RMSE = \sqrt{\sum_{i=1}^{N} \frac{(O_i - P_i)^2}{N}} \qquad (7)$$

with P_i and O_i being the predicted and observed water temperatures and *N* the number of observations.

3.5 Analysis of model results

From the study by El-Jabi et al. (2012), the performances of PNN water temperature models are presented in Table 1. These results showed that, in general, the RMSEs for mean water temperature were slightly lower than those for the maximum and minimum water temperatures. For the testing data sets, the model provided results for the RMSE of 1.33 °C (minimum), 1.58 °C (mean) and 2.02 °C (maximum) in the prediction of water temperatures. The model also showed the highest R^2 (0.95) for the minimum water temperature. Using the results for 2005, as an example, Figure 5 shows how well the PNN models simulated daily stream water temperatures when using air temperatures as an input. A visual inspection confirms that the simulated water temperatures coincided fairly well with the observed water temperatures.

4. RESULTS AND DISCUSSION

Figures 6, 7 and 8 show the changes in the annual cycle of stream water temperatures for the LSWM River for the historical period (1970-99) compared to future climate, years 2010-39, 2040-69 and 2070-99, using emission scenarios B1 and A2. The averaged water and air temperature increases are shown in Table 2. The increase in air temperature within the Miramichi River area is very consistent with expected increase throughout the province of New Brunswick, as shown in Table 3 (Turkkan et al., 2011). A summary of these results is also presented in Figure 9 for the periods 2010-39, 2040-69 and 2070-99 compared to 1970-99, for both climate scenarios. Over the next 30 years (2010-39), water temperatures are expected to increase by between 0.7°C (B1) to 1.2°C (A2). The stream water temperatures show a more significant increase for the period 2070-99 compared to current climate conditions (1970-99), with an increase of 2.1 ºC (B1) and 3.7 ºC (A2). During all periods, the water temperature increases were in the range of 60%-75% of the increases projected for air temperature. This means that water temperature will increase in the future, but at a slower rate than air temperature, mainly due to evaporative cooling of rivers. The evolution of summer water temperatures are plotted in Figure 10, for both climate scenarios. The scenario B1 seems to show a more gradual increase whereas the scenario A2 seems to show a high variability over the years.

Another aspect which is very important in stream water temperature is the analysis of extreme events, i.e., temperature higher than certain thresholds. This is important not only for water quality issues, but also for stress in aquatic resources. These thresholds could also depend on the water quality parameter under investigation; therefore, four different thresholds were studied (20°C, 23°C 26°C and 29°C) for minimum, mean and maximum water temperatures. Figures 11, 12 and 13 illustrate the annual exceedance frequencies of minimum, mean and maximum stream water temperatures for LSWM River, using emission scenarios B1 and A2. The annual exceedance frequencies were calculated for the periods 1970-99, 2010-39, 2040-69. For example, during the historical period (1970-99) the minimum water temperature was exceeded on average 13 days per year (Figure 11). Under climate change the threshold temperature of 20°C could be exceeded between 32 (B1) and 51 (A2) days towards the end of the century (2070-99) and depending on the scenario. Other threshold temperatures are presented in Figure 11 for minimum water temperature. In the case on mean water temperature, the threshold of 26°C is currently not reach (1970-99); however in the future water temperature will most likely reached and exceeded (Figure 12).

The maximum river water temperature has a particular interest, especially at high temperatures and this could have a significant impact on both water quality as well as fishes (as temperatures could become lethal for some species). Figure 13 show that currently the maximum water temperature exceeds 29°C on average of 1 day per year. Such potential lethal events will most likely occur more frequently in the future. For example, during the period 2070-99, the 29 °C will be exceeded on average 6 days per year (B1) and 15 day per year (A2). For lower thresholds, the impact will also be significant. For instance, currently the 23°C is exceeded on average 37 days per year, and in the future these values will more than doubled (60 day B2 to 75 day A1; period 2070-99).

5. CONCLUSION

Climate change impacts within river systems include changes in runoff, river flow and groundwater storage. To these quantitative aspects, some water quality parameters are also expected to change and must be assessed to determine their physical and biogeochemical implications. With respect to biogeochemical water quality, most climate change impacts can be attributed to changes in stream water temperature. When river water temperature increases, dissolved oxygen decreases and biological activities is enhanced, with consequences on nutrients, organic matter, biomass and fish populations in general. The impact of climate change on stream water temperature is highly dependent on the future evolution of air temperature and other meteorological and physical parameters. As air temperature is the parameter that is expected to change most significantly under climate change, therefore, water temperature is also expected to be an extremely important parameter.

Based on these findings, a water temperature model was calibrated, using only air temperature as an exogenous input. The selected PNN water temperature model has proven to be a useful tool in the modeling of water temperatures under different climate change scenarios. Such analyses could focus on future spatial and temporal distribution of river thermal regime and changes in water quality. This model is also important to study the thermal habitats in river as well as the identification of reaches, which will eventually become unsuitable for aquatic habitat. The knowledge gained from this study will enable engineers and water resources managers to better understand the thermal regime of rivers and its impact on water quality related to climate change impact.

Results of the present study showed that the PNN model was effective in predicting river water temperature with RMSE below 2°C. Better model performance was obtained for mean daily water temperature compared to minimum and maximum water temperatures. Under climate change, the model showed that water temperature will increase between 0.7°C and 3.7°C depending on the scenario (B2 or A1) and the period. The increase in water temperature is slightly lower than that observed for air temperature. In fact, water temperature increases are within 60% to 75% of those projected for air temperature under climate change. Furthermore, data from the climate change model are showing an increase in air temperature that is very consistent throughout the province of New Brunswick (Table 3). As such, it is expected that future water temperatures at other sites within the province could be within the same orders of magnitude, based on projected air temperatures at these sites.

An analysis of extreme events, by studying water temperature thresholds, showed that river water temperature exceedance will experience a significant increase under future climate change. For instance, the number of days where summer water temperature will exceed 23°C will more than double at the end of this century. The quantification of these extreme events has important implications on water quality parameters, such as dissolved oxygen, as well as on the stress level experience by fishes.

The present study will provide managers with a better understanding of the future evolution of the thermal regimes in New Brunswick rivers, as well as providing them with potential impact on climate change on water quality and fisheries resources.

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Table 1. PNN model results for the estimation of water temperatures

	Periods	RMSE	R^2
Minimum	Train (1992-96)	1.45	0.946
	Test (2005-10)	1.33	0.950
Mean	Train (1992-04)	1.28	0.963
	Test (2005-10)	1.58	0.946
Maximum	Train (1992-04)	1.76	0.944
	Test (2005-10)	2.02	0.926

Table 2 – Averaged air temperature (Ta) increases at Doaktown and averaged stream water temperature (Tw) increases at LSWM River

	Scenario B1			Scenario A2		
	2010-39	2040-69	2070-99	2010-39	2040-69	2070-99
Tw (ºC)	0.7	1.5	2.1	1.2	2.3	3.7
Ta (ºC)	1.2	2.2	2.9	1.2	2.9	5.0

Table 3 – Mean air temperature increases (°C)

	Scenario B1			Scenario A2		
	2010-39	2040-69	2070-99	2010-39	2040-69	2070-99
Aroostook	1.2	2.2	2.9	1.5	3.3	5.3
Charlo	1.2	2.2	2.9	1.4	3.2	5.2
Chatham	1.2	2.2	2.9	1.4	3.2	5.2
Doaktown	1.2	2.2	2.9	1.2	2.9	5.0
Fredericton	1.2	2.2	2.9	1.5	3.2	5.3
Moncton	1.2	2.2	2.9	1.5	3.2	5.3
Saint John	1.2	2.3	3.0	1.5	3.2	5.3

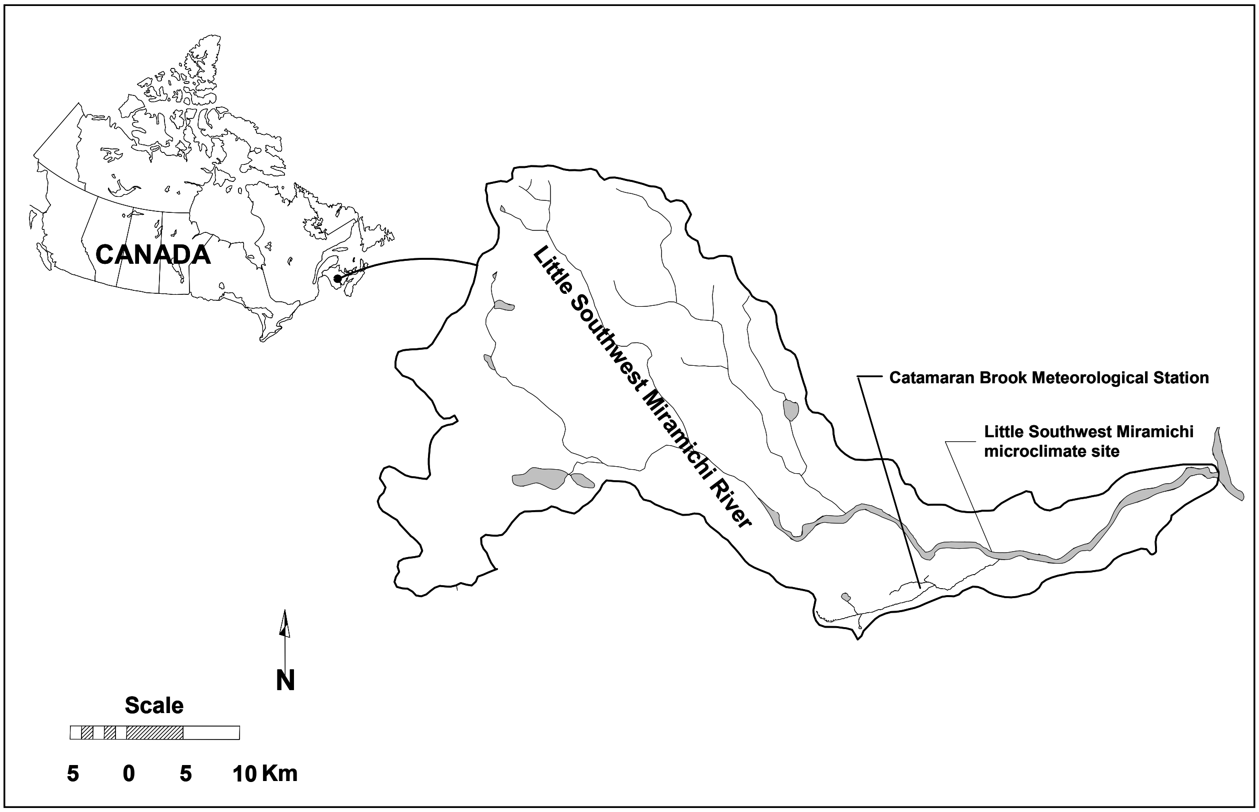


Figure 1. Map showing the location of the water temperature site and the meteorological station

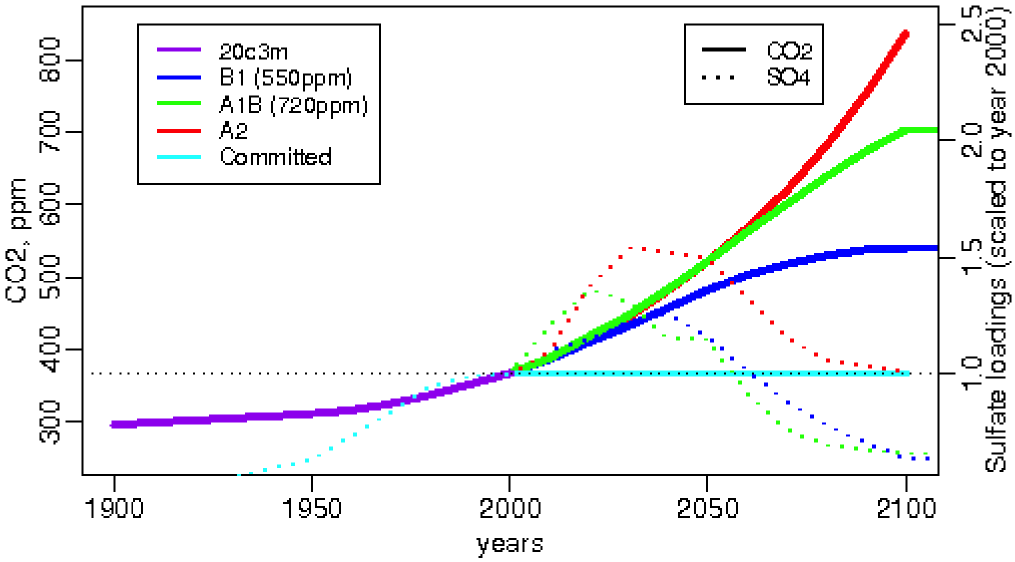


Figure 2 - Time evolution of the CO2 concentrations (solid line curves) and globally averaged sulphate aerosol loadings scaled to year 2000 (dotted line curves) as prescribed in the IPCC 20-th century 20C3M (purple), SRES B1 (blue) and A2 (red) experiment

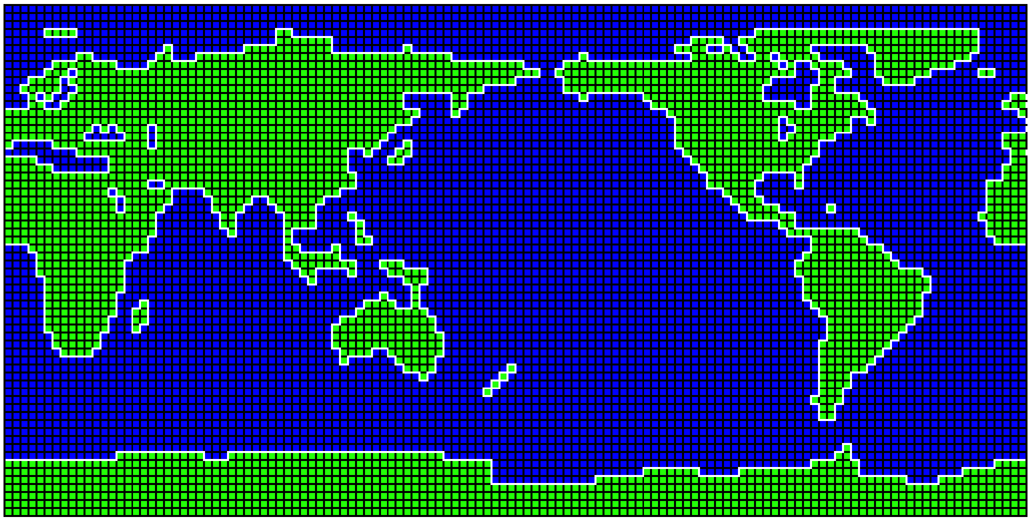


Figure 3 – CCCma 128 x 64 Gaussian grid (grid box size ~ 2.81º lat x 2.81º long)

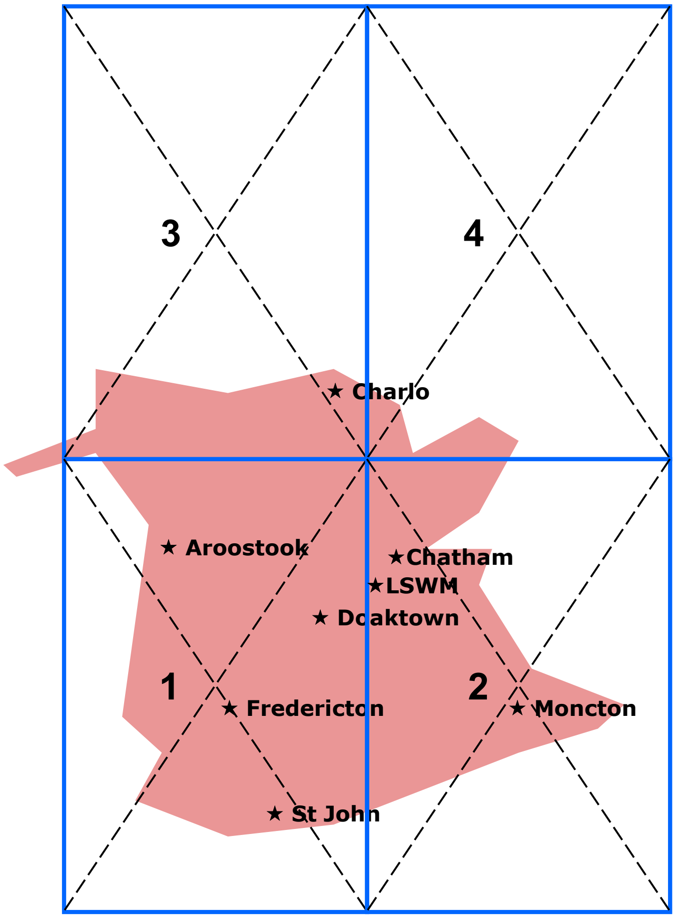


Figure 4 – CCCma subarea corresponding to New Brunswick : 4 grid boxes
(Box size ~200x300 km, ★meteorological station)
(1→67.5° W 46.04°N, 2→64.69°W 46.04°N, 3→67.5°W 48.84°N, 4→64.69°W 48.84°N)

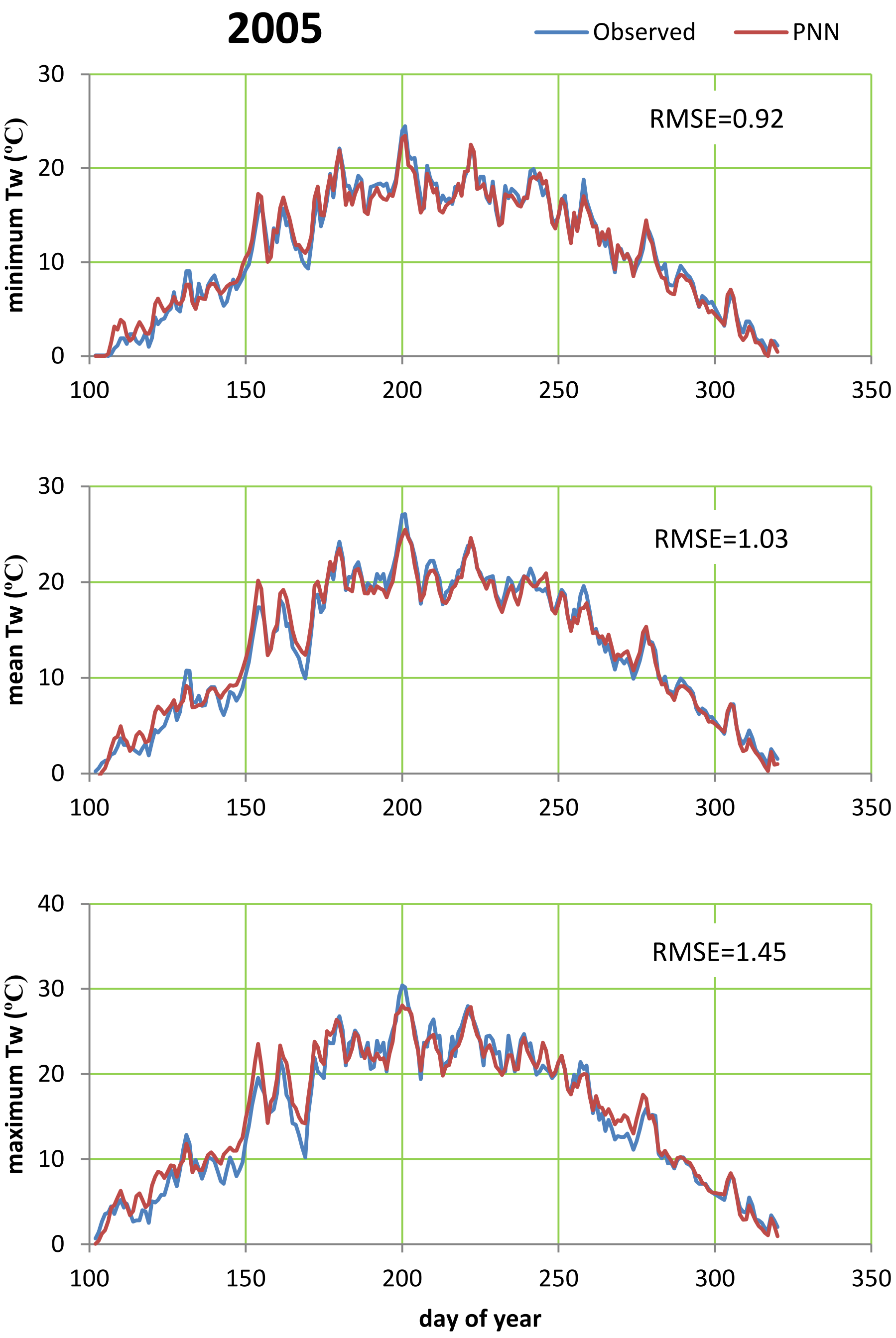


Figure 5 - Observed and modeled minimum, mean and maximum stream water temperature values for year 2005 for LSWM River

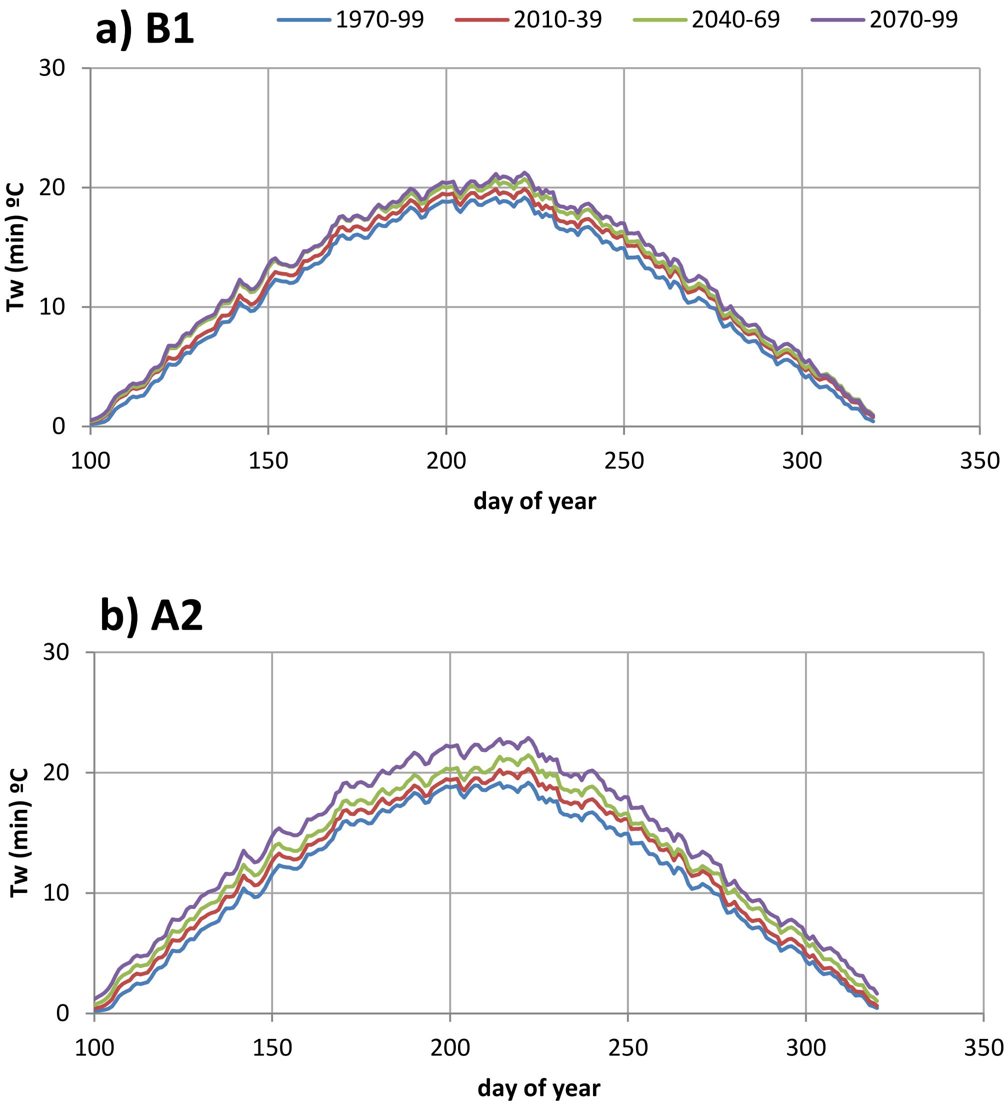


Figure 6. Observed (1970-99) and simulated (2010-39, 2040-69, 2070-99) minimum annual stream water temperatures for LSWM River a) using scenario B1 b) using scenario A2

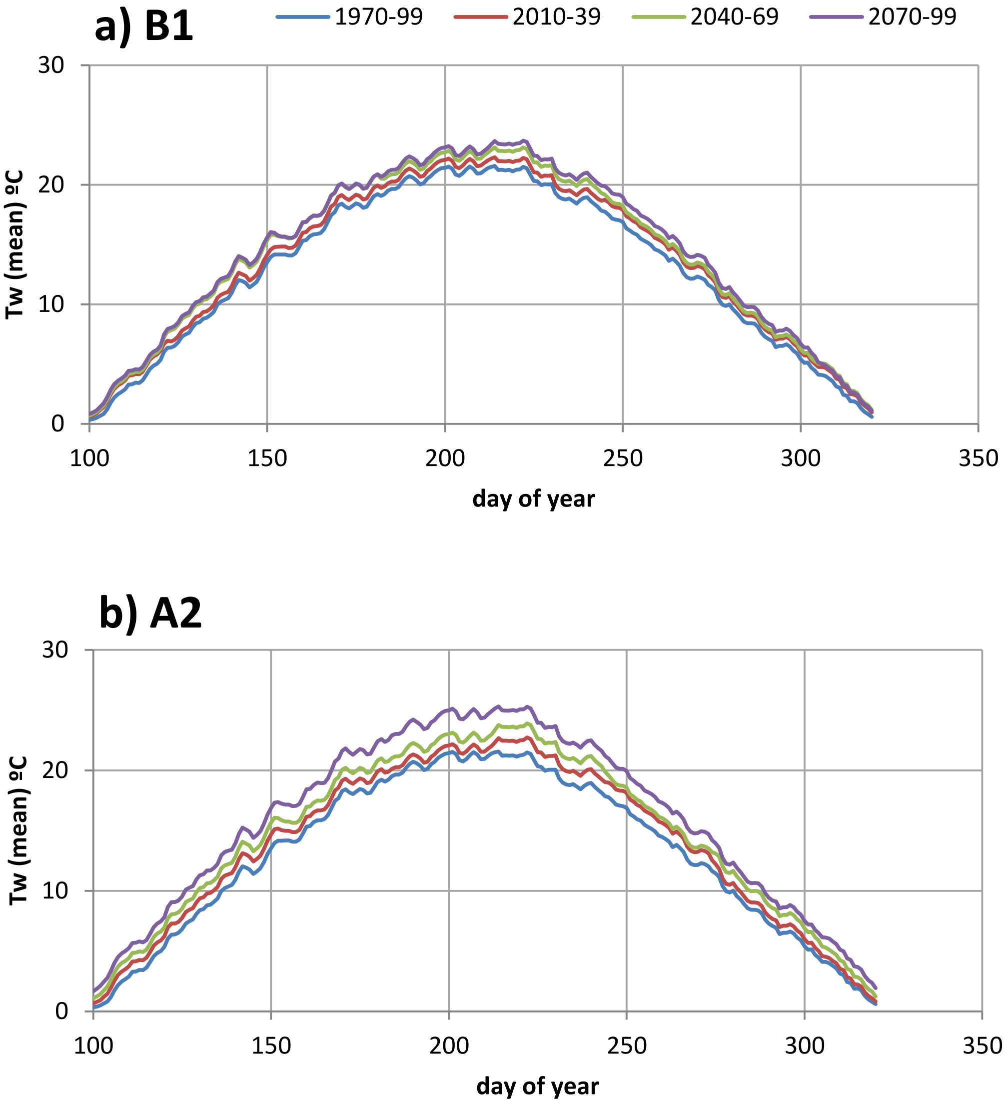
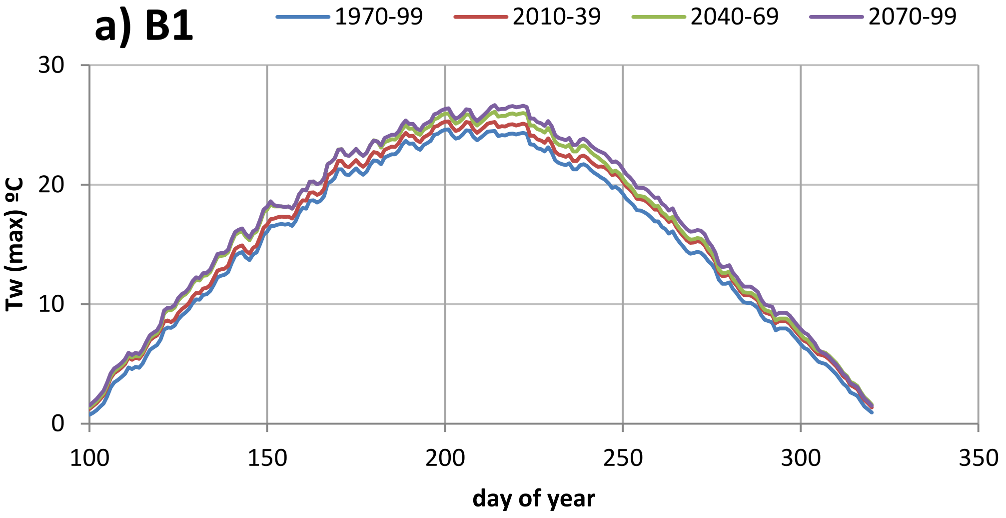


Figure 7. Observed (1970-99) and simulated (2010-39, 2040-69, 2070-99) mean annual stream water temperatures for LSWM River a) using scenario B1 b) using scenario A2



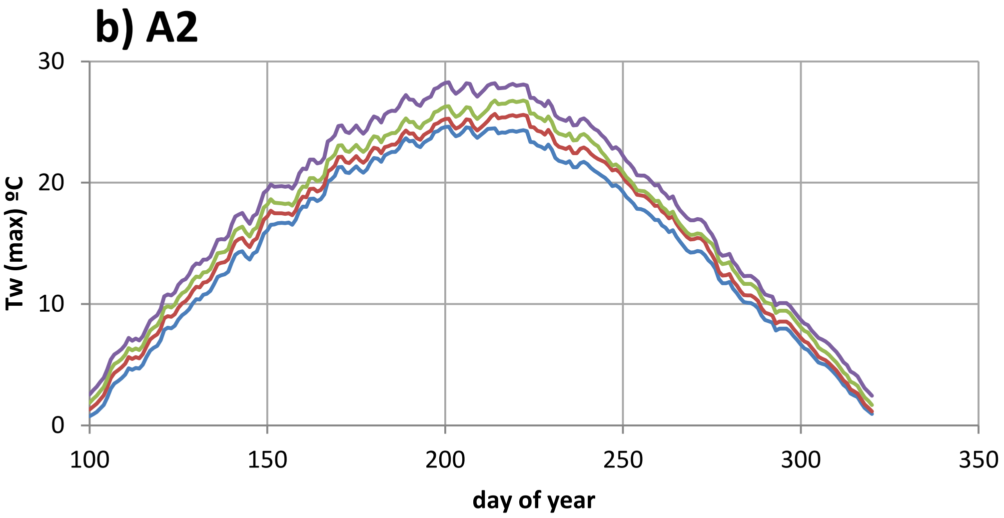
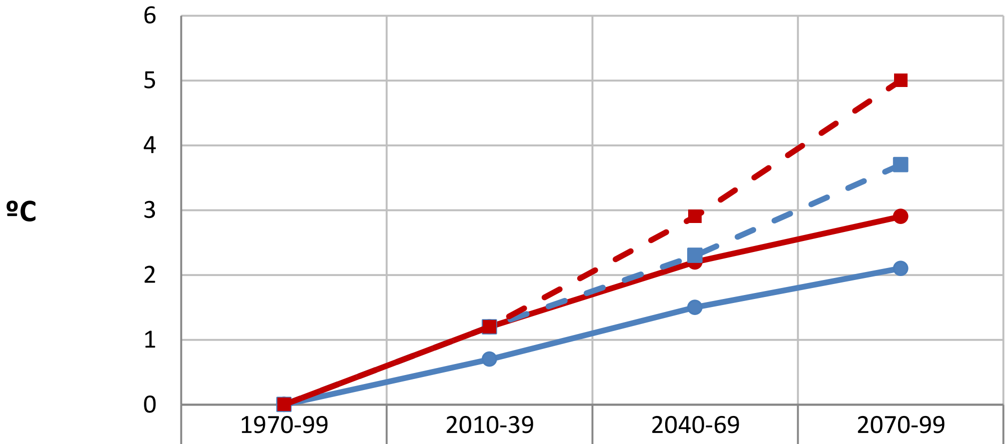


Figure 8. Observed (1970-99) and simulated (2010-39, 2040-69, 2070-99) maximum annual stream water temperatures for LSWM River a) using scenario B1 b) using scenario A2



	1970-99	2010-39	2040-69	2070-99
● Tw (B1)	0	0.7	1.5	2.1
● Ta (B1)	0	1.2	2.2	2.9
■ Tw (A2)	0	1.2	2.3	3.7
■ Ta (A2)	0	1.2	2.9	5.0

Figure 9. Averaged air temperature increases at Doaktown and averaged stream water temperature increases at LSWM River under B1 & A2 scenarios

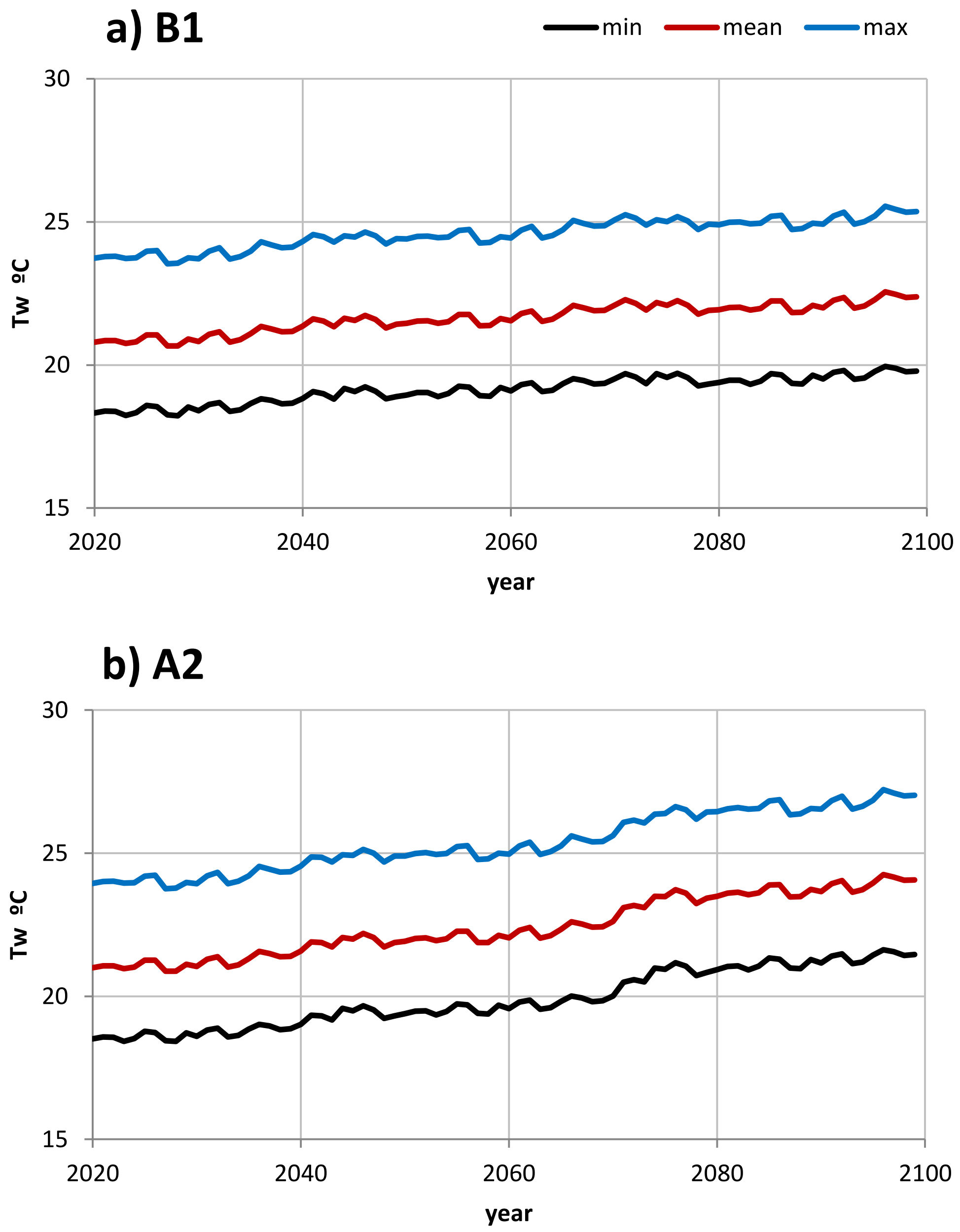
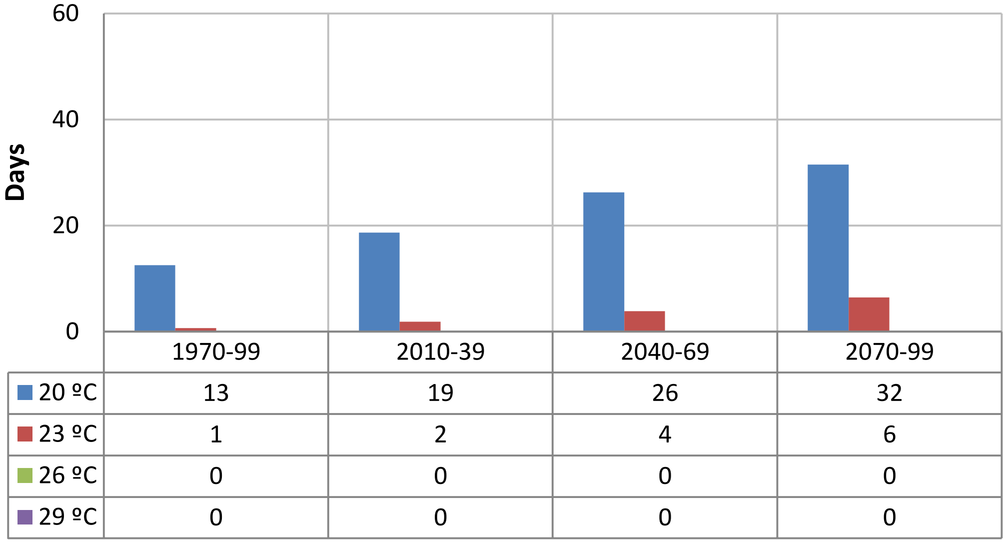


Figure 10. Trends in minimum, mean and maximum summer stream water temperatures for LSWM River a) using scenario B1 b) using scenario A2

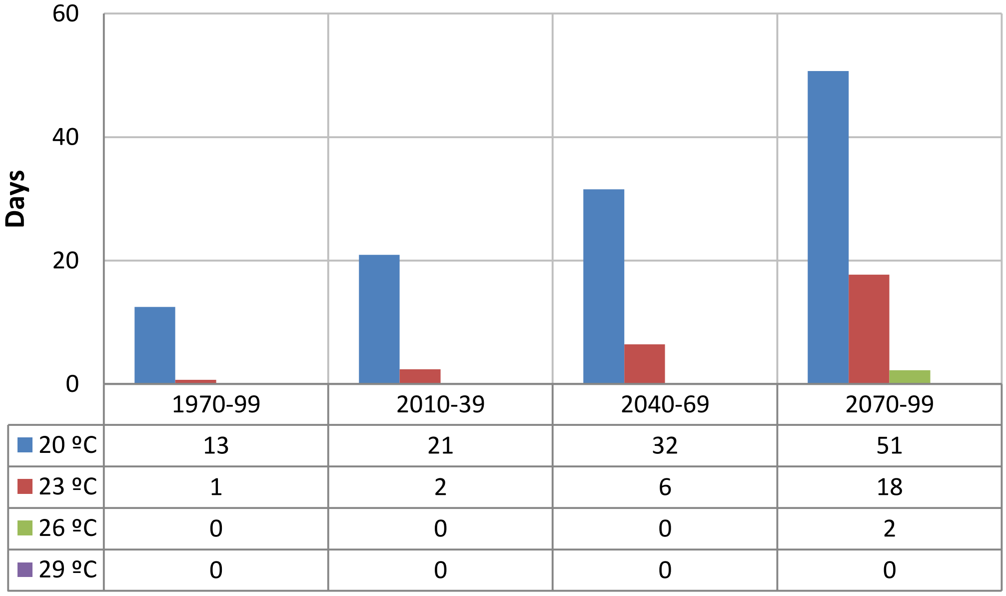
Tw (min) exceedance frequency

a) B1 scenario



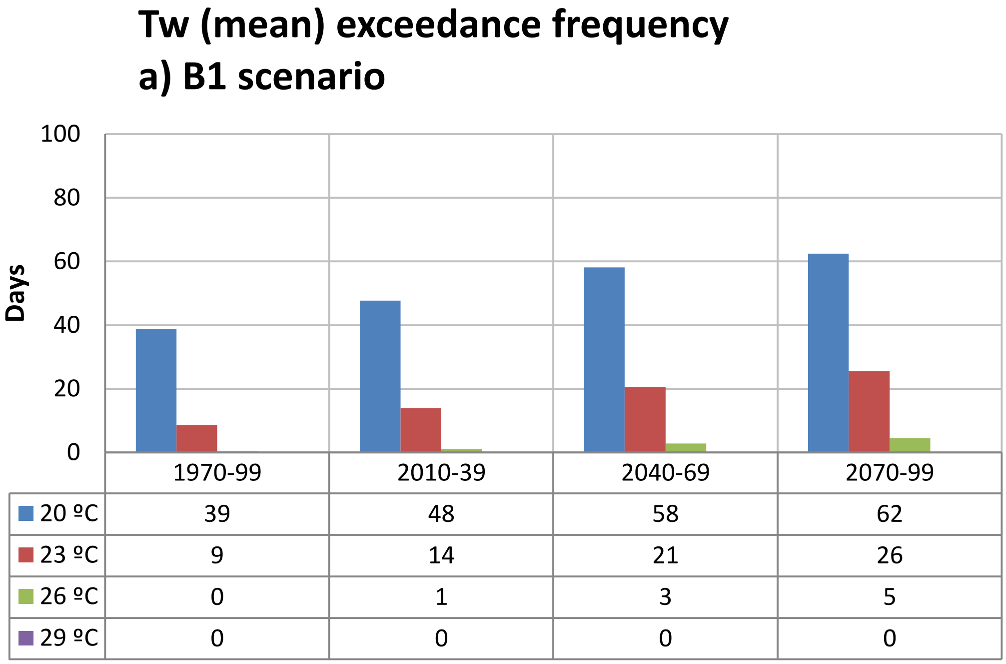
	1970-99	2010-39	2040-69	2070-99
🟦 20 ºC	13	19	26	32
🟥 23 ºC	1	2	4	6
🟩 26 ºC	0	0	0	0
🟪 29 ºC	0	0	0	0

b) A2 scenario

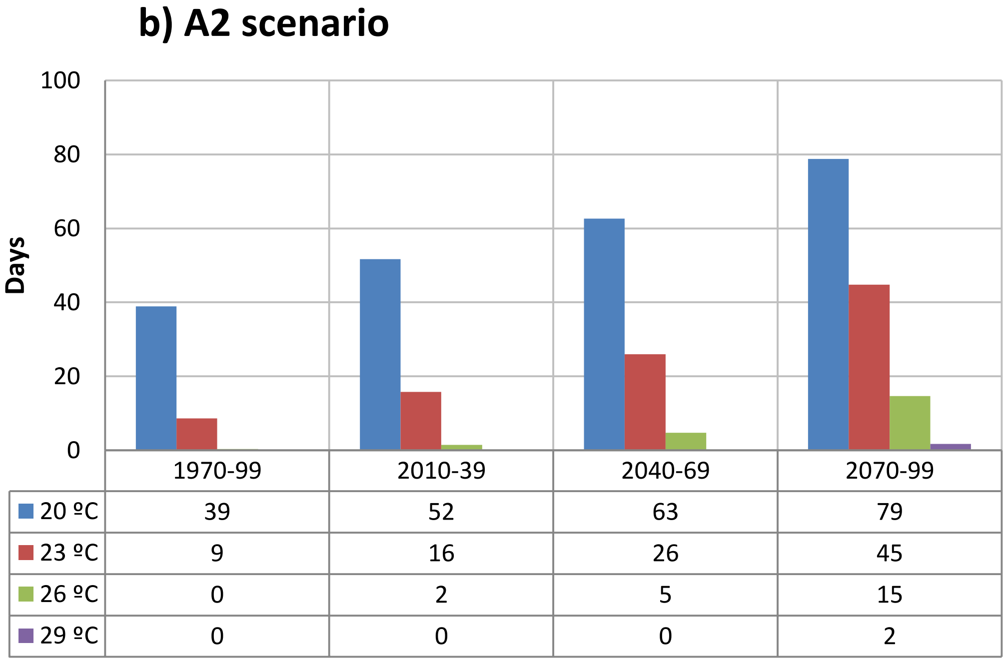


	1970-99	2010-39	2040-69	2070-99
🟦 20 ºC	13	21	32	51
🟥 23 ºC	1	2	6	18
🟩 26 ºC	0	0	0	2
🟪 29 ºC	0	0	0	0

Figure 11. Mean annual exceedance frequencies of minimum stream water temperatures for LSWM River a) using scenario B1 b) using scenario A2



	1970-99	2010-39	2040-69	2070-99
🟦 20 ºC	39	48	58	62
🟥 23 ºC	9	14	21	26
🟩 26 ºC	0	1	3	5
🟪 29 ºC	0	0	0	0

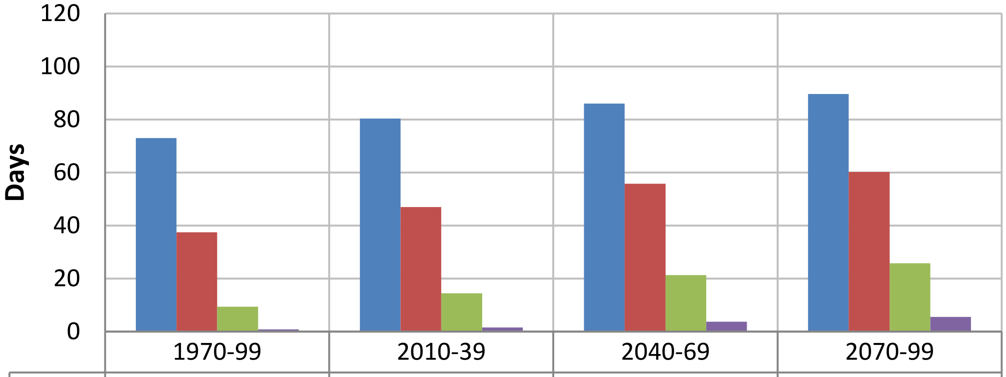


	1970-99	2010-39	2040-69	2070-99
🟦 20 ºC	39	52	63	79
🟥 23 ºC	9	16	26	45
🟩 26 ºC	0	2	5	15
🟪 29 ºC	0	0	0	2

Figure 12. Mean annual exceedance frequencies of mean stream water temperatures for LSWM River a) using scenario B1 b) using scenario A2

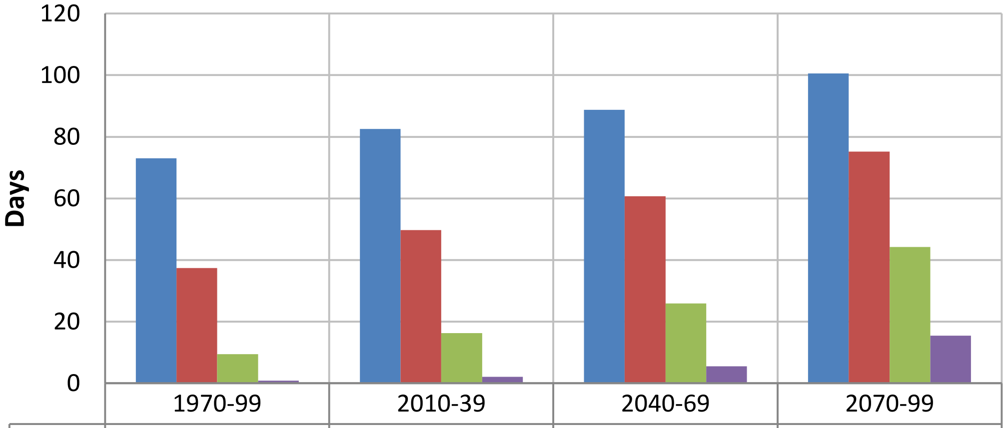
Tw (max) exceedance frequency

a) B1 scenario



	1970-99	2010-39	2040-69	2070-99
🟦 20 ºC	73	80	86	90
🟥 23 ºC	37	47	56	60
🟩 26 ºC	9	14	21	26
🟪 29 ºC	1	2	4	6

b) A2 scenario



	1970-99	2010-39	2040-69	2070-99
🟦 20 ºC	73	83	89	101
🟥 23 ºC	37	50	61	75
🟩 26 ºC	9	16	26	44
🟪 29 ºC	1	2	6	15

Figure 13. Mean annual exceedance frequencies of maximum stream water temperatures for LSWM River a) using scenario B1 b) using scenario A2