New Nouveau Brunswick
ENVIRONMENTAL TRUST FUND

Water Quality Index Under Climate Change Impact

UNIVERSITÉ DE MONCTON
EDMUNDSTON MONCTON SHIPPAGAN

Nassir El-Jabi, Noyan Turkkan
and **Cindie Hébert**
Université de Moncton
Moncton, NB

Fisheries and Oceans Canada / Pêches et Océans Canada

Daniel Caissie
Department of Fisheries & Oceans
Moncton, NB

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Nassir El-Jabi, Noyan Turkkan and Cindie Hébert
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20C3M	Observed 20th century scenario
A2, B1	Climate scenarios
CCCma	Canadian Centre for Climate modeling and analysis
CCME	Canadian Council of Ministers of the Environment
CGCM	Coupled General Climate Model
Cond	Conductivity
DO	Dissolved oxygen
IPCC	Intergovernmental Panel on Climate Change
LSWM	Little Southwest Miramichi
NH3	Ammonia
NO2	Nitrite
NO3	Nitrate
PNN	Polynomial Neural Network
RMSE	Root Mean Square Error
SRES	Special Report on Emission Scenarios
SS	Suspended solids
TP	Total phosphorus
WQI	Water quality index

Ci	Normalized value
excursion	Failed test measure
F_1, F_2, F_3	Parameters used in CCME-WQI calculation
nse	Normalized sum of excursions
Pi	Relative weight
Ta	Mean air temperature
Tw	Mean water temperature

EXECUTIF SUMMARY

Climate Change impacts on river systems include changes in runoff, groundwater flow as well as the timing of streamflow (e.g. high and low flows). To these quantitative aspects, water quality also needs to be assessed for effective water resources management. With respect to the biogeochemical water quality, most climate change impacts can be attributed to changes in stream temperature. With increases in stream temperature, dissolved oxygen will decrease and biological activities will increase. Such changes in stream temperature will also have consequences on nutrients, organic matter as well as biomass within the river environment. The impact of climate change on stream 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, stream temperature is also expected to be an extremely important parameter.

This study will focus on improving modeling of water quality indices and water quality parameters under various climate change scenarios in relationship with stream temperature. It will illustrate the usefulness of the stream temperature models, coupled with Climate Change Scenarios to explain the evolutions of future stream temperature regimes and associated biogeochemical water quality parameters applied to drinking water quality. The objectives of the present study are first, to link changes in air temperature and stream water temperature. Second, the study concentrated on using most reliable climate change scenarios available (CGCM 3.1/T63, SRES 20C3M, B1, A2) to predict stream water temperatures under climate change. Third, this study focused on improving our current understanding of the impact of various climate change scenarios on water quality and biogeochemical parameters, a subject which has not been adequately addressed in the literature but very important for drinking surface water evaluation.

Climate change was shown to affect water quality, possibly violating the Safe Drinking Water Act regulations, therefore the impact of the design and operation of drinking water treatment plants. Many studies have shown a decline in stream water quality under a climate change scenario, but very few have focused on the impact of drinkable water supplies. Expected impacts of climate change are flow reduction that will lower water levels in rivers and lakes, as well as an increase in water demand and higher temperatures. The main impacts of rising temperatures and heavy rainfalls would be the rise in concentration of dissolved organic matter, pollutants and pathogens. Water quantity changes due to climate change have been identified as a water quality related threats to sources of drinking water.

A water quality index is a simple number that expresses the overall water quality for a water sample based on several water quality parameters. A water quality index is a convenient method to summarized complex water quality data and facilitates its communication to managers and the public in general. An index is a useful tool for describing the state of the surface water for human usage or aquatic life. A water quality index (WQI) can also be used to assess the source of water quality in the elaboration of water protection strategies.

To calculate a WQI, the body of water, time period, variables and the objectives needs to be identified. The water quality index can be applied to one station, to monitor a particular river, only if there are enough data available for the analysis. It can also be applied to a number of different stations, e.g., sites throughout a lake. Data are usually collected over a time period of a minimum one year. Data from different years may be combined, but a degree of variability could be lost. Variables are water quality parameters measured to calculate the WQI. The water quality objectives are numerical concentrations or narrative statements establishing necessary conditions to support and protect the most sensitive designated used of water (e.g., drinking water, aquatic life) at the study site.

The climate model used in this study was the third generation coupled global climate model (CGCM3.1). Simulated daily minimum, mean and maximum air temperatures for the period 1970-2100 were obtained from Canadian Centre for Climate Modelling and Analysis and downscaled using the delta change approach. Results indicate that, during all future periods, the water temperature increase will be in the range of 60%-75% of the increases projected for air temperature. Therefore, water temperature in New Brunswick, for all future time slices (2020's, 2050's or 2080's) and scenarios (B1 or A2), were estimated to increase at 70% the average increase of air temperature. It should be noted that the WQI under climate change scenarios were calculated for each site using unchanged future water quality parameters: dissolved oxygen (DO), conductivity (Cond), acidity (pH), total phosphorus (TP), water temperature (Tw), ammonia (NH3), nitrite (NO2), nitrate (NO3) and suspended solids (SS). The only parameters that are projected to change in the present study are water temperature (Tw) and dissolved oxygen (DO),

The present study showed that projected air temperature increase of 2-5°C was very consistent across the province of New Brunswick and that the water temperature would most likely increase in the range of 1.4-3.5°C (70% of air temperature). This information was based on a long-term data analysis at Little Southwest Miramichi River. Therefore, future water temperature was project for each river and corresponding WQI were calculated. Two methods were used in this study to calculate the WQI of 15 studied rivers in New Brunswick. The first is the CCME IWQ method and the second is the weighted IWQ method. The values ranged from 74.0 to 93.3 in the case of CCME IWQ method and ranged from 88.2 to 92.2 in the case of weighted-IWQ method. Following the WQI classification for each method, it was observed that most rivers fall within the GOOD water quality conditions during the study period (2003-2011). A few river showed below GOOD conditions and these were the Kennebecasis River (74.0: FAIR), St. John below Florenceville (79.3: FAIR) and St.Basile (78.6: FAIR) under the CCME IWQ method. All rivers were classified as GOOD water quality conditions, under the Weighted IWQ method (all values for this method were over 90). The impact of Climate Change on the IWQ, using scenarios B1 and A2 had little impact on the water quality conditions based on the criteria used on the present study for drinking water.

In conclusion the water quality in New Brunswick Rivers is not project to deteriorate significantly under climate change (from a drinking water perspective) based on the two methods and criteria used in the present study. Nevertheless, it should be pointed out that the present study makes the assumption that other water quality parameters will remain the same in the future under climate change (SS, pH, Cond, etc.). However, climate change may results in changes among these parameters due to other processes. For instance, if climate change increases runoff, it is very likely that some parameters, particular those related to soil erosion, will also change in the future. In addition, the present study dealt with drinking water quality parameters related criteria. If the water quality was studied for other purposes, e.g. aquatic habitat conditions, the selected criteria as well as thresholds would be very different than the one used in the present study. Under these conditions it is very likely that the results would be different. For instance, a good body of research is showing that from an aquatic habitat perspective, some New Brunswick river (e.g., Miramichi River) are currently experiencing close to lethal water temperatures (30°C) in summer. Such high temperatures may not have a great influence on drinking water quality, but may have a significant impact on Atlantic salmon population as well as for other cold water species.

ABSTRACT / RÉSUMÉ

Abstract:

Surface water quality may change due to climatic variability in the future as natural processes will most likely be modified by anthropogenic activities. As such, stream temperature is very likely to change as well which will impact on surface water quality and aquatic ecosystem dynamics. The present study focused on improving modelling of surface water quality indices and water quality parameters under various climate change scenarios in relationship with stream temperature. Future climate data was 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). This study illustrated the usefulness of the Stream Temperature models, coupled with Climate Change Scenarios. Such models were used to explain the evolutions of future stream water temperature regimes and associated biogeochemical water quality parameters applied to drinking water quality. The specific objectives of the present study were to analyze the surface water quality of 15 rivers of New Brunswick on the basis of 9 parameters using climate change scenarios B1 and A2. A Weighed Method and the Canadian Council of Ministers of the Environment (CCME) Method were used to assess the water quality for each river under present and future climate. The knowledge gained from this study will enable engineers and water resources managers to better understand the thermal regime of rivers and climate change impact on water quality related to Drinking Surface Water.

Résumé:

Due aux changements climatiques, la qualité de l'eau de surface peut changer et modifier ainsi les processus naturels par des activités anthropiques. La température de l'eau est très susceptible de changer et aura un impact sur l'évaluation de la dynamique des écosystèmes aquatiques. La présente étude se concentre sur la modélisation de l'indice de la qualité de l'eau selon divers scénarios de changement climatique en relation avec la température des cours d'eau. Les eaux de surface de 15 rivières au Nouveau-Brunswick ont été analysées sous changements climatiques en utilisant 9 paramètres. Les données climatiques, provenant d'une simulation de la troisième génération de modèle couplé climatique global (MCCG3.1/T63), ont été utilisées pour estimer les températures des cours d'eau dans le contexte actuel et dans le contexte climatique sous les familles de scénarios B1 et A2. Une méthode de poids et une méthode suggérée par le Conseil canadien des ministres de l'environnement (CCME) ont servi pour évaluer l'indice de la qualité de l'eau pour chaque rivière sous le climat présent et futur. Cette étude permettra aux ingénieurs et aux gestionnaires des ressources en eau de mieux comprendre le régime thermique des cours d'eau et l'impact du changement climatique sur la qualité de l'eau des cours d'eau liée à l'eau potable.

1. INTRODUCTION

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 could adversely impact on 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 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), but relatively little is known about the changes in water quality.

Climate Change impacts on river systems include changes in runoff, groundwater flow as well as the timing of streamflow (e.g. high and low flows). To these quantitative aspects, water quality also needs to be assessed for effective water resources management. With respect to the biogeochemical water quality, most climate change impacts can be attributed to changes in stream temperature. With increases in stream temperature, dissolved oxygen will decrease and biological activities will increase. Such changes in stream temperature will also have consequences on nutrients, organic matter as well as biomass within the river environment. The impact of climate change on stream 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, stream temperature is also expected to be an extremely important parameter.

As river temperature will increase in the future, water quality index is also expected to change under climate Change and these changes need to be quantified. A water quality index was developed by the British Columbia (BC) Ministry of Environment, Lands and Parks. After, the Canadian Council of Ministers of the Environment (CCME) Water Quality Guidelines (WQG) Task Group, in cooperation with the CCME State of the Environment Task Group, formed a technical subcommittee to study water quality indices. They modified the BC index to create a CCME Water Quality Index (CCME-WQI) that could be used by all provinces and territories of Canada. Also, they recommended, among other, the development of regionally-specific WQI due to the anticipated regional differences in responses to climate change. As such, the present study will focus on water quality indices in New Brunswick and how such indices many be affected by climate change.

This study will focus on improving modeling of water quality indices and water quality parameters under various climate change scenarios in relationship with stream temperature. It will illustrate the usefulness of the stream temperature models, coupled with Climate Change Scenarios to explain the evolutions of future stream temperature regimes and associated biogeochemical water quality parameters applied to drinking water quality.

The objective of the present study was first, to link changes in air temperature and stream water temperature, as at high temperature the relationship will not be linear (due to evaporative cooling). Second, the study concentrated on using most reliable climate change scenarios available (CGCM 3.1/T63, SRES 20C3M, B1, A2) to predict stream water temperatures under climate change (El-Jabi et al. 2013). Third, this study focused on improving our current understanding of the impact of various climate change scenarios on water quality and biogeochemical parameters, a subject which has not been adequately addressed in the literature but very important for drinking surface water evaluation.

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 drinking water quality related to climate change impact.

2. LITERATURE REVIEW

2.1 Thermal regime of rivers

Thermal regime of rivers represents the natural variation in water temperatures for a selected period (seasonal, daily or diel) and watercourses. Many factors can influence the thermal regime and they can be classified using different categories. Poole and Berman (2001) classified the factors influencing thermal regime in two categories: internal and external factors. The external factors consider the net energy and water inputs whereas 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 influenced by factors such as atmospheric conditions, topography, stream discharge, and riverbed thermal fluxes (Caissie 2006). The atmospheric conditions are considered the most influential group. Atmospheric conditions are principally responsible for the heat exchange process at the water surface. It includes the 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 waterfalls. Streambed conditions can also influence the thermal regime depending on the heat exchange processes at the riverbed. 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 and other parameters related to water temperature. This descriptive study concluded that diel variations of water temperature were more significant during clear sky period. The largest diel fluctuations in water temperature are generally observed in summer while the smallest diel fluctuations are 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 temperatures in winter and spring (close to zero for northern latitude rivers) to maximum water temperatures in mid-summer. Maximum 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 ecological processes and for the flora and fauna within 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 downstream due to a longer run and longer heating exposition (Danehy et al. 2005). Diel variations are also dependent on climate and physical characteristics of rivers. For example, the downstream sections of rivers are deeper and diel variations are less important than upstream sections where the depth of water is small. All of these seasonal or daily variations of stream water temperatures are important for aquatic resources and water quality parameters. This concept is explained in the 'River Continuum concept' (Vannote et al. 1980).

Large scale thermal regime was studied by Ward (1985) by considering many rivers from south hemisphere. Ward (1985) observed that diel fluctuations increased in the downstream direction, where water sources were less dominant by groundwater and streams were more exposed to meteorological conditions. Diel fluctuations decreased further downstream in rivers where water depths increased (became significant) and with a greater volume to be heated (Ward 1985). This study also concluded that the difference in the thermal regimes between the southern and northern hemisphere was mainly related to the size of rivers and not to thermal processes. 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 latitude and altitude as 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 thermal regimes based on geographical parameters. 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 are 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, 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 sometimes influenced at the micro-scale as shown by 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 particularly subjected to high temperatures due to shallow water depths 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 stream flow peaked. Soil temperature increased with depths during the snowmelt period but decreased with depths 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, including latitude (Mohseni et al. 2002). Other studies have shown basin-scale stream temperatures were strongly affected by water sources, as well as basin characteristics like altitude, azimuth and stream length (Brown and Hannah 2008).

2.2 Climate change

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 events (Arnell and Delaney 2006). The impacts and adaptation strategies will greatly depend on local hydrological, economic, social and political conditions (Kundzewick et al. 2008).

Global mean temperatures could increase by 1.7°C by the year 2050 and by 2.7°C towards the year 2100 (Boer et al. 2000). By the 2080s, air temperatures in UK are estimated to increase by up to 4°C with an increase in precipitation between 13% to 16% (Thorne and Fenner 2011). Andersen et al. (2006) is predicting an increase in mean annual precipitation (47 mm) and in mean annual air temperature (3.2°C) in Denmark. Over large parts of Europe, climate change could lead towards heavier summertime precipitation (Christensen and Christensen 2003). For the Colorado River, precipitation is expected to decrease by 3% for the next 100 years (Christensen et al. 2004). Whitehead et al. (2009) stated an increase in winter precipitation and decrease in summer precipitation. From 1940 to 2002, George et al. (2007) observed a progressive increase in winter air temperatures and rainfall in the English Lake District, with less pronounced trends in summer. Minns et al. (1995) showed a decline in precipitation and in the number of rainy days in eastern Canada.

Different methods can be found in the literature to assess the impacts of climate change on hydrological regimes (Rehana and Mujumdar 2011). Methods are either using high-resolution regional climate models (Malmaeus et al. 2006), general circulation models (GCMs) through statistical downscaling techniques (Wilby and Wigley 1997; Cruise et al. 1999; Burlando and Rosso 2002; Andersen et al. 2006) or hypothetical scenarios as input to hydrologic models (Arnell and Reynard 1996; Mimikou et al. 2000; Chang 2004).

2.2.1 Climate change impacts on hydrology

The predicted impact of climate change on the hydrological cycle have been extensively analyzed in various parts of the world based on different emission scenarios and climate models (e.g., Müller-Wohlfeil et al. 2000; Christensen and Christensen 2003; Alcamo et al. 2007). Projected changes in river hydrology are just as dependent on the choice of the global climate model as the choice of anthropogenic emissions scenario (Arnell 1999; Andréasson et al. 2004; Jasper et al. 2004). Another challenge of modelling climate change is the spatial interpolation or extrapolation of results from local to regional or national scales (Park et al. 2010). Studies have shown that the impacts on river flow can vary considerably whether the basin is in northern or southern regions (Arnell 1999, 2004; Etchevers et al. 2002; Andréasson et al. 2004). Areas with an increase in water resources deficits include watersheds around the Mediterranean, in central and southern Africa, Europe, central and southern America, while areas with an increase in water resources have been found by be concentrated in south and East Asia (Arnell 2004).

The reduced snowfall and early snowmelt peak runoff predict a longer summer period in some areas (Sahoo et al. 2011). Climate change will also decrease the snow cover and increase the winter runoff in northern latitude basins (Bouraoui et al. 2004). Evaluation of global warming of six US water resource systems is predicting a reduction of the spring snowmelt peaks whereas winter flows would increase (Lettenmaier et al. 1999). Bouraoui et al. (2004) predicted an increase in precipitation, but a decrease in annual water flow by 3.3%. The increase in air temperature would results in an acceleration of snowmelt. In this study, the hydrological model SWAT was applied to the Vantaanjoki watershed (Southern Finland). Result show that winter will be most impacted, with higher winter flows, and almost entirely eliminating the snowmelt runoff. The snowpack will likely be reduced due to increased winter rainfall and this will results in an earlier snowmelt (Band et al. 1996). The rise in temperature will also significantly affect the spatial distribution and amount of snow cover (Arnell 1999). Jasper et al. (2004) used a statistical-downscaling approach to predict hydrological impacts (monthly mean temperature and precipitation) on two Alpine River basins (Switzerland) under 23 regional climate scenarios. The results showed a strong decreased in the snowpack and a shortened duration of the snow cover caused by an increase in annual mean temperature (1.3°C to 4.8°C). It is likely that the increase in air temperatures will also reduce the influence of snow and snowmelt on River Dee in Scotland (Langan et al. 2001). There will be a decrease of winter ice cover of more than 100 days per year as a result of warmer climatic conditions in North America lakes (Hostetler and Small 1999). By the year 2090, Lake Erie could have 96% of its winter ice-free (Lofgrean et al. 2002). Ice breakups have occurred 9 to 16 days earlier during a 20 year periods (1968-1988) for 20 Wisconsin lakes (Anderson et al. 1996). Under a doubled CO2 scenario, Lake Erken (Sweden) also showed shorter periods of ice cover, even with ice-free years (Blenckner et al. 2002).

There have been several studies of the potential impacts of climate change for river flows in Britain (Arnell and Reynard 1996; Pilling and Jones 1999, 2002; Sefton and Boorman 1997), in Italy (Burlando and Rosso 2002) and in northern Germany (Muller-Wohlfeil et al. 2000). Depending on scenarios, the annual runoff in Great Britain may increase by over 20% (wet scenario) or decline by over 20% (driest scenario) by the year 2050 (Arnell and Reynard 1996). Significant increase in river discharge may be expected in the coming decades as a consequence of increased rainfall amounts in northern Germany (Muller-Wohlfeil et al. 2000). Although climate change scenario tend to forecast more precipitation in the study of Göncü and Albek (2010), some months showed very little precipitation, thus increasing drought potentials as well. Middelkoop et al. (2001) is predicting a higher winter discharge as a result of intensified snowmelt and increased winter precipitation, as well as lower summer discharge due to the reduced winter snow storage and an increase of evapotranspiration.

The study by Limbrick et al. (2000) predicted an important reduction (19%) of the total annual runoff and of the minimum annual flows (46%) in the River Kennet (UK). Another related study (Christensen et al. 2004) showed that under climate change, annual runoff could be lower by 17% on the Colorado River. These impacts could significantly reduce the annual hydropower output.

Arnell (2003) estimated the changes in mean monthly flows and Q95 (the flow exceeded 95% of the time on the flow duration curve) in six catchments in Britain, using the UKCIP98 climate change scenarios. Arnell (1999) studied the effects of climate change on hydrological regimes at the continental scale in Europe using a macro-scale hydrological model under four climate change scenarios. For northern Europe, the model predicted an increase in precipitation, in runoff (up to 25%), whereas, in southern Europe the model predicted a decrease in precipitation and a decrease in runoff (up to 50%). For most of Europe, the model showed a reduction in spring flows and an increase in winter runoff. Global change was projected to strongly affect runoff regimes via the impact on snow cover in Alpine catchments (Zierl and Bugmann 2005).

Andréasson et al. (2004) assessed the hydrological impacts of climate change over a wide range of Swedish basins. For most Swedish basins, the model showed a decrease in spring flood peak frequencies, an increase in autumn and winter runoff and an increase of high flow events during autumn. Andersen et al. (2006) assessed the climate change impacts on hydrology on Gjern river basin (Denmark). An increase in runoff of 58 mm (12.3%) was predicted, with a major increase found in winter. Band et al. (1996) predicted an increase in winter runoff and a decrease in summer flow.

Abu-Taleb (2000) evaluated projected deficits between water demand and supply in Jordan under different climate change scenarios, in terms of social and economic viability. Alcamo et al. (2007) analyzed the impacts of climate change from a global water resources perspective. Results showed water stress regions will most likely increase (62% to 75%) in most global areas caused by a growing withdrawals due to domestic water use. The trend of increasing annual mean temperature in the past century in the Winnipeg area may reduce net recharge and affect groundwater levels (Chen et al. 2004).

2.2.2 Climate change impacts on water quality

2.2.2.1 Stream temperatures

Many 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 data (Webb 1996).

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) showed 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 in the season. Summer water temperatures were predicted to increase by 1.9°C. Another study showed that the greatest increase in water temperatures may 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 a climate change scenario. An increase in water temperatures combined with a predicted reduced precipitation could greatly affect water quality of streams (Mimikou 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 tributary (BC) due to climatic warming. Water temperature of Lake Tahoe (US) was observed to be warming at 0.013°C/year (Sahoo et al. 2011).

Cooter and Cooter (1990) predicted that water surface 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 an atmospheric CO_2 doubling 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 will increase at slower rate at high temperatures due to evaporative. Mohseni et al. 2003 also studied upper bound in stream temperature due to evaporative cooling.

On the Colorado River, average annual stream temperature was simulated to increase by up to 2.4°C by the 2100s (Christensen et al. 2004). By 2050s, George et al. (2007) predicted an increase in water temperatures of up to 1.1°C and 2.2°C for English Lake District. Models of 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).

2.2.2.2 Other parameter of water quality

Water quality parameters can be classified according to physical parameters (temperature, pH, dissolved oxygen (DO), dissolved organic matter (DOM)), nutrients, micropollutant (inorganic and organic, metals, pesticides and pharmaceuticals) and biological parameters (pathogen microorganism, cyanobacteria and water quality peroxides) (Delpla et al. 2009; Kundzewick and Krysanova 2010). Water quality parameters can be influenced by many climatic factors, such as air and water temperature, the amount and frequency of precipitation as well as the occurrence of extreme events (Kundzewick and Krysanova 2010).

Potential impacts of climate change on water quantity have received more attention (Müller-Wohlfeil et al. 2000; Christensen and Christensen 2003; Alcamo et al. 2007), but relatively little is known about the changes in water quality (Whitehead et al. 2009). Higher water temperatures and greater variations in runoff associated with climate change are likely to influence physical, chemical and biological processes that govern water quality, and this could potentially adversely impact human water use (Dale 1997; Murdoch et al. 2000; Schindler 2001; Thorne and Fenner 2011). Water quality studies are more complex and more challenging (than water quantity) due to many factors (e.g., climate, hydrology, land use) (Kundzewick and Krysanova 2010). Impacts of climate change on stream water chemistry can be much more significant than those caused by urban development (Booty et al. 2005).

Booty et al. (2005) presented a methodology for assessing the impacts on water quality (nutrients and dissolved oxygen) caused by climate change. This research was part of a pilot study of the Canada-Ontario Water Use and Supply Project, to determine water supply use and demand, identify ecological sensitivities to water resources and make projections for the future. The Agricultural Non-Point Source model was used to estimate changes in water chemistry under two internationally known climate models: the Canadian Center for Climate Modelling and Analysis (CCCma) CGCM1 and the Hadley Center HadCM2. Depending on the scenario (a wet or dry scenario), this study estimated significant changes in nitrogen (-20.4% to 6.5%), phosphorus (-14.3% to 14.3%), and chemical oxygen demand (COD) concentration (-5.7% to 11.9%).

Dwight et al. (2004) conducted a temporal and spatial analysis in southern California. This study had the objective to determine associations between urban river discharge and an indicator of bacteria levels. A strong association was found between precipitation and water pollution. Water quality can respond to the changing precipitation patterns caused by climate change (Hatfield and Prueger 2004). Climate warming may cause melting glaciers to become an increasing source of contaminants to freshwater, as shown in the Banff National Park (Blais et al. 2001).

Under climate change, the oxygen-carrying capacity of the water will also decrease, thus increasing anoxia in eutrophic water (Murdoch et al. 2000). A modelling undertaken by Chang and Railsback (1992) simulated water temperature and dissolved oxygen (DO) concentrations under current and predicted (GCMs) meteorological and hydrologic data. They found that warmer water temperatures will likely increase stratification and algal growth, with a subsequent algal decay resulting in decreased levels of dissolved oxygen (DO) in waters. Higher water temperatures combined with increased precipitation and longer periods of low flows are projected to increase algal blooms (Hall et al. 2002) and bacterial fungal content (Environment Canada 2001). An increase in stream temperature was found to have enhanced the formation of chloroform on the Suwannee River (Yang et al. 2007).

Sahoo et al. (2011) predicted climate change impacts (air temperature, precipitation, wind speed, long wave radiation, and solar radiation) using tree GSMs models. They estimated the thermal properties and maximum mixing depth of Lake Tahoe using a hydrodynamic model (Lake Clarity Model). Simulation results over a period of 40 years showed that the lake has a warming trend with a reduction in mixing process. Dissolved oxygen (DO) decreased as temperature increased. Dissolved organic carbon (DOC) concentrations in 22 UK upland waters have increased by an average of 91% based on observations of the last 15 years (Evans et al. 2005). This study suggested that DOC might be increasing in response to a combination of declining acid deposition and rising temperatures. Worrall and Burt (2007) suggested that the observed increases in DOC (>10 years) across most of Great Britain were consistent with the long-term increase in air temperature or atmospheric CO2 concentration. The observed decrease of pH in alpine lakes can be related to either the rise in temperature or a decrease in acid precipitation (Psenner and Schmidt 1992). A lower water volume will decrease the dilution effects, increasing the biological oxygen demand (BOD) and lower dissolved oxygen (DO) (Whitehead et al. 2009). Worral et al. (2004) showed that temperature change alone was insufficient to explain observed increases in DOC production. Other explanations included land management or anaerobic degradation following severe droughts.

Artificial neural network (ANN) models can be used to estimate the dissolved oxygen (DO) and biological oxygen demand (BOD) (Clark et al. 2001; Singh et al. 2009). Singh et al. (2009) applied an ANN model on the Gomti River (India) to estimate DO and BOD levels. The ANN models used eleven input water quality variables measured in the river over a period of 10 years (monthly) at eight different sites. The input parameters included were: water pH, total alkalinity (T-Alk), total hardness (T-Hard), total solids, chemical oxygen demand (COD), ammonical nitrogen (NH4-N), nitrate nitrogen (NO3-N), chloride (Cl), phosphate (PO4), potassium (K) and sodium (Na). The modeling showed close agreement between measured and predicted DO and BOD values with RMSE between 1.23 and 1.5 (DO), and between 1.38 and 2.25 (BOD). Clark et al. (2001) used a neural network to examine the relationships between climate and geography on discharge and dissolved organic carbon (DOC) from 15 rivers in Canada's Atlantic region from 1983 to 1992.

Nitrate concentrations were identified as a key water-quality parameter of concern at Grafham in the UK (Thorne and Fenner 2011). Stream nitrate concentrations (NO3-) were found to be positively correlated with mean annual air temperature, suggesting an acidification of surface waters by nitrogen deposition under climate change (Murdoch et al. 1998). Andersen et al. (2006) used a statistical nutrient loss model to simulate the impact of changed hydrology by climate change on diffuse nutrient losses. They predicted an increase in mean annual total nitrogen loads of 2.3 Kg (8.5%) and 1.6 Kg (6.9%) in two sub catchments. Kaste et al. (2006) assessed the impacts of climate change on nitrogen in a Norwegian river basin. They simulated an increase in nitrogen concentrations mainly in winter (50% to 100%), without a significant change during summer.

Schindler et al. (1996) described changes in small boreal lakes and streams in northwestern Ontario over 20 years (1970-1990). They observed higher concentrations of base cations, nitrogen, and higher alkalinity, but lower concentrations of dissolved organic carbon (DOC), silica and phosphorus. Komatsu et al. (2007) assessed the long-term effect of global warming impact on environmental variables (water temperature, dissolved oxygen, nutrients, and aquatic ecosystems) on Shimajigawa reservoir (Japan). They developed a watershed runoff model and reservoir water quality model using meteorological input calculated by a GCM A2 scenario. Under the influence of high temperatures, this study observed an increase in oxygen demand (OD) from aerobic decomposition, an increase in concentration and amount of phosphorus from sediments which promoted further algal growth and changes in aquatic ecosystems. Benitez-Gilabert and Alvarez-Cobelas (2010) observed a relationship between the stream temperature increase and water quality changes in semi-arid streams of Spain from 1973 to 2005. They also suggested a case-by-case approach for understanding climatic variability effects on water quality. A study on the

Spanish Ebro River analyzed 34 physical-chemical variables from 1981 to 2004 (Bouza-Deano et al. 2008). They concluded that parameter variations over time were mainly due to the reduction in phosphate concentration and increase of pH levels. Sommaruga-Wögrath et al. (1997) analyzed an alpine lake for several years. This study showed a strong positive correlation between pH and mean air temperatures, and demonstrated high sensitivity of remote lakes (high altitudes and latitudes) to climate warming. Lakes may face increasing phosphorus levels under climate change (Malmaeus et al. 2006).

General deterioration of the water quality of the Meuse River during droughts, are expected to increase in frequency and intensity (Vliet and Zwolsman 2008). Nutrient loads can be expected to increase in winter and spring due to an expected increase in streaflow on Mid-Atlantic region (Neff et al. 2000). The projected decreases in streamflow and nutrient fluxes in summer (July and August) could restore problems associated with estuarine stratification and eutrophication in late summer.

Results indicated that increases in lake conductivities predicted under current climate change scenarios will have a significant impact on both regional water chemistry and the relative importance of phyto-plankton phyla in saline lakes (Evans and Prepas 1996). The warming of stream temperatures was found to decreased dissolved oxygen (DO), increased phytoplankton biomass during the growth period and reduced it afterwards (Ducharne 2008).

Multiple linear regression model based on monthly average of temperature and interflow explained 67% of the dissolved organic matter (DOM) on the Malse River in South Bohemia (Hejzlar et al. 2003). This study also predicted an increase of 7% in DOM concentration under the possible 2xCO2 climate change. Two dynamic watershed models (HSPF and SWAT) evaluated the impact of climate change on 20 major river rivers throughout the US (Butcher et al. 2011). Impacts of climate change were studied not only on hydrology, but also on nutrient and sediment impacts as well. The results were intended to improve the understanding of system sensitivity to climate and land-use change, and provide a range of potential scenarios on hydrologic and water quality impacts in different regions of the US. On average, loads of total suspended solids (TSS), total nitrogen and total phosphorus were predicted to increase by 44%, 10%, and 24%, respectively. Chang (2004) investigated the potential changes in nitrogen and phosphorus loads under a warmer and wetter climate and urban growth on the Conestoga River Basin (Pennsylvania). Mean annual nitrogen and phosphorus loads are expected to increase mainly in spring, with a light decrease in fall primarily because of changes in monthly precipitation. Combined with urbanization, annual nitrogen loads could increase by up to 50% in the most urbanizing areas. Geographic information system (GIS) and the Soil and Water Assessment Tool (SWAT) found similar water quality response to climate change in the Bai River basin (Ji et al. 2011).

Arheimer et al. (2005) used six regional climate change scenarios to evaluate the impacts of water quality in the Rönnea catchment (Sweden) and biological responses in Lake Ringsjon. The nitrate transport was modeled using the models SOILNDB and HBV-N, and biogeochemical effects (algae and other substances) were modeled with BIOLA. This study noted a decline in lake water quality with an increase concentration of total phosphorus (+50%), total nitrogen (+20%), and planktonic algae such as cyanobacteria (+80%). Johnk et al. (2008) also predicts an increase in cyanobacteria produced by an increase in temperature, as a result of climate change. Cyanobacteria blooms produced by algal toxins are a water quality concern that can have adverse health effects on humans and animals (Soh et al. 2008).

Models demonstrate that river flow was the major determinant in the daily variability of alkalinity, conductivity, hardness and calcium levels (Interlandi and Crockett 2003). A linear relationship was found between the logarithm of flow and conductivity (Caissie et al. 1996) and between the logarithm of flow and pH (Anderson et al. 1993; Caissie et al. 1996). Bastarache et al. (1997) developed an artificial neural network model (ANN) in order to improve the modeling of water conductivity and acidity. The input parameters used were a combination of the following parameters: daily flow, time of year, precipitation, snow depth and daily (minimum and maximum) air temperatures. The coefficient of determination (R^2) for the ANN models varied between 0.716 and 0.976. This study concluded that water acidity and conductivity were influenced by a large number of factors and that the relationship between them can be difficult to establish.

Cruise et al. (1999) assessed the impact of climate change on water quality (dissolved oxygen, total nitrate nitrogen and pH) in the southeastern US. Streamflow estimations were based on the United Kingdom Hadley Center climate model and predicted by a regional stochastic approach and a physically based soil moisture model. The regional stochastic approach was applied on the entire study area, while the physically base model was used at select locations to support the stochastic model. The results of the study revealed that few basins exhibit dissolved oxygen problems, but that several watersheds exhibit high nitrogen levels. As streamflow is projected to decline over the next 30-50 years, it will most likely exacerbate these water quality problems. Prathumratana et al. (2008) studied the relationship between climatic, hydrological and water quality parameter of the lower Mekong River. Some water quality parameters (total suspended solids (TSS), nitrate (NO3), phosphate (PO4), total phosphorus (TP) and chemical oxygen demand (COD)) had weak to fair positive correlations to precipitation, mean water level and discharge flow, while other water quality parameters (dissolved oxygen (DO), acidity (pH), conductivity, calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), alkalinity, chlorine (Cl), sulfate (SO4-2) and silicon (Si)) had fair to strong negative correlations with the same hydrological parameters.

Marshall and Randhir (2008) used the SWAT model to evaluate the potential implications of increasing temperatures on water quantity and quality on the Connecticut River watershed of New England. It predicted a significant impact on streamflow, sediment loading (up to 50% from June to October) and nutrient (nitrogen and phosphorus) loading in the watershed that will lead to important implication on water quality. Rehana and Mujumdar (2011) described the changes in water quality of lakes and stream under conditions of altered river flow and river temperature regimes. The water quality parameters analyzed were the dissolved oxygen (DO), biological oxygen demand (BOD), total organic carbon (TOC), alkalinity, pH and conductivity. To generate scenarios of river water temperature, they used a simple linear regression relation between air and water temperature. The six hypothetical climate change scenarios resulted in impairment in water quality with a significant decrease of the dissolved oxygen (DO) levels and increase in biochemical oxygen demand (BOD).

Mimikou et al. (2000) assessed the impacts of climate change on water resources (surface runoff) and water quality in central Greece. A physically based hydrological model (WBUDG) simulated the effect of two climate scenario (HadCM2 and UKH1) on average monthly runoff. To simulate the impact on water quality (DO, BOD and NH4+), they developed a stream quality model (R-Qual). They observed an increased in biological oxygen demand (BOD) and ammonium (NH4+) and a decreased in dissolved oxygen (DO) caused by loss of stream dilution capacity and reduced flows. Most of the water quality impacts occurred in summer where climate scenarios predicted the greatest precipitation decrease. Nicholls (1999) used multiple regression analysis to show the strong influence of temperature on summer total phosphorus (TP) concentrations of the Bay of Quinte under a doubled CO2 scenario. Results suggested an increase in summer average TP (77% to 98%) as a result of the water temperature increase (3°C to 4°C) for June to September.

The study of Bloomfield et al. (2006) addressed climate change impacts on the fate and transport of pesticides in surface water and groundwater in the UK. Changes in rainfall seasonality, intensity and increase temperatures were thought to be the main drivers for changing pesticide fate and behavior, but the study concluded that land-use change may have a more significant effect under climate change.

2.2.2.3 Drinking water

Climate change was shown to affect water quality, possibly violating the Safe Drinking Water Act regulations, therefore the impact of the design and operation of drinking water treatment plants (Li et al. 2010). Many studies have shown a decline in stream water quality under a climate change scenario (Arheimer et al. 2005; Cruise et al. 1999; Marshall and Randhir 2008; Mimikou et al. 2010), but very few have focused on the impact of drinkable water supplies. Expected impacts of climate change are flow reduction that will lower water levels in rivers and lakes, as well as an increase in water demand and higher temperatures (Carrière et al. 2007). The main impacts of the consequence of rising temperatures and heavy rainfalls would be the rise in concentration of dissolved organic matter, pollutants and pathogens (Delpla et al. 2009). Water quantity changes due to climate change have been identified as a water quality related threats to sources of drinking water (Environment Canada 2001). Some disease outbreaks in the US have been related to the increased heavy precipitation due to climate change (Curriero et al. 2001). In Canada, 288 outbreaks of infectious disease were linked to a drinking water source between 1974 and 2001 (Schuster et al. 2005).

Flow variability was found to deteriorate water quality (Dale 1997; Murdoch et al. 2000; Schindler 2001; Thorne and Fenner 2011). A reduction in water flow is expected to increase water pollutant concentration, resulting from a lower dilution capacity, whereas an increase in water flow will increase the transport of diverse compounds from soil to water resources trough fluvial erosion (IPCC 2008). Kundzewick and Krysanova (2010) have presented some key consequences of declining water quality due to climate change. They cited the increase of water withdrawals from low-quantity sources. They also noted the risk of occurrence of water infrastructure malfunction, overloading the capacity of water and wastewater treatment plants, and greater pollutant loads from diffuse sources during extreme rainfall. An increase in waterborne disease is also expected due to insufficient supply of potable water and higher turbidity, nutrients loads, and pathogens transport into water supply (Kovats et al. 2005; Ebi et al. 2006). In regions where water availability is likely to decrease, water managers will need to ensure adequate water supplies, building new storage reservoirs or using alternative water sources (Harman et al. 2005). Low water availability could lead to groundwater over-exploitation, creating the need to pump water from deeper sources at higher costs (IPCC 2008).

Storm events may also affect the performance of sewer systems; introducing microbial and chemical pollutants to water resources not usually handle in conventional drinking water treatment processes (IPCC 2008). Studies have shown that some pathogens are even resistant to conventional chlorination treatment during high rainy season (Nchito et al. 1998; Kang et al. 2001). Floods, caused by extreme precipitation, can put water structure at risk and leave the population with no sanitary protection (IPCC 2008).

Warmer temperatures have been linked to the increase of algal blooms (Chang and Railsback 1992; Hall et al. 2002) that could impair water quality trough undesirable color, odor and taste, possibly toxic to humans and wildlife (IPCC 2008). Available water treatment technologies to treat these problems have a high cost (Environment Canada 2001).

Climate change will cause the sea-level to rise and increase the risk of salinization of water supplies from coastal aquifers (IPCC 2008). Basins along the Gulf Coast, already having critical conditions of water quality, may significantly increase their salinity levels associated with salt-water intrusion (Cruise et al. 1999). This problem could also affect inland aquifers caused by a reduction in groundwater recharge (Chen et al. 2004). Although the cost desalination is declining, it is much more expensive than conventional method and has a high energy demand (Zhou and Tol 2005).

Thorne and Fenner (2011) have assessed the impact of climate change on the water treatment operations on a reservoir of the UK. Their analysis was limited due to a lack of recorded date relating to the treatment processes, as it relies on tacit knowledge. Presently, nitrate removal relies on a natural process to reduce nitrate levels before water treatments. Nitrate levels exceeding the treatment limit is expected to increase its frequency by 10% by the 2080s. Additional treatment process will be required to meets water quality standards. Algal growth is projected to increase back-wash frequency and decrease filter run times. The projected increase in DOC will result in increased coagulant dosing and disinfection requirements (e.g., chlorination).

Global warming could have a major impact on waterborne disease associated with drinking water for many private water supplies of the UK (Hunter 2003). With heavy rainfalls and higher temperatures, the water supplies and algal blooms problems will only deteriorate further. The major challenge of water treatment plants would be to maintain optimal coagulation conditions following rainstorm events that are predicted to increase with climate change (Hurst et al. 2004). Rainstorm events lead to elevated levels of turbidity and organic matter of river waters (IPCC 2008). Hurst et al. (2004) found that the change in nature and increase in natural organic matter (NOM) concentrations following storm events is the probable cause of turbidity at water treatment plants.

Carrière et al. (2007) determined the vulnerability of over 30 water treatment plants along the St. Lawrence River to water level fluctuations. Low water levels in the river could cause insufficient water in wells, causing pumping problems or interrupted distribution. Other than withdrawal impacts, lower levels could also affect water quality. Moulton and Cuthbert (2000) stated that high temperature and longer water residence time could increase the frequency and intensity of algal blooms, potential producers of toxins in drinking water. In shallow areas of water intake on the St. Lawrence River, water may have an odor and taste problems due to increased weed growth and attached algae population. This deterioration in water quality will necessitate greater use of chemicals at water treatment plants to improve water quality for domestic use.

The quality impacts of climate change will certainly affect the treatment costs of water supply (Carmichael et al. 1996). Frederick and Schwarz (1999) examined the changes in water availability under two climate change scenarios. One scenario (dry) predicted an increase in costs to improve water supply and demand. The other predicted a reduction of costs caused by increased of water supplies. Water quality deterioration by climate change may also cause a cost increase for water treatment operations (e.g., increased chemical consumption), or new infrastructure to remove new target compounds (e.g., heavy metals, algae) or treat other problems (e.g., taste or odor) (IPCC 2008; Emelko et al. 2011). Safe access to drinking water will be harder in regions where runoff and/or groundwater discharge decreased as a result of climate change and will create additional costs for water supply infrastructures (IPCC 2008). For example, the combined chemical costs of coagulation and chlorination are projected to increase by up to 6% on Grafham Reservoir in the UK (Thorne and Fenner 2011). The highest costs related to water treatment are expected to be in the months of low flow conditions, where water quality is already at its worst. Results of Carmichael et al. (1996) indicated that costs require to reach generally acceptable water quality under climate change in the Nitra River Basin (Slovakia) could rise exponentially, particularly in August and October. Marinoni et al. (2011) have developed a cost utility analysis (CUA) to optimize the number of measures that can be implemented by catchment management authorities under a budget constraint. New, improved and flexible engineering designs and operation methods for water management systems needs to be developed under a wide range of climatic conditions (Soh et al. 2008).

2.2.3 Climate change impacts on aquatic species

Increases in summer water temperatures due to climate change could cause the dissolved oxygen (DO) to decrease and aggravate the effects of acid precipitation, threatening the growth and life of many aquatic species (Hill and Magnuson 1990; Schindler 2001; Gooseff et al. 2005). Changes in growth opportunities for fish may be possible, especially in spring and autumn, caused by the increase of water temperature (Hills and Magnuson 1990). Global warming may also increase groundwater temperatures, affecting incubation of eggs within the stream substrate (Meisner et al. 1988). Higher rates of fish mercury levels were associated with higher water temperatures in lakes (Bodaly et al. 1993). Aquatic ecosystems will experience higher water temperatures, possibly leading to increase stress on fish populations during some time of year (Gooseff et al. 2005).

Major reductions in stream habitat could result from climate warming for cold and cool fish species. Eaton and Scheller (1996) studied the effects of climate warming on thermal habitat of 57 fish species in the US under a doubling atmospheric carbon dioxide scenario. Water temperatures were predicted by multiplying air temperature changes by 0.9 (based on several field studies). A temperature-based habitat model showed a large reduction (80%) in trout habitat under the increase of 1.5°C to 2.5°C in stream temperature (Clark et al. 2001). Hrachowitz et al. (2010) have shown that with an increase of 2.5°C or 4°C in air temperatures, thermal habitat of Atlantic salmon and brown trout could potentially be altered. Climate change is already causing anthropogenic changes, affecting aquatic ecosystems in the American Southwest and Mexico (Grimm et al. 1997). Fang et al. (1999) have estimated fish habitat from simulated daily water temperatures and dissolved oxygen profiles in Minnesota USA under a projected $2xCO_2$ climate scenarios. Aquatic habitat of freshwater salmon in Washington State will experience longer periods of higher water temperatures possibly causing thermal migration barriers and increase the risk of fish kills (water temperatures over 21°C) (Mantua et al. 2010). Projected global warming could reduce summer thermal habitat by 30% to 40% for brook trout in two streams of Southern Ontario (Meisner 1990). Projected loss of habitat varied among methods in Rahel et al. (1996), but all methods indicated a noticeable loss of habitat (7 to 76%) even for minor increases in temperature on the Northe Platte River. Climate warming is projected to reduce fish habitat for cold water and cool water fish is small US lakes by 45% and 30% (Stefan et al. 2001).

3. MATERIALS AND METHODS

3.1 Study Area

The study area consists of 15 rivers in New Brunswick as shown in Figure 1. The list of these station is also provided in Table 1. New Brunswick lies on Canada's Atlantic coast, and is bordered by the ocean on its southern (Bay of Fundy), northern and eastern (Gulf of St. Lawrence) shores. Generally, average air temperatures in New Brunswick range from -10°C in January to 19 °C in July. New Brunswick receives approximately 1100 mm of precipitation annually, with 20 to 33% falling in the form of snow. Precipitation tends to be highest in southern parts of the province and the northern part of New Brunswick receives correspondingly higher amounts of precipitation in the form of snow due to colder winters.

Major rivers and many smaller streams flow from the interior highlands of New Brunswick. Rainfall, snowmelt, and groundwater all contribute to the volume of flow, producing variations from season to season and year to year. Most high flows are caused by the spring snowmelt with, at times, a combination of snowmelt and rainfall. Heavy rainfall can also cause high flows, especially in small streams during the summer and autumn periods. Low flows generally occur in late summer, when precipitation is low and evaporation is high, and in late winter, when precipitation is stored until spring in the form of ice and snow. Winter low flows are more dominant in the northern part of the province.

3.2 Water Quality Index

A water quality index is a simple number that expresses overall water quality for a water sample based on several water quality parameters. A water quality index is a convenient method to summarized complex water quality data and facilitates its communication to managers and a general audience. An index is a useful tool for describing the state of the surface water for human usage (Liou et al. 2004; Alobaidy et al. 2010; Wanda et al. 2012) or aquatic life (Hébert 1997; Khuan et al. 2002; Carr and Rickwood 2008). A water quality index (WQI) can also be used to assess the source of water quality in the elaboration of water protection strategies (Islam et al. 2011).

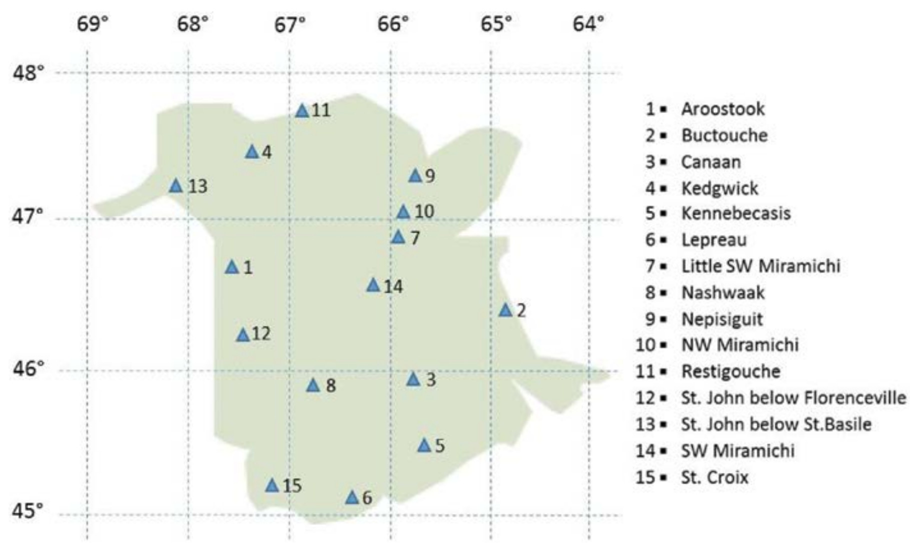

Figure 1 – Locations of sampling stations in New-Brunswick

To calculate a WQI, the body of water, time period, variables and the objectives needs to be identified. The water quality index can be applied to one station, to monitor a particular river (only if there are enough data available for the analysis). It can also be applied to a number of different stations or different sites throughout a lake. Data are usually collected over a time period of a minimum one year (Canadian Council of Ministers of the Environment; CCME 2001). Data from different years may be combined, but a degree of variability could be lost. Variables are water quality parameters measured to calculate the WQI. The water quality objectives are numerical concentrations or narrative statements establishing necessary conditions to support and protect the most sensitive designated used of water (e.g., drinking water, aquatic life) at the study site (CCME 2003). There is no 'rule of thumb' on the selection of input or important variables; however, parameter selection should be based on measurements of water quality relevant to the study site (CCME, 2006). CCME (2001) recommends at least four variables sampled a minimum four times, but they do not set a maximum number of variables. CCME (2006) have conducted a sensitivity analysis of the Canadian Council of Ministers of the Environment (CCME) Water Quality Index (WQI), based on random parameter removal trials on a water quality data set involving 11 parameters. It suggested the CCME WQI should be calculated with a minimum of 7 parameters with a minimum of six samples. The choice of parameters should be based on the significance of the relationship with the goal of the WQI and the availability of monitoring data for the parameter (Lumb et al. 2006; Carr and Rickwood 2008).

Table 1 – Identification of New-Brunswick stations

	Station name	ID	Latitude	Longitude
1	Aroostook	AG0008	46°48'47"	67°43'15"
2	Buctouche	BS0039	46°22'16"	4°56'36"
3	Canaan	AP0195	45°56'07"	65°44'54"
4	Kedgwick	BB0002	47°40'16"	67°30'34"
5	Kennebecasis	AP0241	45°34'48"	65°45'24"
6	Lepreau	AQ0003	45°10'11"	66°28'05"
7	Little SW Miramichi	BP0018	46°57'09"	65°52'26"
8	Nashwaak	AI0036	45°58'45"	66°35'27"
9	Nepisiguit	BK0042	47°26'28"	65°42'22"
10	NW Miramichi	BQ0020	47°08'02"	65°50'02"
11	Restigouche	BJ0057	47°54'29"	66°56'57"
12	St. John below Florenceville	AJ0080	46°24'22"	67°36'21"
13	St. John below St.Basile	AF0084	47°21'18"	68°13'54"
14	SW Miramichi	BN0015	46°33'55"	66°05'36"
15	St. Croix	AR0092	45°10'12"	67°17'49"

3.3 Calculation of Water Quality Index (WQI)

In this study ***CCME WQI Method*** and the *WQI Weighted Method* were considered for the calculation of the WQI. These two WQI were then be applied on 15 stations across the province of New Brunswick.

3.3.1 CCME WQI Method:

This water quality index was developed by the British Columbia (BC) Ministry of Environment, Lands and Parks (Rocchini and Swain, 1995; Zandbergen and Hall, 1998). The Canadian Council of Ministers of the Environment (CCME) Water Quality Guidelines Task Group, in cooperation with the CCME State of the Environment Task Group, formed a technical subcommittee. They modified the BC index to create a CCME Water Quality Index (CCME WQI) that could be used by all provinces and territories of Canada. The CCME WQI was developed for simplifying the reporting of water quality data, useful to technical and policy individuals, as well as the general public interested in water quality. The CCME WQI is useful for many different purposes including drinking water quality data communications, ambient water quality data analysis, integrated watershed planning and management in the forestry sector, and assess the effectiveness of best management practices (Khan et al. 2005). The CCME WQI requires the use of a benchmark (or guideline), useful for comparison purposes (Rickwood and Carr 2009).

The CCME WQI relies on measures of three factors (CCME 2001):

1. The number of variables whose objectives are not met (scope)
2. The frequency with which the objectives are not met (frequency)
3. The amount by which the objectives are note met (amplitude)

These values are combined to produce a single value (between 0 and 100) describing the water quality. A value of 100 is the best possible index score and a value of 0 is the worst possible (Table 2). Table 3 shows the objectives or thresholds required for a good water quality index used the by CCME WQI. Health Canada (2012) used three indexes to describe the guidelines for chemical and physical parameters:

1. Health based and listed as a maximum acceptable concentrations (MAC).
2. Based on aesthetic considerations and listed as an aesthetic objectives (AO).
3. Established based on operational considerations and listed as an Operational Guidance values (OG).

Table 2 - Categorization of the WQI CCME and Weighted Methods

Categorization	CCME WQI Value	Water quality
Excellent	95-100	• Virtual absence of threat or impairment. • Conditions very close to natural or pristine levels.
Good	80-94	• Minor degree of threat or impairment. • Conditions rarely depart from natural or desirable levels.
Fair	65-79	• Occasionally threated or impaired. • Conditions sometimes depart from natural or desirable levels.
Marginal	45-64	• Frequently threatened or impaired. • Conditions often depart from natural or desirable levels.
Poor	0-44	• Almost always threatened or impaired. • Conditions usually depart from natural or desirable levels.

Table 3 – Variables and objectives used with CCME method

Variables		Objectives
DO (mg/l)	>	5.5
pH	<>	6.5-9
TP (mg/l)	<	0.05
Cond (μS/cm)	<	500
Tw (°C)	<	15
NH3 (mg/L)	<	0.05
NO2 (mg/L)	<	3.2
NO3 (mg/L)	<	45
SS (mg/L)	<	20

The Canadian Council of Ministers of the Environment Water Quality Index (CCME WQI) is calculated as follows:

$$CCME\ WQI = 100 - \frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732} \tag{1}$$

where

$$F_1(Scope) = \left(\frac{Number\ of\ failed\ variables}{Total\ number\ of\ variables}\right) \times 100$$

$$F_2(Frequency) = \left(\frac{Number\ of\ failed\ tests}{Total\ number\ of\ tests}\right) \times 100$$

$$F_3(Amplitude) = \frac{nse}{0.01\ nse + 0.01}$$

$$nse = \frac{\sum_{i=1}^{n} excursion_i}{\#\ of\ tests}$$

$$excursion_i = \frac{FailedTestValue_i}{Objective_j} - 1 \quad (TestValue < Objective)$$

$$excursion_i = \frac{Objective_j}{FailedTestValue_i} - 1 \quad (TestValue > Objective)$$

3.3.2 WQI Weighted Method:

In this widely used method, the WQI is calculated as the weighted sum of the different sub index scores (Sanchez et al., 2007, Liu et al., 2012). The individual parameter scores are aggregated into a final index value (between 0 and 100).

At each site, water quality parameters are selected. In our study monthly values of the 9 water quality-related parameter values for the period 2003-2011 were obtained from New Brunswick Environment. These parameters included: dissolved oxygen (DO), conductivity (Cond), pH, total phosphorus (TP), water temperature (Tw), ammonia (NH3), nitrite (NO2), nitrate (NO3) and suspended solids (SS).

Table 4 - Relative weights (Pi) and normalized values (Ci) of the water quality variables

	P_i	C_i						
		100	90	80	70	60	50	40
DO (mg/l)		7.5	7	6.5	6	5	4	3.5
pH	1	7	6.9-7.5	6.7-7.8	6.5-8.3	6.2-8.7	5.8-9	5.5-9.5
TP (mg/l)	1	0.05	0.2	0.5	1	1.5	2	5
Cond (μS/cm)	2	600	700	850	1000	1250	1500	2000
Tw (°C)	4	15	18	20	22	24	26	28
NH3 (mg/L)	3	0.01	0.025	0.05	0.1	0.2	0.3	0.5
NO2 (mg/L)	2	0.005	0.008	0.01	0.04	0.075	0.1	0.15
NO3 (mg/L)	2	0.5	2	4	6	8	10	15
SS (mg/L)	4	20	40	60	80	100	120	160

The following empirical equation was used for the determination of the WQI (Debels et al., 2005, Sanchez et al., 2007, Liu et al., 2012,):

$$WQI = \frac{\sum_i C_i P_i}{\sum_i P_i} \quad (2)$$

where is the normalized value of the parameters and is the relative weight of each parameter in term of its importance for aquatic life and drinking water source. The parameter Pi has a maximum value of 4, assigned to parameters of relevant importance for drinking water, such as Dissolved Oxygen (DO), Suspended Sediments (SS) and Water Temperature (Tw). Also, the minimum value assigned to parameters with minor relevance is the value of 1. Table 4 shows the weights and the normalization factors of the parameters used in this study. WQI Weighted Method is also an objective based index similar to the CCME WQI (Table 2). As such, the index will provide an indication if the water quality is fair, good, etc.

3.4 Statistical analysis

For each of the 15 sites, the Pearson's correlation matrix for chemical and physical properties of water parameters were calculated using Excel's Data Analysis Tool. The resulting matrix was used to determine the correlation among water quality variables. As expected at each site a strong correlation was found between dissolved oxygen (DO) and water temperature (Tw). As an example, Table 5 shows the correlation matrix for the Little Southwest Miramichi River site and the Figure 2 illustrates the regression relation results between DO and Tw.

Table 5 – Pearson's correlation matrix for chemical and physical properties of water quality in Little Southwest Miramichi River

	DO	pH	TP	Cond	Tw	NH3	NO2	NO3	SS
DO	1.000E+00								
pH	-7.102E-02	1.000E+00							
TP	-5.409E-02	4.900E-01	1.000E+00						
Cond	-1.470E-01	-2.694E-01	-3.525E-01	1.000E+00					
Tw	-8.669E-01	2.568E-01	2.877E-01	1.350E-01	1.000E+00				
NH3	-1.504E-01	-1.010E-01	3.169E-02	-1.047E-02	-6.681E-02	1.000E+00			
NO2	4.088E-16	5.672E-16	-6.359E-15	1.461E-15	1.455E-17	4.179E-16	1.000E+00		
NO3	4.088E-16	3.778E-01	-1.600E-01	-1.602E-01	1.455E-17	-5.188E-02	1.008E-15	1.000E+00	
SS	-1.472E-01	2.940E-01	-1.825E-01	-1.249E-01	-4.859E-02	1.782E-01	-1.213E-16	2.796E-01	1.000E+00

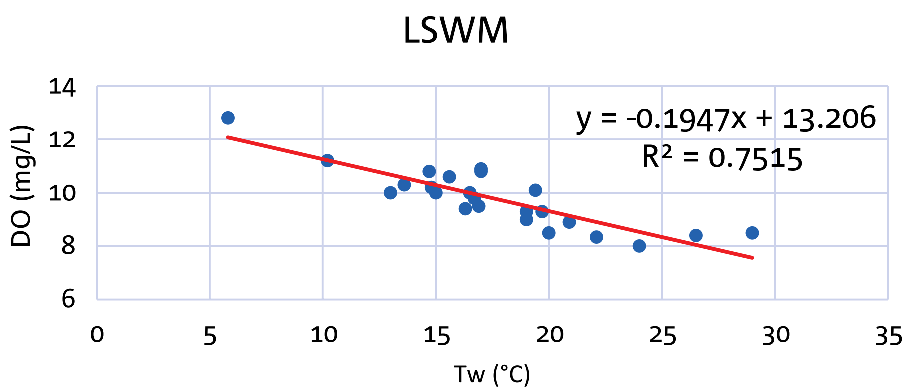

Figure 2 – Dissolved oxygen (DO) vs water temperature (Tw) at LSWM river site

3.5 WQI modeling under climate change

In a previous study, stream water temperature and air temperature relationships were modeled by means of a polynomial neural network (PNN) (El-Jabi et al., 2013). The climate model used in the study was the third generation coupled global climate model (CGCM3.1). The time-slice simulations followed the Intergovernmental Panel on Climate Change (IPCC, 2008; Alcamo et al., 1995) "observed 20th century" 20C3M scenario for years 1970-2000 and the Special Report on Emissions Scenarios (SRES) B1 and A2 for years 2010-2100. Simulated daily minimum, mean and maximum air temperatures for the period 1970-2100 were obtained from Canadian Centre for Climate Modelling and Analysis and downscaled using delta change approach.

Table 6 – 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 (°C)	0.7	1.5	2.1	1.2	2.3	3.7
Ta (°C)	1.2	2.2	2.9	1.2	2.9	5.0

Table 6 shows the averaged water and air temperature increases using emission scenarios B1 and A2 within the Miramichi River area and Table 7 show the increase in air temperature throughout the province of New Brunswick (Turkkan et al., 2011). Results from Table 6 indicate that, during all future periods, the water temperature increases will be in the range of 60%-75% of the increases projected for air temperature. Therefore, water temperature in New Brunswick, for all future time slices (2020's, 2050's or 2080's) and scenarios (B1 or A2), were estimated as:

$$T_w = 0.7\,T_a \tag{3}$$

where T_w, T_a are water and air temperatures, respectively.

Table 7 – Mean air temperature increases (°C) in New Brunswick

	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

It should be noted that the WQI under climate change scenarios were calculated for each site using unchanged future water quality parameters pH, Cond, TP, NH3, NO2, NO3 and SS. The only parameter that are projected to change in the present study are Tw and DO. Changes in order parameters identified above is beyond the scope of the present study.

4. RESULTS AND DISCUSSION

4.1 Water temperature characteristics and relationships

Prior to the modeling, important water temperature characteristics were studied, in particular the thermal regime (i.e., the annual cycle) as well as air to water temperature relations. The first characterization analysis was carried out to study the linear relationship between mean (and maximum) daily air and water temperatures (Caissie et al. 2014).

The computed stream water temperatures under climate change, four models, namely the Genetic programming (GP), the Polynomial Neural Networks (PNN) and two stochastic models were calibrated. These models were calibrated using the data from the Little Southwest Miramichi River. Caissie et al. (2014) showed that all four models showed equally good modeling performances. Because of the consistent results between models, only one model was used to predict river temperature under climate change scenarios. As such, the PNN model was used to predict mean and maximum stream temperature for the Little Southwest Miramichi (LSWM) River, used as control station for future river temperature conditions in New Brunswick (Caissie et al. 2014):

The following equation (from the PNN model) was used for mean stream temperature:

$$\begin{aligned}
T_w(t) &= 0.6480A + 0.4551B - 0.0200B^2 - 0.1361C + 0.0220C^2 \\
A &= -26.87 + 0.3372t - 0.0008t^2 + 0.2854T(t) + 0.0030T(t)^2 + 0.1345T(t-2) \\
&\quad + 0.0060T(t)T(t-2) + 0.0009T(t-2)^2 \\
B &= -33.96 + 0.4287t - 0.0010t^2 - 0.1391Tmn(t) + 0.0010t\,Tmn(i) + 0.4185T(t-1) \\
&\quad - 0.0008t\,T(t-1) + 0.0021Tmn(t)T(t-1) + 0.0070T(t-1)^2 \\
C &= -34.87 + 0.4442t - 0.0010t^2 - 0.0075Tmx(t-1) - 0.0001t\,Tmx(t-1) + 0.0037Tmx(t-1)^2 \\
&\quad + 0.1405T(t-1) + 0.0003t\,T(t-1) + 0.0060Tmx(t-1)T(t-1)
\end{aligned} \tag{4}$$

For maximum stream temperature:

$$\begin{aligned}
T_w^{\max}(t) &= 0.9709A - 0.0735A^2 - 0.3653B + 0.1129AB - 0.0378B^2 + 0.3691C \\
A &= -33.33 + 0.4328t - 0.0010t^2 + 0.2095T(t) + 0.0162T(t)^2 + 0.1880T(t-1) \\
&\quad - 0.0191T(t)T(t-1) + 0.0128T(t-1)^2 \\
B &= -38.91 + 0.4986t - 0.0012t^2 + 0.0501Tmx(t) + 0.0115Tmx(t)^2 - 0.0097Tmx(t-1) \\
&\quad + 0.0002t\,Tmx(t-1) - 0.0118Tmx(t)Tmx(t-1) + 0.0119Tmx(t-1)^2 \\
C &= -33.39 + 0.4267t - 0.0010t^2 + 0.1771T(t-2) - 0.0002t\,T(t-2) + 0.0033T(t-2)^2 \\
&\quad + 0.0792Tmx(t) + 0.0002t\,Tmx(t) + 0.0029T(t-2)Tmx(t) + 0.0059Tmx(t)^2
\end{aligned} \tag{5}$$

where Tw is the stream temperature (mean or max), t is the day of year (100 … 320, e.g., July 1=182), T, Tmx and Tmn are the mean, maximum and minimum air temperatures, respectively.

4.2 Water temperature modeling under climate change

For the climate change study under emission scenarios B1 and A2, only the PNN model was used to predict future water temperature conditions. Result of the climate change analysis showed that the increase in air temperature is projected between 1.2°C and 5.0°C depending on the scenario and time period. The corresponding increase in water temperature was between 0.7°C and 3.7°C (Caissie et al. 2014). The increase in air temperature within the Little Southwest Miramichi River area is expected to be consistent with increases throughout the province of New Brunswick (Turkkan et al. 2011). Accordingly, 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 °C (B1) and 3.7 °C (A2) (Caissie et al. 2014). 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. This is mainly due to evaporative cooling of rivers. The scenario B1 seems to show a more gradual increase whereas the scenario A2 seems to show a high variability over the years.

a) Determination of empirical relationship between Tw and DO

Following the study of increase river temperatures under climate change, the relationship between Tw and DO was studied for each studied rivers. Only DO was selected because the correlation analysis showed that this parameter was the only parameter related to river temperature. Therefore, other quality parameters are projected not to change as a result of increased water temperature. However, other parameters could change as a result of other factors, e.g., increase runoff and soil erosion, etc. As pointed out in Caissie et al. (2014) and from equation 3 (above), each river is projected to increase in water temperature by 0.7 Ta. Therefore, the Tw - DO relationship will be subject to these changes under climate change, i.e., . In the example for the Little Southwest Miramichi River, a very good relationship was observed between DO and river water temperature (Figure 2). The coefficient of determination (R2) was 0.75 and the equation was (DO = -0.1947 Tw + 13.206). As such, for an increase of 2°C in Tw (or 2.9°C Ta) the DO would decrease by 0.4 mg/L. The relationship for all other sites was calculated as the Tw - DO relation is specific to each river and this relationship is required to calculate future water quality index. Then the WQI was calculated for all sites under current and future conditions by both approaches.

b) Status of WQI in NB

Current conditions of water quality in New Brunswick are presented in Table 8, for the time slice 2003-2011 for each site. These results show that the CCME WQI varied between 74.0 (Kennebecasis – Fair conditions) and 93.3 (Kedgwick – Good conditions), such that most NB rivers are in the FAIR to GOOD conditions (Table 8). By the Weighted WQI, values ranged between 88.2 (St. John below St.Basile – GOOD conditions) and 92.2 (Kedgwick – GOOD conditions), showing slightly higher index but less variable than the CCME WQI. On average the WQI for both method are presented in Figure 3. The CCME WQI shows a mean value of 84.0 for the province of New Brunswick whereas the Weighted WQI showed a mean value of 90.6. Clearly the Weighted method show a higher WQI than the CCME, but similar water quality, i.e., GOOD conditions.

Table 8 – WQI values under scenario B1

	CCME method				Weighted method			
River Name	2003-11	2020's	2050's	2080's	2003-11	2020's	2050's	2080's
Aroostook	80.4	79.9	79.8	79.8	90.0	89.6	89.5	89.1
Buctouche	86.8	86.3	86.2	86.2	91.1	90.7	90.5	90.1
Canaan	80.4	79.9	79.9	79.8	90.9	90.5	90.3	89.9
Kedgwick	93.3	92.7	92.7	92.6	92.2	91.8	91.6	91.2
Kennebecasis	74.0	73.6	73.5	73.5	89.7	89.3	89.1	88.7
Lepreau	85.2	84.6	84.6	84.5	88.9	88.5	88.3	87.9
Little SW Miramichi	80.3	79.8	79.8	79.7	90.4	90.0	89.8	89.4
Nashwaak	80.6	80.1	80.0	79.9	91.4	91.0	90.8	90.4
Nepisiguit	80.5	80.0	79.9	79.9	91.2	90.8	90.6	90.2
NW Miramichi	86.7	86.1	86.0	86.0	91.1	90.7	90.5	90.1
Restigouche	93.3	92.8	92.7	92.6	91.8	91.4	91.2	90.8
St. John below Florenceville	79.3	78.8	78.7	78.7	90.8	90.4	90.2	89.8
St. John below St.Basile	78.6	78.1	78.1	78.0	88.2	87.9	87.7	87.3
SW Miramichi	93.1	92.5	92.4	92.3	92.0	91.7	91.5	91.0
St. Croix	86.8	86.2	86.2	86.1	89.0	88.6	88.4	88.0

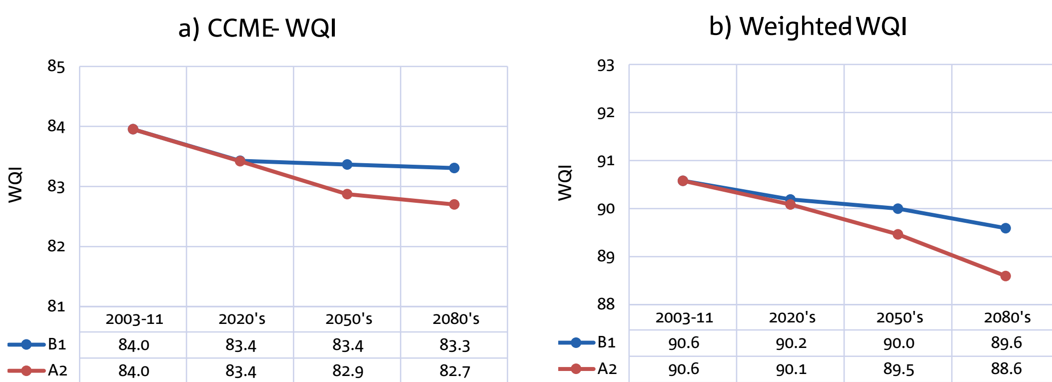

Figure 3 – Averaged WQI decreases in New-Brunswick under B1 & A2 scenarios a) CCME method b) Weighted method

c) Influence of Climatic Change on the WQI

Table 8 and 9 show, for all sites, the future CCME WQI and Weighted Method WQI values under B1 and A2 scenarios. For both methods the WQI was not highly different than during current conditions (section 4.4); however, a slight decrease in WQI is expected in the future. Figure 3 show average future WQI values for New Brunswick using scenarios B1 and A2 for the three future time slices. By the CCME approach, the average WQI for the province of New Brunswick will most likely decrease from 84.0 (current 2003-11) to 83.4 (2020's), 82.9 (2050's) and to 82.7 (2080's) under A2 scenario. Overall, the CCME

Table 9 – WQI values under scenario A2

	CCME method				Weighted method			
River Name	2003-11	2020's	2050's	2080's	2003-11	2020's	2050's	2080's
Aroostook	80.4	79.9	79.4	79.2	90.0	89.5	88.9	88.1
Buctouche	86.8	86.3	85.7	85.5	91.1	90.6	89.9	89.1
Canaan	80.4	79.9	79.4	79.2	90.9	90.4	89.8	88.9
Kedgwick	93.3	92.7	92.1	91.9	92.2	91.7	91.1	90.2
Kennebecasis	74.0	73.6	73.1	72.9	89.7	89.2	88.6	87.7
Lepreau	85.2	84.6	84.1	83.9	88.9	88.4	87.8	87.0
Little SW Miramichi	80.3	79.8	79.3	79.1	90.4	89.9	89.3	88.4
Nashwaak	80.6	80.1	79.5	79.4	91.4	90.9	90.3	89.4
Nepisiguit	80.5	80.0	79.5	79.3	91.2	90.7	90.0	89.2
NW Miramichi	86.7	86.1	85.5	85.4	91.1	90.6	89.9	89.1
Restigouche	93.3	92.7	92.1	91.9	91.8	91.3	90.7	89.8
St. John below Florenceville	79.3	78.8	78.3	78.1	90.8	90.3	89.7	88.8
St. John below St.Basile	78.6	78.1	77.6	77.5	88.2	87.8	87.2	86.3
SW Miramichi	93.1	92.5	91.9	91.7	92.0	91.5	90.9	90.0
St. Croix	86.8	86.2	85.6	85.5	89.0	88.5	87.9	87.0

WQI does not show a significant decrease in the future based on projected increase in air and river temperature under climate change. Under A2 scenario, the average Weighted WQI will most likely decreased from 90.6 (current 2003-11), to 90.1 (2020's), 89.5 (2050's) and 88.6 (2080's), again a decrease that is very small overall.

Somewhat large differences are noted between the two approaches and Figure 4 shows the comparison of both WQI approaches. Figure 4a compares the calculated WQI by CCME method and the Weighted method under B1 whereas Figure 4b compares WQI under the A2 scenarios. The Weighted method generally showed a consistent 7 points higher than the CCME WQI.

d) Conclusion

Climate change impacts within river systems include changes in runoff, river flow and groundwater storage. In addition 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 present study showed that dissolved oxygen (DO) was the only parameter (from the available water quality data in New Brunswick) which was correlated to water temperature. Therefore, a DO – Tw relationship was established for each river in order to predict future water quality index based

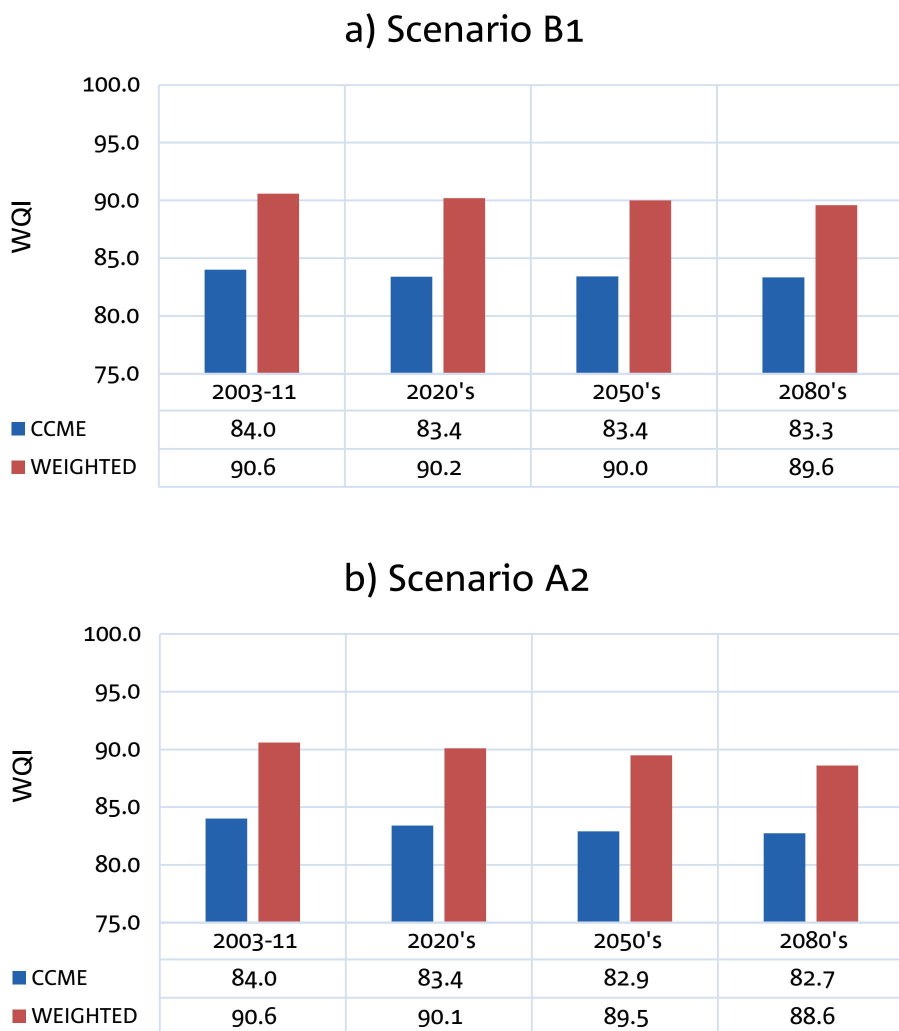

Figure 4 - Comparison of CCME WQI and WEIGHTED WQI using a) scenario B1 b) scenario A2

on both water temperature and dissolved oxygen. The impact of climate change on stream water temperature is highly dependent on the future evolution of air temperature as well as on other meteorological and physical parameters. As air temperature is the parameter that is expected to change most significantly under climate change, as such, water temperature is also expected to be an extremely important parameter. The present study showed that projected air temperature increase of 2-5°C was very consistent across the province of New Brunswick and that the water temperature would most likely increase in the range of 70% of air temperature increase. This information was based on a long-term data analysis at Little Southwest Miramichi River. Therefore, future water temperature was project for each river and corresponding WQI were calculated.

Two methods were used in this study, to calculate the WQI of 15 studied rivers in New Brunswick. The first is the CCME IWQ method and the second is the weighted IWQ method. The values ranged from 74.0 to 93.3 in the case of CCME IWQ method and ranged from 88.2 to 92.2 in the case of weighted-IWQ method. Following the WQI classification for each method, it was observed that most rivers fall within the GOOD water quality conditions during the study period (2003-2011). A few river showed below GOOD conditions and these were the Kennebecasis River (74.0: FAIR), St. John below Florenceville (79.3: FAIR) and St.Basile (78.6: FAIR) under the CCME IWQ method. All rivers were classified as GOOD water quality conditions, under the Weighted IWQ method (all values for this method were over 88). The impact of Climate Change on the IWQ, using scenarios B1 and A2, will most likely have little impact on the water quality conditions based on the criteria used on the present study for drinking water quality (Tables 8 and 9).

In conclusion the water quality in New Brunswick Rivers is not project to deteriorate significantly under climate change (from a drinking water perspective) based on the two methods and criteria used in the present study. Nevertheless, it should be pointed out that the present study makes the assumption that other water quality parameters will remain constant in the future under climate change (SS, pH, Cond, etc.; Table 5). However, climate change may results in these parameters changing by other processes. For instance, if climate change increases runoff, it is very likely that some parameters, particular those related to soil erosion, will also change in the future. In addition, the present study dealt with drinking water quality parameters and criteria. If the water quality was studied for other purposes, e.g. aquatic habitat conditions, the selected criteria as well as thresholds would be very different than the one used in the present study. Under these conditions it is very likely that the results would be different. For instance, a good body of research is showing that from an aquatic habitat perspective, some New Brunswick river (e.g., Miramichi River) are currently experiencing close to lethal water temperatures (30°C) in summer. Such high temperatures may not have a great influence on drinking water quality, but may have a significant impact on Atlantic salmon population as well as for other coldwater species.

AKNOWLEGMENTS

This study was funded by the New Brunswick Environmental Trust Fund. The authors remain thankful to M. Darryl Pupek and his team at the Department of Environment New Brunswick for helpful comments.

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Water Quality Index Under Climate Change Impact

MARCH 2014