Scientific Research

# Water Quality Index Assessment under Climate Change

## Nassir El-Jabi[1], Daniel Caissie[2], Noyan Turkkan[1]

[1]Department of Civil Engineering, Université de Moncton, Moncton, Canada
[2]Department of Fisheries and Oceans Canada, Moncton, Canada
Email: nassir.el-jabi@umoncton.ca

## Abstract

**Surface water quality may change in the future due to climatic variability 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 were extracted from the Canadian Coupled General Climate Model (CGCM 3.1/ T63) under the greenhouse emission scenarios B1 and A2, as defined by the Intergovernmental Panel on Climate Change (IPCC). This study illustrates the usefulness of the stream temperature models, coupled with Climate Change Scenarios to predict the evolution of future stream water temperature regimes and associated biogeochemical water quality parameters pertaining to drinking water quality. The specific objectives of the present study were to analyze the surface water quality of 15 rivers in New Brunswick (Canada) on the basis of 9 parameters under climate change. 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 river thermal regimes and climate change impact on water quality related to Drinking Surface Water.**

## Keywords

## 1. Introduction

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 [1]. As air temperature is the parameter that is expected to change most significantly under climate change; therefore, stream temperature is also expected to be an extremely important parameter.

The 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 methods. Poole and Berman [2] 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 will ultimately modify water temperature variability along river reaches.

According to Caissie [3] the main drivers or factors influencing stream temperatures can be classified into: atmospheric conditions, topography, stream discharge, and riverbed thermal fluxes. This study showed that 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 size of the river and these mainly include the heat conduction at riverbed and the contribution of groundwater flow.

In eastern Canada, the air temperature is expected to increase by 2˚C to 6˚C in the next 100 years [4]. 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 [5]. Many studies have looked at the impact of climate change on river water temperatures [6]. However, the impact of climate change is difficult to predict due to a lack of long-term water temperature data [7]. Climate change was shown to affect water quality, potentially violating the Safe Drinking Water Act regulations [8]. Many studies have shown a decline in stream water quality under a climate change scenario [9]-[12], but very few have focused on the impact of drinking water quality. 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 [13]. 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 [14]. Water quantity changes due to climate change have been identified as a water quality related threat to sources of drinking water [15]. In Canada, 288 outbreaks of infectious disease were linked to a drinking water source between 1974 and 2001 [16].

Flow variability was found to deteriorate water quality in general [17]-[20]. 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 [5]. Kundzewick and Krysanova [21] 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 [22] [23]. In regions where water availability is likely to decrease, water managers will need to ensure adequate water supplies, such as building new storage reservoirs or using alternative water sources [24]. Low water availability could lead to groundwater over-exploitation, creating the need to

pump water from deeper sources at higher costs [5].

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. The Canadian Council of Ministers of the Environment Water Quality Index (CCME-WQI) as well as the Weighted Water Quality Index could be used in Canada. As such, the present paper will focus on water quality indices in New Brunswick (Canada) applied to drinking water quality and how such indices many be affected by climate change.

## 2. Methods

### 2.1. Water Quality Index

A Water Quality Index (WQI) 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. To calculate a WQI, the body of water, time period, variables and the objectives need 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 [25]. 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 [26]. 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 [27]. CCME [25] recommends that CCME WQI should not be run with less than four parameters and four sampling visits per year, but they do not set a maximum number of variables. CCME [27] 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 [28] [29]. In this study the *CCME WQI Method* and the *WQI Weighted Method* were considered for the calculation of the WQI. These two WQI will then be applied on 15 stations across the province of New Brunswick. The monthly values for 9 water quality-related parameters for the period 2003-2011 were obtained from New Brunswick Department of the Environment. These parameters included: dissolved oxygen (DO), conductivity (Cond), pH, total phosphorus (TP), water temperature ($T_w$), ammonia ($NH_3$), nitrite ($NO_2$), nitrate ($NO_3$) and suspended solids (SS).

### 2.2. CCME-WQI Method

The Canadian Council of Ministers of the Environment (CCME) Water Quality Index (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 [30]. The CCME WQI relies on measures of three factors [25]:

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 1**).

**Table 2** shows the objectives or thresholds required for a good water quality index used the by CCME WQI.

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

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

where

**Table 1.** Categorization of the WQI CCME and WQI Weighted Methods.

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

**Table 2.** Variables and objectives used with CCME method.

| Variables | | Objectives |
|---|---|---|
| Dissolved Oxygen—DO (mg/l) | > | 5.5 |
| pH | <> | 6.5-9 |
| Total Phosphorus—TP (mg/l) | < | 0.05 |
| Conductivity—Cond (μS/cm) | < | 500 |
| Water temperature—$T_w$ (°C) | < | 15 |
| Ammonia—$NH_3$ (mg/L) | < | 0.05 |
| Nitrite—$NO_2$ (mg/L) | < | 3.2 |
| Nitrate—$NO_3$ (mg/L) | < | 45 |
| Suspended Solids—SS (mg/L) | < | 20 |

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

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

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

$$\text{nse} = \frac{\sum_{i=1}^{n} \text{excursion}_i}{\#\text{of tests}}$$

$$\text{excursion}_i = \frac{\text{Failed Test Value}_i}{\text{Objective}_j} - 1 \quad (\text{Test Value} < \text{Objective})$$

$$\text{excursion}_i = \frac{\text{Objective}_j}{\text{Failed Test Value}_i} - 1 \quad (\text{Test Value} > \text{Objective})$$

## 2.3. WQI Weighted Method

In this widely used method, the WQI is calculated as the weighted sum of the different sub index scores [31] [32]. The individual parameter scores are aggregated into a final index value (between 0 and 100).

The following empirical equation was used for the determination of the WQI [31]-[33]:

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

where $C_i$ is the normalized value of the parameters and $P_i$ is the relative weight of each parameter in term of its importance for aquatic life and drinking water. The parameter $P_i$ 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 ($T_w$). Also, the minimum value assigned to parameters with minor relevance is the value of 1. **Table 3** 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 1**). As such, the index will provide an indication if the water quality is fair, good, etc.

## 2.4. Study Area

The study area consists of 15 rivers in New Brunswick as shown in **Figure 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.

## 2.5. WQI Modeling under Climate Change

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 [5] [34] "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. Water temperatures were then obtained through modeling using these air temperature data [1].

**Table 3.** Relative weights ($P_i$) and normalized values ($C_i$) 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 |
| $T_w$ (˚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 |

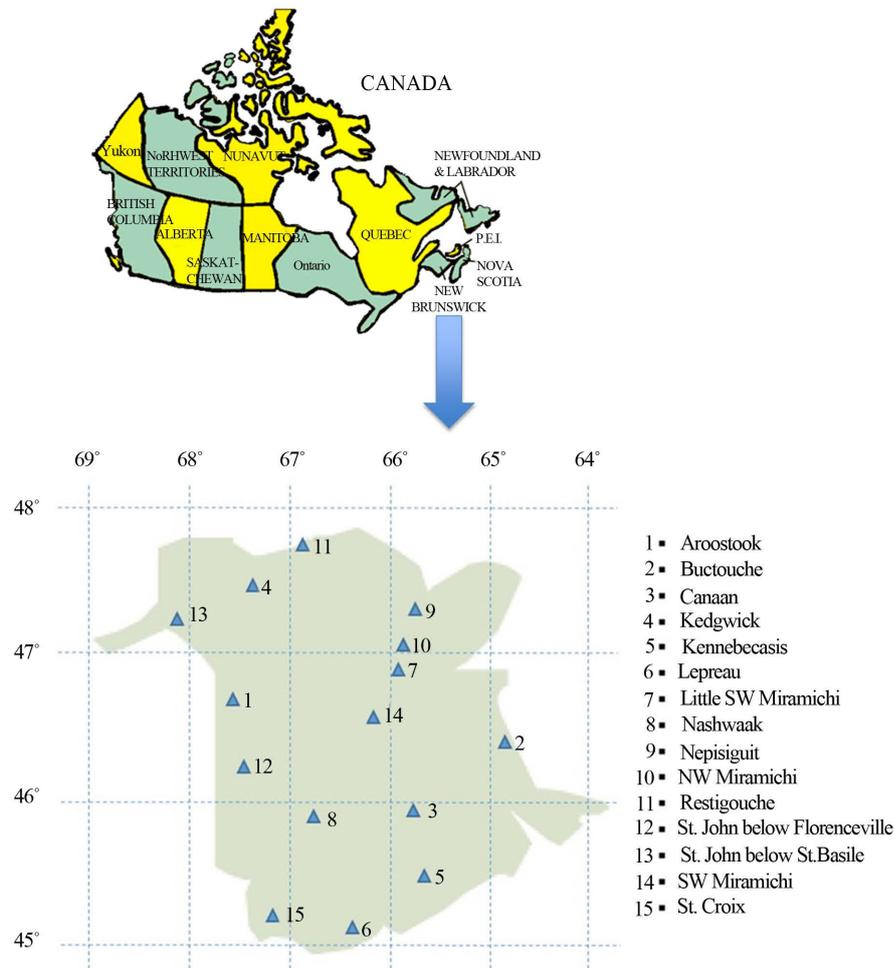**Figure 1.** Locations of studied stations in New Brunswick (Canada).

## 3. Results and Discussion

**Table 4** shows results of the averaged water and air temperature increases using emission scenarios B1 and A2 at Doaktown (air) and for the Little Southwest Miramichi River (LSWM River). Over the next 30 years (2010-2039), 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 2070-2099 compared to current climate conditions (1970-1999), with an increase of 2.1˚C (B1) and 3.7˚C (A2) [1]. Results from Little Southwest Miramichi River (**Table 4**) 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. 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. 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:

$$T_w = 0.7 T_a \qquad (3)$$

where $T_w, T_a$ are water and air temperatures, respectively. The projected increases in water temperature were then applied for each of the 15 sites, as similar increases are expected throughout the province [35].

It should be noted that the WQI under climate change scenarios were calculated for each site using unchanged future water quality parameters for pH, Cond, TP, $NH_3$, $NO_2$, $NO_3$ and SS. The only parameter that are projected

**Table 4.** Averaged air temperature ($T_a$) increases at Doaktown and averaged stream water temperature ($T_w$) increases at LSWM River.

|  | Scenario B1 | | | Scenario A2 | | |
|---|---|---|---|---|---|---|
|  | 2010-2039 | 2040-2069 | 2070-2099 | 2010-2039 | 2040-2069 | 2070-2099 |
| $T_w$ (˚C) | 0.7 | 1.5 | 2.1 | 1.2 | 2.3 | 3.7 |
| $T_a$ (˚C) | 1.2 | 2.2 | 2.9 | 1.2 | 2.9 | 5.0 |

to change in the present study are $T_w$ and DO. Changes in other parameters identified above are beyond the scope of the present study.

Following the study of increase river temperatures under climate change the relationship between $T_w$ 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.* [1] and from equation 3 (above), each river is projected to increase in water temperature by 0.7 $T_a$. Therefore, the $T_w$-*DO* relationship will be subject to these changes under climate change, *i.e.*, $DO = f\left(0.7T_a\right)$. As such, for an increase of 2˚C in $T_w$ (or 2.9˚C $T_a$) the *DO* would decrease by 0.4 mg/L. The relationship for all other sites was calculated as the $T_w$-*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.

For both methods the WQI was not highly different than during current conditions; however, a slight decrease in WQI is expected in the future under A2 scenario. Overall, the CCME 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 Weighted WQI will most likely decreased from 90.6 (current 2003-2011), 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 2** shows the comparison of both WQI approaches. **Figure 2(a)** compares the calculated WQI by CCME method and the weighted method under B1 whereas **Figure 2(b)** compares WQI under the A2 scenarios. The Weighted method generally showed a consistent 7 points higher than the CCME WQI.

## 4. 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. With respect to biogeochemical water quality, most climate change impacts can be attributed to changes in stream water temperature. 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. The present study showed that projected air temperature increase of 2˚C - 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 and modeling analysis at Little Southwest Miramichi River. These changes will have an impact on dissolved oxygen concentrations and instream biological activities. 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 $T_w$-DO relationship was established for each river in order to predict future water quality index based on both water temperature and dissolved oxygen. Therefore, future water temperature was project for each river and corresponding WQI were calculated. The present study concluded that the water quality in New Brunswick Rivers was not projected 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. However, climate change may results in these parameters changing by other processes that increased air temperature. 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,
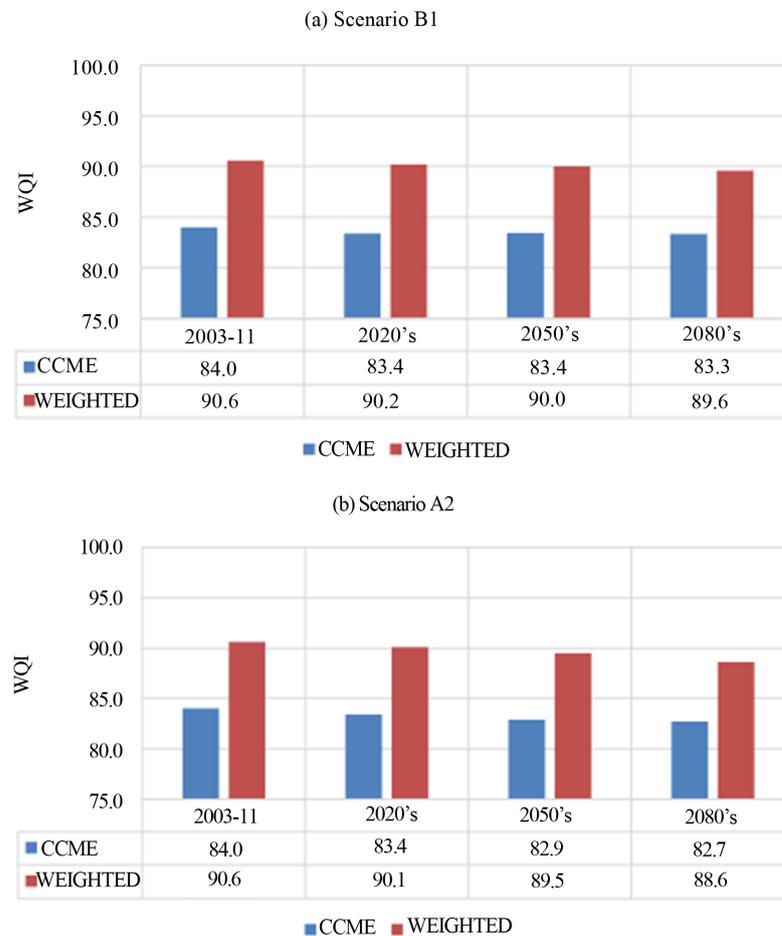
(a) Scenario B1



| | 2003-11 | 2020's | 2050's | 2080's |
|---|---|---|---|---|
| CCME | 84.0 | 83.4 | 83.4 | 83.3 |
| WEIGHTED | 90.6 | 90.2 | 90.0 | 89.6 |

(b) Scenario A2



| | 2003-11 | 2020's | 2050's | 2080's |
|---|---|---|---|---|
| CCME | 84.0 | 83.4 | 82.9 | 82.7 |
| WEIGHTED | 90.6 | 90.1 | 89.5 | 88.6 |

**Figure 2.** Comparison of CCME WQI and WEIGHTED WQI using a) scenario B1 b) scenario A2.

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 rivers 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.

## Acknowledgements

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