FINAL REPORT

Climate Change Impacts and Adaptation Program
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CLIMATE CHANGE IMPACTS ON LOW FLOW CHARACTERISTICS OF NEW BRUNSWICK RIVERS AND ADAPTATION STRATEGIES FOR INSTREAM FLOW NEEDS

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1.0 INTRODUCTION

The conflict between the ever-increasing demand for water withdrawal from rivers (i.e. irrigation, drinking water, aquatic habitat protection, etc.) and water availability during drought and low flow periods is a recurring problem in water resources management. Low flow events are also known to limit available fish habitat and in some severe conditions can also prevent the connectivity between habitats (Lake 2003). Competition between water abstraction and instream flow needs (minimum flow for river protection) will undoubtedly increase in the near future given the projected reduction under climate change (Hengeveld 1990, Minns et al. 1995). Presently, over 50% of total accessible runoff world wide is being used and in the next 25 years this will increase over 70% (Postel et al. 1996). In the 1990s, many rivers in eastern Canada experienced record low flow conditions coupled with record high water temperatures (Caissie 1999a; Caissie 2000). Increased water demand and low flow occurrence are factors that need to be considered when establishing instream flow requirements or minimum flows to protect aquatic habitat. During, recent years of drought conditions, an increase in water withdrawal demand (offstream use), especially for irrigation, was observed in the province of New Brunswick. Instream flow protection methods as well as a good knowledge of low flow characteristics, including long-term trends, are the primary and essential tools used during environmental impact assessment to evaluate the level of protection required for habitat under reduced flow in rivers (Caissie and El-Jabi 1995).

The vulnerability of water to resources to climate change impacts is highly dependent on the adaptation of the water management systems to changing hydro-climatic conditions and on the capacity of rivers to sustain water demands under low flow conditions. Existing thresholds for instream flow protection (minimum flows) need to be revised for the protection of aquatic life under a projected warmer climate in Atlantic Canada and elsewhere. Alternatively, instream flow requirements will need to adapt under climate change and the current level of instream flow protection needs evaluation. Such evaluation is only possible with a good knowledge of water resource / aquatic resource response to climate change.

Instream flow protection and low flows are highly linked in both water resources management and planning as well as in aquatic impact assessment. The economic impact of a varied level of protection for instream flow needs is determined by offstream water availability and use. Unlike some western US rivers, which have been almost dried up due to offstream water availability and use (Postel et al. 1998), natural flow conditions still exist in most Canadian rivers, especially in New Brunswick. Any research results in relation to climate change impacts on instream flow and low flow of these natural river systems, or any adaptation measures, will enable Canadians to better understand the complex issues and relations between water usage by humans and instream flow needs for aquatic resources.

1.1 Objectives

The objectives of this study were to:

i) evaluate and report low flow characteristics in New Brunswick (NB) and associated long-term trends using hydrometric data;

ii) quantify potential climate change impacts, using GCM (Global Coupled Model) projections, on runoff disturbance (McCarthy et al. 2001), low flows, water availability and aquatic resources in New Brunswick;

iii) based on projected climate change in Atlantic Canada, identify potential impacts of reduced flow on water usage, including impacts on irrigation, drinking water supply and industrial water usage;

iv) determine sensitive areas within the province with increased demand for water usage (e.g. irrigation, municipal and industrial demands) and of potential conflict with instream flow requirements (e.g. aquatic habitat protection);

v) determine new thresholds for instream flow and for the protection of river ecology in general, based on projected flow availability and climate change (McCarty et al. 2001);

vi) inform the general and professional public of the potential impacts of climate change on low flows and water usage in New Brunswick by producing project reports and other deliverables.

Objective v) was not completed in the scope of this project and is ongoing. The remaining objectives were achieved by dividing the project into three sub-sections. The first part was to characterize low flow in New Brunswick. The low flow frequency analysis was carried out using two different methods. The most widely applied of the methods is the statistical analysis, also know as the minimum annual series, and consists of analyzing the annual extreme low flow events. However, this approach of low flow analysis is not suitable when characteristics such as low flow duration, volume and magnitude are important. Therefore, the Deficit Below Threshold method was also applied.

Second, long term-trends and climate change impacts on low flows were identified. Long-term temperature, precipitation and discharge trends were identified for 7 sites in New Brunswick. Climate scenarios including temperature, precipitation and discharge were also developed for 7 sites in New Brunswick. Based on these scenarios, potential impacts of reduced flows on water usage, including impacts on irrigation, drinking water supply and industrial water usage were identified.

The third section objectives were to link water use and adaptation strategies under climate change. To achieve this, an offstream water use in New Brunswick report was prepared. A meeting of water resource professionals, environmental specialists and climatic change experts was organized to develop adaptation strategies under climate change.

2.0 LOW FLOW CHARACTERIZATION

Hydrologic data constitutes the basis of information used by hydrologists to make predictions of low flow events and frequencies. The probabilistic approach is useful in the analysis due to the random nature of the low flow events and the flexibility of this approach in characterizing low flow events. Such analysis of hydrologic data, also called a low flow frequency analysis, can be carried out following one of two methods. The first method, which has been widely applied in low flow studies, consists of analyzing the annual extreme low flow events (i.e. the annual minimums). When applied to river flows, this method considers only the most severe low flow event within a given time period, often chosen annually or by season. This classic approach of low flow analysis is not suitable when characteristics such as low flow duration, volume and magnitude are important. Also, the annual minimum flow time series eliminates secondary low flow events within a year/season, which results in a loss of valuable information. To remedy the situation and to better characterize low flow in terms of duration, volume and intensity, a second approach can be applied. This approach considers all low flow below a certain threshold, also called a partial duration series or Deficit Below Threshold (DBT) (Ashkar et al. 1998). The Deficit Below Threshold approach has not only the advantage of better characterizing low flow events (e.g. duration, volume, etc.), it also considers many low flow events during specific year/season not considered by the annual minimum approach, which considers only one event per year.

Data was gathered for 31 hydrometric stations across New Brunswick based on years of record and data quality. The characteristics of low flow for different recurrence intervals were determined using both the annual minimum series and the DBT approaches. Quantifying low flows in terms of intensity, duration and volume deficit (i.e. DBT) is becoming very important in both water resources an aquatic management. In fact, not only intensity of low flow has been shown to be important to aquatic habitats, the duration of low flow events has been observed to be equally important (e.g. stress to fish). Also, these low flow events have been of longer duration in the 1990s under low flow conditions (Caissie 1999b).

Following the characterization of low flows by station, a regionalization of low flow in New Brunswick was performed. Low flow characteristics were applied for the entire Province of New Brunswick (i.e. the province considered as a homogeneous region). The procedure of regionalization is a standard and prerequisite hydrologic method for adequate representation of low flows for a specific region. The majority of regional low flow frequency studies reported in the literature have been carried out using the annual minimum series approach, and very few studies have used the DBT approach (El-Jabi et al. 1998). Therefore, this regional study, using both the annual minimum series and the DBT approach, resulted in a better characterization of low flows in NB.

2.1 Data and Methodology used

2.1.1 Station data

Hydrometric stations in New Brunswick were selected for the low flow analysis using Environment Canada's hydrometric station database (HYDAT) based on years of record and data quality. The following criteria were used: (i) natural flow at the gauging station, (ii) a time series of at least 20 years, and (iii) station in operation in the year 2000. The 31 selected stations represent all areas of the province with the exception of north central New Brunswick (Fig. 1). These stations have an average drainage area of 1576 ± 526 km^2 (mean ± 1 SE). Table 1 provides a summary of the selected stations, station identification, latitude, longitude and the years used in the analysis. Daily river flows for each station were used for the analysis.

2.1.2 Annual minimum series method

At each station, the annual (January 1 - December 31) average minimum daily flow for 1, 7, and 14-day duration were fitted using a Type III Extremal (Weibull) distribution in order to assess low flows for recurrence periods of 2, 10, 20, and 50 years (Kite, 1988). Three methods of parameter estimation were used: the method of moments, the method of smallest observed drought (Kite, 1988), and the method of maximum likelihood.

The cumulative distribution function is described as:

$$P(x) = e^{-\left(\frac{x-\gamma}{\beta-\gamma}\right)^{\alpha}} \qquad [1]$$

and the probability density function is written as :

$$p(x) = \frac{\alpha}{(\beta-\gamma)}\left\{\frac{x-\gamma}{\beta-\gamma}\right\}^{(\alpha-1)} e^{-\left\{\frac{x-\gamma}{\beta-\gamma}\right\}^{\alpha}} \qquad [2]$$

where :

α = shape parameter.

β = characteristic drought.

γ = lower limit to x.

If $\gamma = 0$ in the Weibull distribution, the lower limit to x is zero.

The parameters of the type III extremal distribution can be estimated by different methods including the method of moments. The general equation for calculating the n^th^ moment about the origin of a distribution is given by:

$$\mu'_n = \int_{-\infty}^{\infty} x^n p(x) dx \qquad [3]$$

This equation calculates the first moment about the origin of the distribution to estimate the parameters of the distribution. In this particular study the method of moments was used to estimate the parameters based on Kite (1988).

2.1.3 Deficit Below Threshold method

The Deficit Below Threshold (DBT) or partial duration series analysis, is the stochastic analysis of low flow series below a certain threshold, Q_R. This method characterizes low flow in terms of duration, volume and magnitude and can consider many low flow events during a specific time period.

For the low flow analysis, events were characterized in terms of duration (T), volume (D) and magnitude or intensity (I). Figure 2 shows the following characteristics of a low flow event ν: the reference value Q_R (m^3/s), the duration T_ν (days) i.e. number of consecutive days for which the flow is below the reference value, the volume D_ν (m^3/s*days) i.e. cumulative deficit of streamflow for the duration, the intensity I_ν (m^3/s) i.e. the maximum flow deficit, the time of the beginning of the event $\tau_b(\nu)$ and the time of the end of the event $\tau_e(\nu)$.

Some of the low flow events may be close to each other and therefore mutually dependent. To avoid the dependency between events from a practical point of view, three simplifying assumptions were made based on Zelenhasic and Salvai (1987):

(i) very minor low-flow events with volumes D_i (i=1,2…) satisfying the following inequality $D_i < 0.005 \max D_{rec}$ (i=1,2…), where $\max D_{rec}$ is the maximum observed volume deficit, were neglected because these events are insignificant compared to severe low-flow events with respect to volume;

(ii) for the remaining events, it was possible that the time period between two events $\Delta T_{\nu,\nu+1}$ is relatively short. In the case where $\Delta T_{\nu,\nu+1} \leq 6$ days, the events E_ν and $E_{\nu+1}$ can be assumed mutually dependent and the volume and duration become the following

$$D_\nu' = D_\nu + D_{\nu+1}, \text{ and} \quad [4]$$

$$T_\nu' = T_\nu + \Delta T_{\nu,\nu+1} + T_{\nu+1}\,; \quad [5]$$

(iii) it was possible a low-flow event begins in one year and ends in the following year. The time of occurrence of the event was then calculated as $\tau = \frac{1}{2}(\tau_b + \tau_e)$ and the event was placed in the year that τ belongs to.

The threshold value or the river-flow reference value (Q_R) was chosen as the median monthly flow (Q_{50}) for August (i.e. 50th percentile of August daily river flows classified in descending order). This threshold, also referred to as the Aquatic Base Flow, has been used as a minimum flow in instream flow evaluation. The threshold value for each station was determined using Atlantic Canada Flow Analysis Software Version 1.0, ACFA 1.0 (Université de Moncton 1994). All low flow events below this threshold were identified for the period of analysis using in-house software.

Univariate analysis

Once the low flow events were identified, the volume, duration and intensity data were fitted by a probability distribution function. Three different distribution functions were investigated: the exponential distribution, the generalized Pareto distribution and the Weibull distribution. The exponential and generalized Pareto distributions were chosen because they have been widely used in the study of extreme hydrological phenomena such as floods (Todorovic, 1978; Cunnane, 1979; North, 1980; Ashkar and Rousselle, 1981; Davidson and Smith, 1990; Madsen et al., 1997). The Weibull distribution was chosen because it has been widely applied for studying minimal extremes or low flows.

For the exponential distribution, the cumulative distribution function (cdf) of the variable X representing the volume, duration or intensity is given by:

$$H(x) = 1 - \exp\left(-\frac{x}{\alpha}\right) \qquad [6]$$

where α is a scale parameter. For the largest duration, volume or intensity in a time interval [0,t], which we shall denote by X_G, the distribution function is given by:

$$F(x_G) = \exp\left[-\Lambda(t)\exp\left(-\frac{x_G}{\alpha}\right)\right] \qquad [7]$$

where $\Lambda(t)$ is the average number of low-flow events in the interval [0,t] .

For the generalized Pareto distribution, the cdf of X is given by:

$$H(x) = 1 - \left(1 - k\frac{x}{\alpha}\right)^{\frac{1}{k}}, \; k \neq 0 \qquad [8]$$

where $\alpha > 0$ is a scale parameter and k is a shape parameter. The maximum volume, duration or intensity $\chi(t)$ in a time interval [0,t] in this case follows a generalized extreme value distribution, which has the following distribution function (Rosbjerg et al. 1992):

$$F(x_G) = \exp\left[-\Lambda(t)\left(1 - \frac{kx_G}{\alpha}\right)^{\frac{1}{k}}\right] \qquad [9]$$

For the Weibull distribution, the cdf of X is given by:

$$H(x) = 1 - \exp\left[-\left(\frac{x-b}{m-b}\right)^{n}\right] \qquad [10]$$

For the largest volume, duration or intensity in the interval [0,t], the distribution function is as follows:

$$F(x_G) = \exp\left\{-\Lambda(t)\exp\left[-\left(\frac{x-b}{m-b}\right)^{n}\right]\right\} \qquad [11]$$

More detailed information is presented in Low flow characterization in New Brunswick using the Deficit Below Threshold approach (Savoie et al. 2004).

Bivariate analysis

When the joint occurrence of two or more variables is involved, the frequency analysis of these variables can be based on their joint probability distribution (bivariate or multivariate). It is possible to develop bivariate distributions with the Singh-Singh method or the Nagao-Kadoya method as outlined in Ashkar et al. (1998). In the present study, only the Nagao-Kadoya method was used because of the high correlation between variables.

A bivariate distribution with exponential marginals can easily be obtained from a bivariate distribution with gamma-distributed marginals, by equating the shape parameters of the gamma marginals to 1. A practical bivariate density with gamma marginals has been presented by Nagao and Kadoya (1971), from which a bivariate density with exponential marginals takes the following form:

$$f(x_1, x_2) = \frac{\lambda_1\lambda_2}{(1-\rho)} \exp\left\{-\frac{\lambda_1 x_1}{(1-\rho)} - \frac{\lambda_2 x_2}{(1-\rho)}\right\} I_0\left(2\frac{\sqrt{\rho}}{1-\rho}\sqrt{x_1 x_2 \lambda_1 \lambda_2}\right) \qquad [12]$$

where X_1 and X_2 are random variables with exponential marginals of parameter λ_1 and λ_2 respectively, and I_0 is the modified Bessel function with argument 0, which can be expressed as:

$$I_0\left(2\frac{\sqrt{\rho}}{1-\rho}\sqrt{\lambda_1\lambda_2 x_1 x_2}\right) = \sum_{j=0}^{\infty}\left[\frac{\rho\lambda_1\lambda_2 x_1 x_2}{(1-\rho)^2}\right]^j \frac{1}{(j!)^2} \qquad [13]$$

In this equation, ρ measures the correlation between the random variables X_1 and X_2. The equation representing the density of the variable X_1 conditioned by $X_2 = x_2$ is:

$$f(x_1 \mid x_2) = \frac{\lambda_1}{(1-\rho)} \exp\left\{-\frac{\lambda_1 x_1}{(1-\rho)} - \frac{\rho\lambda_2 x_2}{(1-\rho)}\right\} I_0\left(\frac{2\sqrt{\rho}}{1-\rho}\sqrt{\lambda_1\lambda_2 x_1 x_2}\right) \qquad [14]$$

When the variables X_1 and X_2 are standardized, i.e. divided by their means, the following conditional cdf is obtained:

$$F(\xi \mid \eta) = \int_0^{\xi} f(\xi \mid \eta)\, d\xi = \frac{1}{1-\rho}\exp\left(\frac{\rho\eta}{1-\rho}\right)\int_0^{\xi}\exp\left(-\frac{\xi}{1-\rho}\right) I_0\left(\frac{2\sqrt{\rho}}{1-\rho}\sqrt{\xi\eta}\right) d\xi \qquad [15]$$

where ξ and η correspond to the standardized values of X_1 and X_2, respectively. The integral in [15] can be calculated by a numerical approach, such as by the trapezoidal method (Ashkar et al. 1998).

Consider a pair of random variables (Y_1, Y_2) with the joint pdf (Ashkar and Bayentin 2001):

$$g(y_1, y_2) = \frac{1}{1-\rho} \exp\left(\frac{y_1 + y_2}{1-\rho}\right) \; I_0\left(\frac{2\sqrt{\rho y_1 y_2}}{1-\rho}\right) \qquad [16]$$

To obtain a bivariate distribution with Weibull marginals for (X_1, X_2), the following procedure can be applied.

A pair of random variables (Y_1, Y_2) is considered with the joint pdf [16], and the following variable transformations:

$$X_1 = \frac{(Y_1)^{\frac{1}{s_1}}}{\alpha_1} = u_1(Y_1) \qquad [17]$$

$$X_2 = \frac{(Y_2)^{\frac{1}{s_2}}}{\alpha_2} = u_2(Y_2) \qquad [18]$$

Solving for the Y_i's gives:

$$Y_1 = (\alpha_1 X_1)^{s_1} = w_1(X_1) \qquad [19]$$

$$Y_2 = (\alpha_2 X_2)^{s_2} = w_2(X_2) \qquad [20]$$

The joint pdf of X_1 and X_2 is obtained as:

$$f(x_1, x_2) = g[w_1(x_1), w_2(x_2)] \mid J \mid \qquad [21]$$

where $\mid J \mid$, the Jacobian of the transformation, is given by

$$\mid J \mid = \left| w_1'(x_1) \bullet \; w_2'(x_2) \right| \qquad [22]$$

where $w_1'(x_1) = \alpha_1 - k_1 x_1$ and $w_2'(x_2) = \alpha_2 - k_2 x_2$.

The conditional pdf's and cdf's are developed as follows:

$$f\left(x_1 \mid x_2\right) = \frac{f\left(x_1, x_2\right)}{f_2\left(x_2\right)} \qquad [23]$$

where $f_2\left(x_2\right) = \alpha e^{-(\alpha x)^s} (\alpha x)^{s-1}$, and

$$F_1\left(x_1 \mid x_2\right) = \int_{-\infty}^{x_1} f_1\left(x_1 \mid x_2\right)\ dx_1 \qquad [24]$$

which is equivalent to

$$F\left(x_1 \middle| x_2\right) = \int_{-\infty}^{y_1} g_1\ \left(y_1 \middle| y_2\right)\ dy_1 = \int_{-\infty}^{w_1(x_1)} g_1\ \left[y_1 \middle| y_2 = w_2\left(x_2\right)\right]\ dy_1 \qquad [25]$$

where

$$g_1\left(y_1 \middle| y_2\right) = \frac{g\left(y_1, y_2\right)}{g_2\left(y_2\right)} = e^{y_2} g\left(y_1, y_2\right) \qquad [26]$$

Finally, the joint cdf is given by:

$$F\left(x_1, x_2\right) = \int_{-\infty}^{x_1}\int_{-\infty}^{x_1} f\ \left(x_1, x_2\right) dx_1\ dx_2 \qquad [27]$$

which is equivalent to

$$F\left(x_1, x_2\right) = \int_{-\infty}^{w_2(x_2)} \int_{-\infty}^{w_1(x_1)} g\ \left[u_1\ \left(y_1\right), u_2\ \left(y_2\right)\right] dy_1\ dy_2 \qquad [28]$$

For more details, please refer to Savoie et al. (2004)

2.2 Results and Discussion

2.2.1 Annual minimum series method

The program “Frequency Analysis of Maxima or Minima” (Kite 1988) was used for the analysis of each station. Not all parameter estimation methods converged for every station. Therefore, the method of moments was used throughout the analysis because this method did not have a convergence problem, and it provided results similar to the other estimation methods. Low flows of 1, 7, and 14 days duration at recurrence periods of 2, 10, 20, and 50 years are presented in Tables 2-4. Due to extremely low water conditions at a few stations, the program did not provide any results for them (in particular for station 01AK006, 01AL004 and 01AM001 for higher return low flows). Also, depending on the duration (1-day, 7-day, and 14-day), other stations had to be eliminated from the analysis due to extreme low flows not representative of the general low flow conditions (01AK007 and 01AQ001 for the 1-day low flows and 01AK007 for the 7-day low flows).

2.2.2 Deficit Below Threshold method

Low flow events were identified for the 31 selected stations following the DBT method. The years of data used for each station is indicated in Table 1. The number of low flow events below the threshold value that were identified for each station ranged from 42 to 178. Table 5 gives a summary of the threshold values (Q_R) and the number of low flow events identified for each station.

Univariate analysis

The volume, duration and intensity as well as the maximum volume, maximum duration and maximum intensity were modeled with the exponential, generalized Pareto and Weibull distribution. For the observed distribution, the data was divided into 12 to 16 classes. To evaluate the goodness of fit, Kolmogorov-Smirnov tests accompanied by graphical representations were used. For example, at station 01BU002, the best fit was from the generalized Pareto for the volume and duration and from the Weibull distribution for the intensity.

Table 6 gives a summary of the best fitted distributions H(x) for volume, duration and intensity for the 31 stations. For volume, no distribution fitted the data for station 01BU003. For duration, no distribution fitted the data for station 01AD002. For intensity, no distribution fitted the data for stations 01AJ003 and 01BO001.

The annual maximum volume, maximum duration and maximum intensity were modeled as well. For station 01BU002, the best-fitted distribution for the maximum volume, maximum duration and maximum intensity was the Weibull distribution. Figures 3, 4 and 5 show the graphical representation of the best-fitted theoretical and observed distributions for station 01BU002.

Table 7 gives a summary of the best fitted distributions F(x) for the largest volume, largest duration and largest intensity on an annual basis. For volume, no fit was found for one station (i.e., 01AQ001). For intensity, no fit was found for stations 01AD003, 01AQ001 and 01BV006.

The volume, duration and intensity for recurrence intervals of T years were calculated using the following equation:

$$T = \frac{1}{1 - F(x)} \qquad [29]$$

The distribution function F(x) to calculate low flow characteristics used was based on the best fitted distribution (exponential, generalized Pareto or Weibull), as presented in Table 7. As such, the Weibull distribution seemed to provide an overall best fit according to Kolmogorov-Smirnov tests and graphical representations. Table 8, 9 and 10 respectively give the volume, duration and low flow calculated for recurrence intervals of 2, 10, 20 and 50 years. It should be noted that data in Table 10 include the reference value Q_R (m^3/s) as well as the low flow (m^3/s), which was calculated from the intensity (m^3/s) value for each station.

Bivariate analysis

The bivariate analysis was used to describe the distribution for variable X_1 conditioned by a variable X_2. In this study, intensity conditioned by 7-day and 14-day durations were calculated using a bivariate distribution with Weibull marginals.

Using the Nagao-Kadoya method, the first step was to estimate the parameters (α_1, s_1, α_2 and s_2) using ML. The data was then transformed from a Weibull distribution to a standard exponential distribution via equations [19] and [20], by replacing (α_1, s_1, α_2 and s_2) by their ML estimates. The transformed data was then used in the analysis from this point. The data was divided into three classes using equal probabilities to guarantee a large number of observations within each class to construct the empirical cdf's (Ashkar et al. 1998). The classes were divided such that:

Class 1: $0 \leq F_2(x_2) \leq 1/3$
Class 2: $1/3 \leq F_2(x_2) \leq 2/3$
Class 3: $2/3 \leq F_2(x_2) \leq 1$

where $F_2(x_2)$ is the marginal cdf of the random variable X_2. In the space of the variable X_2, these three classes correspond to classes of the form $a_i < X_2 < b_i$, where a_i and b_i are the bounds of class i. The mean of each class is used as the value of x_2 to be placed in the cdf's $F(x_1 | x_2)$. The mean for each class is as follows:

Class 1: -ln(5/6)
Class 2: -ln(3/6)
Class 3: -ln(1/6)

To estimate ρ, a 3x3 contingency table was constructed from the observed couples (x_1, x_2) ("observed contingency table") and compared to a series of 3x3 contingency tables calculated from the hypothesized model (i.e., based on Equations [28] and [16]), for different correlation coefficients (ρ) ("theoretical contingency tables"). The chosen ρ value was the one that minimized the chi-squared distance between the cell counts from the observed and the theoretical contingency tables (Ashkar and El-Jabi 2002).

The empirical cdf's conditioned by duration corresponding to the different classes were calculated using a plotting position formula:

$$p(q) = \frac{q - 0.35}{N} \qquad [30]$$

where q is the rank for values of the class (arranged in ascending order), N is the sample size, and p(q) is the empirical probability.

The intensity conditioned by durations of 7 and 14 days were calculated for recurrence periods of 2, 10, 20 and 50 years. For these calculations, data were chosen so that the median was respectively 7 and 14 days. For some stations, it was impossible to calculate the intensity conditioned by a 7-day duration because of insufficient data. Kolmogorov-Smirnov tests accompanied by graphical representations were used to determine the goodness of fit. Figures 6 and 7 show the plotted theoretical and empirical distribution for intensity conditioned by 7-day and 14-day durations for station 01AJ003. The results for each station are presented as low flow (m^3/s) calculated from intensity values conditioned by 7- and 14-day durations (Tables 11 and 12).

2.2.3 Regionalization

In New Brunswick, low flow characteristics are not available for all drainage basins due to the absence of gauging stations or to the poor quality of collected streamflow data. Therefore, regional relationships can be developed for drainage basins within homogeneous low flow zones having similar physiographic and climatic characteristics (Environment Canada and New Brunswick Department of the Environment, 1990). Many physiographic and climatic characteristics such as the area of lakes and swamps, the average water content of snow cover, the basin perimeter, the drainage area, the latitude, the longitude, the mean annual precipitation, and the mean annual runoff influence low flow characteristics. However, these characteristics are not readily available or easily calculated at drainage basins of interest in New Brunswick. Drainage area and mean annual precipitation were used for the regionalization of low flow characteristics.

2.2.3.1 Annual minimum series method

Regional low flow models were developed for 1, 7, and 14-day low flow for recurrence periods of 2, 10, 20, and 50 years using regression analysis. Hydrometric stations 01AK006, 01AL004, and 01AM001 were excluded from regionalization due to insufficient streamflow data. Depending on the duration (1-day, 7-day and 14-day), more stations had to be eliminated from the regionalization due to extremely low flow not representative of the general low flow conditions. In particular, stations 01AK007 and 01AQ001 for the 1-day low flows and station 01AK007 for the 7-day low flows. Initially, low flow and basin drainage area were included in the linear regression model according to the following equation :

$$\mathrm{Log}(LF_{t,d}) = a_1 + b_1 \log(DA) \qquad [31]$$

where: $LF_{t,d}$ = low flow (m^3/s) for return period (t) and duration (d)

DA = drainage area (km^2) upstream of the site

a_1, b_1 = regression constant and coefficient

Subsequently, in an effort to further enhance the predictability of low flow, average annual precipitation was included in the regionalization models. New Brunswick was divided into homogenous precipitation zones according to Thiessen polygons, giving 7 distinct regions each represented by a meteorological station (Hébert et al. 2003). Hydrometric stations within a given region were associated with the average annual precipitation for that region. Multiple regression analysis was carried out with the low flows as a function of drainage area and average annual precipitation, according to the following equation:

$$\mathrm{Log}(LF_{t,d}) = a_2 + b_2 \log(DA) + c_2 \log(PREC) \qquad [32]$$

where: $LF_{t,d}$ = low flow (m^3/s) for return period (t) and duration (d)

DA = drainage area (km^2) upstream of the site

PREC = average annual precipitation (mm)

a_2, b_2, c_2 = regression constant and coefficients

Regionalization using linear regression analysis gave good results with coefficients of determination (R^2) varying from 0.73 to 0.92, and p values of less than or equal to 0.001 (Table 13). Regional low flow models (1-, 7-, and 14-day) are presented in Figures 8-10. The inclusion of precipitation in regionalization models slightly improves the coefficients of determination (0.78 – 0.95, Table 14). However, it does not contribute significantly to the explanation of the variance of low flows in NB.

2.2.3.2 Deficit Below Threshold method

Because inclusion of precipitation in the regionalization models only slightly improves the coefficients of determination with the annual minimum series method (section 2.2.3.2), only drainage area was used in the regionalization with the DBT method. For the DBT method, after the univariate and bivariate analyses were complete, the regionalization of low flow characteristics was carried out. The intensity data were transformed into low flow data (i.e. intensity subtracted from reference value) before the regionalization was undertaken.

Univariate

For the univariate results, the values for volume, duration and low flow were related to the drainage area. Stations 01AK006 and 01AL004 were not used in this analysis because their drainage areas were small (<100km^2). Two types of linear regressions were done. The first was performed with the untransformed data ($Y = \alpha + \beta DA$), whereas the second was done using a logarithmic transformation (equation [31] but substitute $LF_{t,d}$ by Y). Y corresponds to volume, duration or intensity, DA corresponds to drainage area, and α and β correspond to regression constant and coefficient for the linear regression with untransformed data. Figures 11, 12, 13, 14, 15 and 16 show the regressions for volume, duration and intensity. The estimates of α, β, a_1 and b_1 and for the regressions as well as the R^2 and the p value are given in Tables 15 and 16.

From Figures 11 to 16 and Tables 15 and 16, it was observed that the regression analysis gave slightly better results without the logarithmic transformation for volume and low flow. The R^2 values were slightly higher for untransformed data (normal scale rather than logarithmic). However, for volume, when the data is not in a logarithmic scale, the regression equations will give negative values for smaller basins (<500km^2). For this reason, it may be better to use the regression with logarithmic scale. For duration, there does not seem to be a significant relationship between duration and drainage area, i.e. size of basin. The p values show that the slope (β, in the case of untransformed data, and b_1, in the case of logarithmically transformed data) is not significantly different than 0. Although the low flow duration data did not show a level of association with basin size, duration data clearly showed that low flows of higher return events were of longer durations. For instance, the 2-year average low flow represented approximately 50-60 days in duration, while the 50-year average low flow was in the range of 160-170 days (Fig. 13). More data for basins with drainage areas ranging from 4000 to 15000km^2 would be necessary to truly determine whether or not a relationship existed between duration and drainage area.

Bivariate

For the bivariate analysis, the intensity conditioned by duration data was transformed into low flow conditioned by duration data and then related to the drainage area. The regressions were developed in the same manner as for the univariate analysis. Figures 17, 18, 19 and 20 show the regressions for the low flow conditioned by 7- and 14-day durations. The estimates of α, β, a_1 and b_1 for the regressions as well as the R^2 and the p value are given in Tables 17 and 18.

The regression results for the bivariate analysis are also better without using the logarithmic scale based on the R^2 criterion . However, the R^2 values are lower (62-74%) for the 7-day durations than the 14-day durations (83-94%). The 14-day duration probably gives better results than the 7-day duration because there is more volume, duration and intensity data points for the 14-day regression.

It should also be pointed out that the choice of the reference value Q_R and the simplifying assumptions may influence the results of the analysis. If these were modified, the results may differ. This would be interesting to study but may be difficult to generalize for a large number of stations as was studied here.

The Deficit Below Threshold Approach can provide a better analysis for engineering design projects because it characterizes low flows in terms of volume, duration and intensity which provides more information than annual minimums series. This method can also provide a better description of low flows for fish habitat studies and assessments.

3.0 LONG-TERM TRENDS AND CLIMATE CHANGE IMPACTS ON LOW FLOWS

Over the next 100 years, mean surface air temperature is expected to increase by 2 to 6 °C in Atlantic Canada (Parks Canada 1999), contributing to potentially large reductions in streamflow (Hengeveld 1990; Minns et al. 1995; Natural Resources Canada 2002). Water demand is also expected to increase, with 70% of total accessible runoff withdrawn from worldwide sources in the next 25 years (Postel et al. 1996). Climate change will undoubtedly enhance the conflict between water withdrawal and aquatic resource protection. However, the vulnerability of water resources to climate change impacts is highly dependent on the adaptation of water management systems to changing hydro-climatic conditions and on the capacity of rivers to sustain water demands under low flow conditions.

Long-term trends in air temperature, precipitation and discharge were identified in New Brunswick. Site-specific future climate scenarios for locations across New Brunswick were also generated by statistical downscaling of GCM projections. Future scenarios were then compared to past climate trends and effects on water resources (i.e. low flow, water availability, and aquatic resources) were discussed. These items are presented in the following sections.

3.1 Climate trends

New Brunswick lies on Canada's Atlantic coast, and is bordered by ocean on its southern (Bay of Fundy), northern and eastern (Gulf of St. Lawrence) shores. Despite its coastal location, the province has a typically continental flavour to its climate, with continental and maritime influences blending near the coasts. Generally, average 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 as snow. Precipitation tends to be highest in southern parts of the province (Phillips 1990).

Major rivers and many smaller streams radiate outward from the interiour highlands of New Brunswick. Major rivers include the Saint John River (drainage area ~ 55,000 km^2), Miramichi River (drainage area ~ 14,000 km^2), and Restigouche River (drainage area ~ 10,000 km^2). Rainfall, snowmelt, and groundwater all contribute to the volume of flow, producing variations from season to season and year to year. Most high flows and floods are caused by spring snowmelt. Heavy rainfall can also cause high flows and floods, especially on small streams. Lowest 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 (Environment Canada 2001).

3.1.1 Data and Methodology used

Daily maximum and minimum air temperature and total precipitation data from 7 meteorological stations in New Brunswick were obtained from Environment Canada (Fig. 1). Air temperature data from the National Climate Data Archive was "homogenised" at 6 of the 7 stations to remove any non-climatic inconsistencies due to station alterations including changes in site exposure, location, instrumentation, observer, observer program, or a combination of the above (Vincent 1998). Homogenisation of precipitation data is ongoing, and as a result quality controlled, archived data was used instead. Air temperature and precipitation series extend from 35 to 105 years at some stations (Table 19).

Daily discharge (m^3/s) data from the 7 hydrometric stations in New Brunswick (Table 20, Fig. 1) were obtained from Environment Canada's National Water Data Archive (HYDAT CD-ROM). A single station was selected from 7 distinct precipitation zones (Hébert et al. 2003) in New Brunswick. Natural, rather than regulated flow, was observed at all stations and daily discharge was recorded using both manual and recording gauges under continuous operation. Discharge series included data from 1919 to 1999, with continuous series extending 37 to 73 years at some stations (Table 20).

Annual and seasonal trends in air temperature, total precipitation, and discharge were examined by linear regression (STATISTICA™, StatSoft, Tulsa, OK). Seasons were defined as follows; winter (December-January-February, DJF), spring (March-April-May, MAM), summer (June-July-August, JJA), and autumn (September-October-November, SON). Extreme temperature, precipitation, and discharge events were also characterized at each station. Extreme air temperature and discharge, defined by the 5th (low) and 95th (high) percentile of air temperature (minimum and maximum) and discharge distributions were estimated on a seasonal basis for every year (Bonsal et al. 2001). Additionally, median discharge (Q_{50}) in August, a measure of instream flow, was also determined. Trends in precipitation were estimated by examining the number of days receiving precipitation (>0.2 mm), annually and seasonally, and the average amount recorded per precipitation event. All variables used in the above analyses are defined in Table 21.

3.1.2 Results

Air temperature

Monthly air temperatures (minimum and maximum) were coldest in January and warmest in July, with 7 months of the year having above freezing mean air temperatures. Across the province, minimum and maximum air temperatures were lowest in northern and western New Brunswick (i.e. Charlo and Aroostook) and highest in central and eastern parts (i.e. Fredericton, Moncton, and Chatham) of the province. Maximum air temperature was greatest in 1999 at all stations in New Brunswick. Maximum air temperature increased significantly in spring (Saint John) and summer (Doaktown, Fredericton, Moncton, and Saint

John). At Charlo, maximum temperature decreased significantly in winter and autumn, while no significant changes in maximum air temperature were observed at Aroostook (Table 22). Annual and seasonal minimum air temperature increased significantly at Chatham, Fredericton, Moncton, and Saint John. Minimum air temperature increased significantly in spring and summer in Charlo, spring, summer, and autumn in Doaktown, and winter, spring, and autumn in Aroostook (Table 23).

Extreme high (i.e. 95th percentile) and low (i.e. 5th percentile) temperatures changed significantly in New Brunswick, although these changes were not consistent among stations. Extreme high, maximum air temperatures increased significantly in spring, summer, and autumn at Doaktown and Saint John (Table 22). Positive and negative trends in extreme low, maximum air temperatures were observed as some stations. Extreme minimum temperatures increased significantly in summer at most stations in New Brunswick (Table 23). No changes in extreme temperatures (5 and 95%) were observed at Aroostook.

Precipitation

The amount of annual precipitation recorded in New Brunswick was highly variable, ranging from 629 to 1,975 mm. Generally, more precipitation was observed at southern stations in New Brunswick (i.e. Fredericton, Moncton, and Saint John). At all stations, similar amounts of precipitation fall in each season. No changes in precipitation were observed at Aroostook, Charlo, Chatham or Fredericton. Significant increases in precipitation were observed in all seasons at Doaktown (14-69 mm/decade), while only winter precipitation increased significantly at Moncton (11 mm/decade). Conversely, winter precipitation decreased significantly at Saint John (17 mm/decade) (Table 24).

The frequency of precipitation in spring increased significantly at most stations by 1-4 d/decade (Table 24). Significant increases in the number of days with precipitation were also observed in winter (Doaktown), summer (Chatham, Doaktown, Moncton), and autumn (Doaktown, Moncton). The amount of precipitation falling per precipitation event remained unchanged at most stations, with slight decreases at Chatham (autumn), Doaktown (autumn), and Saint John (winter).

Discharge

Average annual discharge ranged from 13.3 to 274.5m^3/s, following increasing trends in drainage area. At all hydrometric stations, highest flows were observed during spring. Lowest flows occurred during winter or summer months. Mean annual and seasonal discharge did not change significantly at any of the hydrometric stations examined. Likewise, few significant changes in extreme discharge or instream flow were observed. Low spring discharge became less extreme (i.e. increased) in the Saint John River (5.3 m^3/s/decade, r^2 = 0.143, p<0.001, n = 72), while low August discharge became more extreme (i.e. decreased) in the Nashwaak River (1.3 m^3/s/decade, r^2 = 0.118, p<0.035, n = 38).

3.1.3 Discussion

Climate affects all aspects of life in New Brunswick, affecting the productivity of our agricultural, water, and fisheries resources, among others. Globally, mean temperature has increased by approximately 0.4 to 0.8 °C in the twentieth century (Panel on Reconciling Temperature Observations 2000), with much of this increase occurring in the last 40 years (Nicholls et al. 1996). In Canada, mean air temperature has warmed by 0.3 °C in the last 50 years due to small increases in daily maximum temperatures and large increases in daily minimum temperatures (Zhang et al. 2000). In New Brunswick, air temperature increased significantly in the last 100 years. Generally, minimum air temperature, indicators of nighttime temperatures (Zhang et al. 2000), showed the greatest warming trends with increases at all meteorological stations in the province. Fewer changes in maximum air temperatures were observed. Trends in temperature are consistent with mid-latitude Northern Hemisphere continental warming observed by Bonsal et al. (2001), Zhang et al. (2000), and Nicholls et al. (1996).

Warming trends in New Brunswick are strengthened by similar trends in extreme temperatures. Regions of the province are getting hotter as evidenced by increases in upper quantile (95%) temperatures (maximum and minimum) and becoming less cold (increases in lower minimum temperature quartiles), particularly in summer. Similar trends in extreme temperatures have been observed across Canada (Bonsal et al. 2001) and these trends are expected to continue under climate change scenarios (Hengeveld 1990; Houghton et al. 2001; McCarthy et al. 2001).

Few changes in total precipitation were observed at meteorological stations in New Brunswick. However, at Doaktown seasonal precipitation increased significantly by 51% in winter, 129% in spring, 69% in summer and 43% in autumn in the last 70 years. Across Canada, precipitation increases were more conservative (5 to 35%) in the last half-century, with all seasons in most areas experiencing more precipitation (Zhang et al. 2000). Wang and Cho (1997) observed similar upward trends in precipitation in Russia. Precipitation events occurred more frequently in Doaktown, and in some seasons in Aroostook, Chatham, and Moncton with similar or less precipitation falling per event.

With few changes in precipitation, mean discharge in New Brunswick was unchanged, despite warmer air temperatures and presumably, increased rates of evaporation. In the past 30-50 years, environmental conditions, such as temperature and precipitation changed significantly in New Brunswick. Climate change is expected to further alter climatic regimes, affecting the productivity of our natural resources.

3.2 Statistical downscaling of temperature, precipitation and river discharge

According to the Intergovernmental Panel on Climate Change (IPCC), mean global surface temperature increased 0.6 ± 0.2 ºC in the 20th century. Snow cover decreased by 10% since the late 1960's, and the duration of ice cover in lakes and rivers decreased by two weeks in mid and high latitude regions of the Northern Hemisphere. Average sea level rose 0.1 to 0.2 metres globally, and precipitation increased by 0.5 to 1%, with an increase in the frequency of heavy precipitation events (Houghton et al. 2001). In the 21st century, greenhouse gas concentrations will continue to rise, however, the rate of increase and thus the response of the global climate system remains largely unknown, limiting our ability to anticipate and adapt to these changes.

General Circulation Models (GCM's), based on mathematical representations of atmosphere, ocean, ice cap and land surface processes, are considered to be the only credible tools currently available for simulating the response of the global climate system to increasing greenhouse gas concentrations. Accordingly, mean surface air temperature is projected to increase by 1.4 to 5.8 ºC globally in the next 100 years, with more rapid warming in the northern regions of North America. Precipitation is expected to increase by 3 to 15 % globally, with intense precipitation events occurring more frequently. Global sea level is projected to rise by 9 to 88 cm, with significant regional variations (Houghton et al. 2001).

According to the Canadian Global Coupled Model (CGCM1) in conjunction with the greenhouse gas + aerosol emission experiment (GA1) (Boer et al. 2000a, b; Flato et al. 2000), maximum and minimum temperature will increase by ~4.0 °C, while precipitation will increase by 3 to 5 % annually in New Brunswick. However, the extent of climate change and therefore, the subsequent local impacts across the province of New Brunswick are relatively unknown due to the limited spatial resolution of General Circulation Models (GCM). And while the complexity of the global climate system is well captured by GCM's, they are unable to represent local scale features and processes due to limited spatial resolution (Wigley et al. 1990; Carter et al. 1994; MacKay et al. 1998; Wilby 1998). Large geographic areas represent the basic unit of the GCM. The Canadian Global Coupled Model (CGCM), for example, has a surface grid resolution of roughly 3.7° latitude x 3.7° longitude (i.e. approximately 120,000 km^2) (Fig. 21). Limited spatial resolution of GCM output results in the simplification and homogenisation of climatic conditions of large geographic areas, contributing to the loss of characteristics which may have important influences on regional climate. At odds with GCM resolution, researchers focusing on the impacts of climate change are primarily interested in the local and regional consequences of large-scale changes (Xu 1999).

Given these limitations, methods to derive more detailed regional and site-specific scenarios for climate studies have emerged in recent years. Statistical "downscaling" is based on GCM output and involves the development of significant relationships between local and large-scale climate. Statistical downscaling, a transfer function approach, assumes that regional climate can be determined by the large-scale climatic state and regional / local physiographic features (e.g., topography, land-sea distribution and land use) (von Storch 1995, 1999). Regional or local climate information is derived by first developing a statistical model which relates large-scale climate variables, or "predictors", to regional and local variables, or "predictands" (Fig. 22). Large-scale predictor variables are then extracted from GCM output and used to drive the statistical model, generating local-scale climate projections for a future time period.

3.2.1 Data and Methodology used

3.2.1.1 Site description

Please refer to section 3.1.

3.2.1.2 Data collection

Daily maximum and minimum air temperature and total precipitation data (1961-1990) from 7 meteorological stations in New Brunswick were obtained from Environment Canada's National Climate Data Archive (Fig. 1, Table 25). Air temperature data was "homogenised" at 6 of the 7 stations to remove any non-climatic inconsistencies due to station alterations including changes in site exposure, location, instrumentation, observer, observer program, or a combination of the above (see Vincent 1998). Homogenisation of precipitation data is incomplete and therefore, quality controlled, archived data was used.

Daily discharge (m^3/s) data (1961-1990) from 7 hydrometric stations in New Brunswick were obtained from Environment Canada's National Water Data Archive (HYDAT CD-ROM) (Fig. 1, Table 26). A single station was selected from 7 distinct precipitation zones (Hébert et al. 2003) in New Brunswick. At all stations, natural, rather than regulated, flow was observed at all stations and daily discharge was recorded using both manual and recording gauges under continuous operation.

3.2.1.3 Statistical downscaling

Output from the Canadian Global Coupled Model in conjunction with the greenhouse gas + aerosol emission experiment (CGCM1-GA1) was used to generate site-specific scenarios in New Brunswick (Boer et al. 2000a, b; Flato et al. 2000). This model was driven by the Intergovernmental Panel for Climate Change (IPCC) "IS92a" emissions scenario in which the change in greenhouse gases forcing corresponds to that observed from 1900 to 1990 and increases at a rate of 1 % per year thereafter, effectively tripling CO_2 concentration (476 to 1422 ppm) by 2100 (Alcamo et al. 1995).

Surface and upper-atmospheric predictor variables (Table 27) were obtained from the National Center for Environmental Prediction / National Center for Atmospheric Research (NCEP/NCAR) Reanalysis dataset (Kalnay et al. 1996). Observed NCEP/NCAR predictor data were interpolated to the CGCM grid and made available by the Canadian Institute for Climate Studies (CICS). Predictor variables (5) were selected for statistical downscaling according to a strong and consistent correlation with the predictand as determined by stepwise multiple regression (STATISTICA, StatSoft, Tulsa, OK) (Wilby et al. 2002).

Statistical downscaling models were developed from daily series of maximum (T_{MAX}, equation [33]) and minimum (T_{MIN}, equation [34]) temperature:

$$T_{MAX_i} = \alpha_0 + \alpha_T T_i + \alpha_{T_{i-1}} T_{i-1} + \sum_{j=3} \left(\alpha_X X_i\right)_j \qquad [33]$$

$$T_{MIN_i} = \delta_0 + \delta_T T_i + \delta_{T_{i-1}} T_{i-1} + \sum_{j=3} \left(\delta_X X_i\right)_j \qquad [34]$$

where T_i = mean air temperature at 2-m;

X_i = other variables (3) selected on a per site basis (see Table 28);

α, δ = regression constant and coefficients

and wet-day amounts of precipitation (P, equation [35]):

$$P_i = \sqrt{\mu_0 + \mu_{q_{500}} q_{500_i} + \mu_{U_s} U_s + \sum_{j=3} \left(\mu_X X_i\right)_j} \qquad [35]$$

where q_{500} = specific humidity at 500 hPa;

U_s = surface zonal velocity;

X = other variables (3) selected on a per site basis (see Table 29);

μ = regression constant and coefficients

and river discharge (Q, equation [36]):

$$Q_i = 10^{\lambda_0 + \lambda_q q_i + \lambda_{q_{500}} q_{500i} + \lambda_T T_i + \sum_{j=2} \left(\lambda_X X_i\right)_j} \qquad [36]$$

where q = near surface specific humidity;

q_{500} = specific humidity at 500 hPa;

T_i = mean air temperature at 2-m;

X = other variables (2) selected on a per site basis (see Table 30);

λ = regression constant and coefficients and NCEP/NCAR predictor variables (Table 28-30). Downscaling models were calibrated using observed predictor variables and the observed predictand from 1961-1975 and validated with data withheld from the calibration process (i.e. 1976-1990). Following validation, models were re-calibrated with all 30 years of data (Table 28-30). Some predictors were consistent among stations, while others were selected per station according to the strength of their association with station specific observed data sets. Using the calibrated and validated models, daily climate data from 2010-2099 was generated at each station using Statistical DownScaling Software (SDSM, Version 2.2, Wilby et al. 2002).

3.2.1.4 Data analysis

Annual and seasonal trends in air temperature, precipitation, and river discharge were examined according to 30-yr time slices; 2020s (2010-2039), 2050s (2040-2069), and 2080s (2070-2099). The IPCC recommends this approach because most GCMs exhibit substantial inter-decadal climate variability, making it difficult to distinguish a climate change signal from background noise. Tri-decadal values of average temperature, precipitation, and river discharge were compared by analysis of variance (ANOVA), followed by post-hoc comparisons (Least Square Difference). Seasons were defined as follows; winter (December-January-February, DJF), spring (March-April-May, MAM), summer (June-July-August, JJA), and autumn (September-October-November, SON).

3.2.2 Results

Air temperature

Given a tripling in CO_2 concentrations, annual and seasonal maximum and minimum air temperature (Figures 23-24) increased significantly ($p<0.05$) across New Brunswick from 2010-2099 compared to current climate conditions (1961-1990). Annually, minimum air temperature increased by approximately 4 to 5 ºC, while maximum temperature increased by approximately 4 ºC at all meteorological stations. Larger increases in air temperature were observed at central New Brunswick stations (i.e. Aroostook, Chatham, Doaktown, Fredericton, and Moncton) than in northern (i.e. Charlo) or southern (i.e. Saint John) regions of the province. Seasonally, the greatest increases were observed in maximum spring air temperature (~ 5 to 6 ºC; Fig. 25) and minimum winter air temperature (~ 4 to 6 ºC; Fig. 26). Much of the increase in winter temperature is anticipated in 2010-2039, while in spring, summer, and autumn the greatest increases in temperature are anticipated in 2070-2099.

Precipitation

Mean daily annual precipitation increased significantly from 2010-2099 ($p<0.001$) compared to current climate conditions (Fig. 27). Precipitation increased from 25-50 % in northern and central stations and 9-14 % in southern stations. Seasonal precipitation increased significantly and by similar percentages at northern and some central stations (i.e. Charlo, Aroostook, and Chatham) (Fig. 28). At remaining central and southern stations, summer precipitation did not change significantly, while precipitation patterns in other seasons were less consistent. No significant changes in precipitation were observed at Saint John. No one time slice consistently demonstrated increases in precipitation across all meteorological stations.

Discharge

Average annual discharge increased significantly at all hydrometric stations, by 16 to 45% compared to current discharge conditions (Fig. 29). Large increases (i.e. >40%) were observed in both northern (e.g. Restigouche River) and central (e.g. Northwest Miramichi River) stations, and in both large (e.g. drainage area > 2,500 km^2) and small (i.e. drainage area < 1,000 km^2) drainage basins. Winter and spring discharge increased significantly at all hydrometric stations, with the largest increases observed in 2070-2099 (Fig. 30). Summer discharge decreased significantly at all stations, while autumn discharge decreased significantly in all rivers except the Saint John (i.e. 01AD002) and Restigouche (i.e. 01BC001) (Fig. 30).

3.2.3 Discussion

Climate change is expected to alter global temperature and precipitation patterns, exerting significant pressures on water resources. However, specific regional projections about the impact of climate change are hampered by the limited spatial resolution of global circulation models, making it difficult to determine the degree of climate change, how fast it will happen, and where it will occur. Alternatively, statistical downscaling generates local climate change projections, providing future climate scenarios on which adaptation strategies can be developed.

In the 20th century, changes in climate, particularly increases in temperature, have already affected physical and biological systems in many parts of the world (McCarthy et al. 2001).

In New Brunswick, air temperature increased significantly in the last century contributing to record high water temperatures and record low flow conditions (Caissie 1999a, 1999b; Caissie 2000). Given the scenario presented (~ 3 x CO_2 in 2100), air temperature in New Brunswick will increase by as much as 4 to 5 ºC by 2100. This rate of warming is much greater than that observed in the 20th century but is consistent with that predicted by Parks Canada (1999) (2 to 6 ºC) and Houghton et al. (2001) (3 to 5 ºC) for the Atlantic provinces. Significant warming will result from both higher maximum and minimum air temperatures, particularly in spring and winter, respectively. Minimum air temperatures are expected to increase more rapidly than maximum air temperatures, following trends already observed at these stations and at stations throughout Canada in the last 100 years (Bonsal et al. 2001; Zhang et al. 2000). Increases were fairly consistent throughout the province, with slightly greater temperature change occurring in the central region of New Brunswick, rather than western New Brunswick, as anticipated by Minns et al. (1995).

A warmer climate in New Brunswick would result in significant changes in water withdrawal demand and availability. A warmer climate will contribute to warmer water temperatures in rivers, lakes, and groundwater aquifers. Warmer water temperatures may result in changes in the abundance, diversity, and distribution of aquatic species inhabiting New Brunswick streams and rivers. Stream water temperature has an obvious effect on an aquatic organism's rate of growth and development (Elliott and Hurley 1997), their behaviour, and ultimately, their survival (Lee and Rinne 1980; Bjornn and Reiser 1991). Species with specific cold-water preferences, such as Atlantic salmon, will be particularly susceptible (McCarthy et al. 2001), as warmer water is significantly associated with smaller juvenile Atlantic salmon, which ultimately could reduce the overall productivity of Atlantic salmon populations in this region (Swansburg et al. 2002).

Increased rates of evapotranspiration can also be expected in a warmer climate, contributing to lower water levels in summer and increased irrigation demand. Demand for irrigation of agricultural land currently represents only a small proportion (<5 %) of water withdrawal demand in the province (New Brunswick Department of Environment and Local Government, unpublished report). However, irrigation demand coincides with peak demand (i.e. summer) from all other water users (municipal, commercial, industrial, aquaculture, etc.) in the province, and as a result, may intensify water conflict.

Warmer winter temperature will result in a shorter duration of snow cover and a reduced snow pack due to more precipitation falling as rain, hastening the break-up of ice on rivers and lakes (Hengeveld 1990; Minns et al. 1995; McCarthy et al. 2001; Natural Resources Canada 2002). Timing of the spring freshet, at least in the Miramichi River, is already advancing at a rate of 5 days/decade since the 1960s (Swansburg et al. 2004). Earlier snowmelt and runoff advances the start of a drier spring-summer season and has been observed to contribute to more extreme low flow conditions in summer (Manabe and Wetherald 1987).

Given the scenario presented (~ 3 x CO_2 in 2100), annual precipitation is expected to increase significantly in the 21st century, by 0.4 mm/day (9 %) up to 1.5 mm/day (48 %) at some stations. This increase is much greater than that predicted by the CGCM1 (3 to 5 %) and the IPCC (0 to 0.25 mm/day) (Houghton et al. 2001). Large differences in precipitation scenarios are not uncommon amongst models. Precipitation is an inherently heterogeneous variable, where large differences in local precipitation patterns are common. Therefore, it is a more difficult variable to model on a large scale, and as a result, precipitation scenarios have a greater degree of uncertainty associated with them.

Increases in annual and seasonal precipitation may increase the magnitude and frequency of flooding, particularly if the frequency of extreme precipitation events also increases as predicted by the IPCC (Houghton et al. 2001). More frequent and intense floods would increase infrastructure damage, cause soil erosion and crop damage. However, increased precipitation patterns may enhance water resources (groundwater and streamflow) in northern New Brunswick, benefiting communities on the Acadian Peninsula (e.g. Dalhousie, Tracadie-Sheila) where the quantity or quality of the water supply is of concern (New Brunswick Department of Environment and Local Government, unpublished report). In southern New Brunswick, where precipitation amounts are unchanged or increasing slightly, evapotranspiration is high due to increasing air temperature, and demand for water is generally increasing due to population growth (e.g. Moncton-Dieppe-Riverview), meeting water demand may be difficult in the future.

Average annual discharge is expected to increase significantly at all hydrometric stations, by as much as 45%, due to significant increases in winter and spring river discharge. Historically, low water conditions are not uncommon in winter in New Brunswick, due to cold temperatures and a substantial snow pack. However, with warmer air temperatures, a greater proportion of winter precipitation may fall as rain, contributing to substantially larger flows. Less snow and ice build-up may also contribute to smaller spring freshets and result in less intense flooding events. However, mid-winter thaws may become more frequent, contributing to more severe ice jam conditions, damaging infrastructure and scouring river beds (Beltaos and Burrell 2003). Summer discharge, however, is expected to decrease at all stations, presumably due to increased evaporative loss. Severe low water conditions are already being observed in some streams and rivers in New Brunswick (Caissie 1995; 2000), resulting in fish kills and more frequent closures of rivers to recreational fishers. Offstream use of water resources will also be affected due to a reduction in water quantity and quality (McCarthy et al. 2001).

4.0 LINKING WATER USE AND ADAPTATION STRATEGIES UNDER CLIMATE CHANGE

Global warming is expected to affect both water supply and water demand. Projected changes in meteorological conditions can alter hydrological processes that result in significant reductions in regional water availability by changing the seasonality, variability, and recurrence of runoff and shifting precipitation and runoff patterns spatially. A changed climate and water budget could modify land use and vegetation, and also effect hydrological processes. Modifications to land use and agricultural practices (for example, greater use of water for irrigation), resulting from climatic change, can alter the demand for water.

Although New Brunswick overall has an abundance of water, there are areas of the province where utilization of the resource has strained nature's capability and where withdrawal (outstream) use may conflict with instream water uses. To identify these areas, investigations of both outstream and instream water uses are necessary for both present and projected hydroclimatic conditions.

The following section presents the offstream water use in New Brunswick and some adaptation strategies developed to address water resources management under a changing climate.

4.1 Offstream water use in New Brunswick

The offstream water use in New Brunswick is presented in Withdrawal Water Use in New Brunswick (New Brunswick Department of the Environment and Local Government, unpublished report).The demand in water resources for offstream use (e.g municipal water, irrigation, hydroelectric) was evaluated using available data from various departmental and external souces. The report was prepared to provide an overview of water use in New Brunswick and to be a background document that can be used for water management activities in New Brunswick, including the assessment of the effects of climate change on industrial, municipal and agricultural water use. The report includes a general discussion of water use and presents information from various reports that have dealt with water management in New Brunswick. Withdrawal water uses include: domestic water use, commercial water use, industrial water use, mining water use, agricultural water use and aquacultural water use. The background reports presented in this report are: i) Atlantic province Water Study, ii) Saint John River Basin Reports, iii) Regional Water Resources Review, iv) Land and Water Use Documents, and v) summary of several non-provincial documents that pertain to water use. This is followed by information gathered from various sources on water use by different sectors such as municipal water use, domestic water use, industrial water use, commercial water use and waste disposal return flow in the Province. Finally, results by geographic region are presented with a discussion of water availability, areas of concern, and water conservation. Some areas where the supply of water in sufficient quantity or quality is of concern are: i) Dalhousie and surrounding communities, ii) Saint John, iii) Tracadie and other communities on the Acadian Peninsula and iv) the Moncton-Dieppe-Riverview area. For more information on offstream water use in New Brunswick, please consult Withdrawal Water Use in New Brunswick (New Brunswick Department of the Environment and Local Government, unpublished report).

4.2 Adaptation strategies for water resources management in New Brunswick

A meeting of water resource professionals, environmental specialists and climatic change experts was organized to propose strategies for dealing with greater hydrologic variability and extreme events, consider strategies for water demand management considering the possibility of reduced water availability, and consider the effect of lower water levels and warmer water temperatures on aquatic resources and instream uses in New Brunswick rivers. Several presentations related to CCIAP project A367 and to climate change were made to present results from this research and to lead to discussions to develop adaptations strategies for water resources under a changing climate.

The results of this workshop are presented in a summary report entitled Developing Adaptation Strategies for Water Resources Management in New Brunswick Under a Changing Climate (Riley Environment Limited 2003). The principal recommendations from the workshop were:

i) as there are still many unknowns associated with climate change, additional monitoring is required;
ii) New Brunswick needs a water resource management policy that recognizes the value of water;
iii) New Brunswick needs to develop at a high priority, an adaptation strategy, to enable the province to plan for the inevitable and substantial impacts expected from climate change;
iv) New Brunswick infrastructure design criteria needs to be revised to reflect changes in climate;
v) efforts of the various government agencies, both federal and provincial, need to be coordinated;
vi) public education on the expected effects of climate change on water resources is needed;
vii) better use/conservation of our water resources should be encouraged.

5.0 CONCLUSION

The conflict between the ever-increasing demand for water withdrawal from rivers (i.e. irrigation, drinking water, aquatic habitat protection, etc.) and water availability during drought and low flow periods is a recurring problem in water resources management. Competition between water abstraction and instream flow needs (minimum flow for river protection) will undoubtedly increase in the near future given the projected reduction under climate change (Hengeveld 1990, Minns et al. 1995). In the 1990s, many rivers in eastern Canada experienced record low flow conditions coupled with record high water temperatures (Caissie 1999a; Caissie 2000). Increased water demand and low flow occurrence are factors that need to be considered when establishing instream flow requirements or minimum flows to protect aquatic habitat. During recent years of drought conditions, an increase in water withdrawal demand (offstream use), especially for irrigation, was observed in the province of New Brunswick. Instream flow protection methods as well as a good knowledge of low flow characteristics, including long-term trends, are the primary and essential tools used during environmental impact assessment to evaluate the level of protection required for habitat under reduced flow in rivers (Caissie and El-Jabi 1995). Existing thresholds for instream flow protection (minimum flows) need to be revised for the protection of aquatic life under a projected warmer climate in Atlantic Canada and elsewhere. Alternatively, instream flow requirements will need to adapt under climate change and the current level of instream flow protection needs evaluation. Such evaluation is only possible with a good knowledge of water resource / aquatic resource response to climate change.

Analysis of streamflow characteristics is important for mitigating the conflict between instream water use and withdrawal demand. The risk of occurrence of low flow, a hydrologic parameter of rivers, is used in the design of water supply systems, water treatment installations, and hydraulic structures such as culverts, irrigation ditches and dams. Characteristics of low flow are also important for the management of aquatic resources, namely fish populations. With our climate changing, there is a need to adapt the way the risk of occurrence of low flow is used in design and in the management of aquatic resources. Quantifying low flows in terms of intensity, duration and volume deficit is becoming increasingly important in both water and aquatic resources management. In fact, not only intensity of low flow has been shown to be important to aquatic habitats, the duration of low flow events has been observed to be equally important (e.g. stress index to fish). It may become interesting to use low flow analysis methods such as the Deficit Below Threshold approach to characterize low flows in terms of volume, duration and intensity which provides more information than classic approaches that only characterize low flow in terms of intensity.

In the 20th century, changes in climate, particularly increases in temperature, have already affected physical and biological systems in many parts of the world (McCarthy et al. 2001). In New Brunswick, air temperature increased significantly in the last century contributing to record high water temperatures and record low flow conditions (Caissie 1999a, 1999b; Caissie 2000). Given the scenario presented (~ 3 x CO_2 in 2100), air temperature in New Brunswick will increase by as much as 4 to 5 ºC by 2100. This rate of warming is much greater than that observed in the 20th century but is consistent with that predicted by Parks Canada (1999) (2 to 6 ºC) and Houghton et al. (2001) (3 to 5 ºC) for the Atlantic provinces. Significant warming will result from both higher maximum and minimum air temperatures, particularly in spring and winter, respectively. Minimum air temperatures are expected to increase more rapidly than maximum air temperatures, following trends already observed at these stations and at stations throughout Canada in the last 100 years (Bonsal et al. 2001; Zhang et al. 2000).

A warmer climate in New Brunswick would result in significant changes in water withdrawal demand and availability. A warmer climate will also contribute to warmer water temperatures in rivers, lakes, and groundwater aquifers. Warmer water temperatures may result in changes in the abundance, diversity, and distribution of aquatic species inhabiting New Brunswick streams and rivers. Stream water temperature has an obvious effect on an aquatic organism's rate of growth and development (Elliott and Hurley 1997), their behaviour, and ultimately, their survival (Lee and Rinne 1980; Bjornn and Reiser 1991). Species with specific cold-water preferences, such as Atlantic salmon, will be particularly susceptible (McCarthy et al. 2001), as warmer water is significantly associated with smaller juvenile Atlantic salmon, which ultimately could reduce the overall productivity of Atlantic salmon populations in this region (Swansburg et al. 2002).

Increased rates of evapotranspiration can also be expected in a warmer climate, contributing to lower water levels in summer and increased irrigation demand. Demand for irrigation of agricultural land currently represents only a small proportion (<5 %) of water withdrawal demand in the province (New Brunswick Department of Environment and Local Government, unpublished report). However, irrigation demand coincides with peak demand (i.e. summer) from all other water users (municipal, commercial, industrial, aquaculture, etc.) in the province, and as a result, may intensify water conflict.

Warmer winter temperature will result in a shorter duration of snow cover and a reduced snow pack due to more precipitation falling as rain, hastening the break-up of ice on rivers and lakes (Hengeveld 1990; Minns et al. 1995; McCarthy et al. 2001; Natural Resources Canada 2002). Timing of the spring freshet, at least in the Miramichi River, is already advancing at a rate of 5 days/decade since the 1960s (Swansburg et al. 2004). Earlier snowmelt and runoff advances the start of a drier spring-summer season and has been observed to contribute to more extreme low flow conditions in summer (Manabe and Wetherald 1987).

Increases in annual and seasonal precipitation may increase the magnitude and frequency of flooding, particularly if the frequency of extreme precipitation events also increases as predicted by the IPCC (Houghton et al. 2001). More frequent and intense floods would increase infrastructure damage, cause soil erosion and crop damage. However, increased precipitation patterns may enhance water resources (groundwater and streamflow) in northern New Brunswick, benefiting communities on the Acadian Peninsula (e.g. Dalhousie, Tracadie-Sheila) where the quantity or quality of the water supply is of concern (New Brunswick Department of Environment and Local Government, unpublished report). In southern New Brunswick, where precipitation amounts are unchanged or increasing slightly, evapotranspiration is high due to increasing air temperature, and demand for water is generally increasing due to population growth (e.g. Moncton-Dieppe-Riverview), meeting water demand may be difficult in the future.

Average annual discharge is expected to increase significantly in New Brunswick, by as much as 45%, due to significant increases in winter and spring river discharge. Historically, low water conditions are not uncommon in winter in New Brunswick, due to cold temperatures and a substantial snow pack. However, with warmer air temperatures, a greater proportion of winter precipitation may fall as rain, contributing to substantially larger flows. Less snow and ice build-up may also contribute to smaller spring freshets and result in less intense flooding events. However, mid-winter thaws may become more frequent, contributing to more severe ice jam conditions, damaging infrastructure and scouring river beds (Beltaos and Burrell 2003). Summer discharge, however, is expected to decrease, presumably due to increased evaporative loss. Severe low water conditions are already being observed in some streams and rivers in New Brunswick (Caissie 1995; 2000), resulting in fish kills and more frequent closures of rivers to recreational fishers. Offstream use of water resources will also be affected due to a reduction in water quantity and quality (McCarthy et al. 2001).

Projected changes in meteorological conditions can alter hydrological processes that result in significant reductions in regional water availability by changing the seasonality, variability, and recurrence of runoff and shifting precipitation and runoff patterns spatially. A changed climate and water budget could modify land use and vegetation and also effect hydrological processes. Modifications to land use and agricultural practices (for example, greater use of water for irrigation), resulting from climatic change, can alter the demand for water. Although New Brunswick has an overall abundance of water, there are areas of the province where utilization of the resource has strained nature's capability and where withdrawal (outstream) use may conflict with instream water uses. To identify these areas, investigations of both outstream and instream water use are necessary for both present and projected hydroclimatic conditions (New Brunswick Department of the Environment and Local Government, unpublished report). Some areas where the supply of water in sufficient quantity or quality is of concern are: i) Dalhousie and surrounding communities, ii) Saint John, iii) Tracadie and other communities on the Acadian Peninsula and iv) the Moncton-Dieppe-Riverview area.

Climate change will undoubtedly alter the quantity and quality of water resources, presenting significant challenges in a province highly dependent on industries such as agriculture and fisheries. However, the vulnerability of water resources to climate change impacts is highly dependent on the adaptation of water management systems to changing hydro-climatic conditions and on the capacity of rivers to sustain water demands under low flow conditions. Strategies such as additional monitoring, policies that recognize the value of water, planning for the inevitable and substantial impacts expected from climate change, revision of infrastructure design criteria to reflect climate change, coordinating efforts of various government agencies, public education and encouraging better use/conservation of our water resources have been proposed and may be useful for water management systems to adapt to changing hydro-climatic conditions.

6.0 REFERENCES

Alcamo, J., A. Bouwman, J. Edmonds, A. Grübler, T. Morita, and A. Sugandhy. 1995. An evaluation of the IPCC IS92 emission scenarios. In J. T. Houghton, L. G. Meira Filho, J. Bruce, H. Lee, B. A. Callander, E. Haites, N. Harris and K. Maskell (editors). Climate Change 1994, Radiative Forcing of Climate Change and An Evaluation of the IPCC IS92 Emission Scenarios. Cambridge University Press, Cambridge, UK. pp. 233-304.

Ashkar, F. and J. Rousselle. 1981. Design discharge as a random variable: A risk study. Water Resources Research, 17(3): 577-591.

Ashkar, F., N. El-Jabi and M. Issa. 1998. A bivariate analysis of the volume and duration of low-flow events. Stochastic Hydrology and Hydraulics 12:97-116.

Ashkar, F. and L. Bayentin. 2001. Quelques fonctions de probabilité bivariées: intérêts et applications en hydrologie. Rapport de recherche, Juillet 2001, Département de mathématiques et statistiques, Université de Moncton, Moncton, NB, Canada.

Ashkar, F. and N. El-Jabi. 2002. Risk assessment using a generalized Pareto-based bivariate model. In: C.A. Brebbia (ed.) Risk Analysis II, Proceedings of the Third International Conference on Computer Simulation in Risk Analysis and Hazard Mitigation, June 19-21, Sintra, Portugal, pp.181-190.

Beltaos, S., and B. C. Burrell. 2003. Climate change and river ice breakup. Can. J. Civ. Eng. 30: 145-155.

Bjornn, T. C., and D. W. Reiser. 1991. Habitat requirements of salmonids in streams. In W. R. Meehan (editor). Influences of forest and rangeland management on salmonid fishes and their habitats. American Fisheries Society, Special Publications Series 19, Bethesda, Maryland. pp. 83-138

Boer, G. J., G. M. Flato, and D. Ramsden. 2000a. A transient climate change simulation with historical and projected greenhouse gas and aerosol forcing: projected climate for the 21st century. Clim. Dyn. 16: 427-450.

Boer, G. J., G. M. Flato, M. C. Reader, and D. Ramsden. 2000b. A transient climate change simulation with historical and projected greenhouse gas and aerosol forcing: experimental design and comparison with the instrumental record for the 20th century. Clim. Dyn. 16: 405-426.

Bonsal, B. R., X. Zhang, L. A. Vincent, and W. D. Hogg. 2001. Characteristics of daily and extreme temperatures over Canada. J. Clim. 14: 1959-1976.

Caissie, D. 1995. Hydrometeorological conditions for the Miramichi River basin during 1994. Department of Fisheries and Oceans, Atlantic Fisheries Research Document 95/88, Ottawa, ON. 20 p.

Caissie, D. and N. El-Jabi. 1995. Comparison and regionalization oh hydrologically based instream flow techniques in Atlantic Canada. Canadian Journal of Civil Engineering, Vol. 22, pp.235-246.

Caissie, D. 1999a. Hydrological conditions for Atlantic salmon rivers in the Maritime Provinces in 1997. Canadian Stock Assessment Secretariat, Research Document, 99/188.

Caissie, D. 1999b. Hydrological conditions for Atlantic salmon rivers in the Maritime Provinces in 1998. Canadian Stock Assessment Secretariat, research Document, 99/189.

Caissie, D. 2000. Hydrological conditions for Atlantic salmon rivers in 1999. Canadian Stock Assessment Secretariat Research Document, 2000/01.

Carter, T. R., M. L. Parry, H. Harasawa, and S. Nishioka. 1994. IPCC technical guidelines for assessing climate change impacts and adaptations. IPCC Special Report to Working Group II of IPCC. London: University College London, and Tsukaba, Japan: Centre for Global Environmental Research.

Cunnane, C. 1979. A note on the Poisson assumption in partial duration series model. Water Resources Research, 15: 489-494.

Davison, A.C. and R.L. Smith. 1990. Models for exceedances over high thresholds. Journal of the Royal Statistical Society, Great Britain, 52(3): 393-442.

El-Jabi, N., F. Ashkar and S. Hebabi. 1998. Regionalization of floods in New Brunswick Canada). Stochastic Hydrology and Hydraulics 12:65-82.

Elliott, J. M., and M. A. Hurley. 1997. A functional model for maximum growth of Atlantic salmon parr, Salmo salar, from two populations in northwest England. Funct. Ecol. 11:592-603.

Environment Canada. 2001. The Nature of Water: Rivers. Retrieved November 19, 2003, from The Green Lane™, Environment Canada's World Wide Web site: http://www.ec.gc.ca/water/en/nature/rivers/e_rivers.htm

Environment Canada and New Brunswick Department of the Environment. 1990. Low flow estimation guidelines for New Brunswick. Inland Waters/Water Resource Planning Branch, 43p.

Flato, G. M., G. J. Boer, W. G. Lee, N. A. McFarlane, D. Ramsden, M. C. Reader, and A. J. Weaver. 2000. The Canadian Centre for Climate Modelling and Analysis Global Coupled Model and its Climate. Clim. Dyn. 16: 451-468.

Hébert, C. N. El-Jabi, and D. Caissie. 2003. Low flow estimation for New Brunswick Rivers. Can. Tech. Rep. Fish. Aquat. Sci. 2493: 24p.

Hengeveld, H.G. 1990. Global climate change: implication for air temperature and water supply in Canada. Transactions of the American Fisheries Society 119:176-182.

Houghton, J. T., Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, and D. Xiaosu. 2001. Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, Cambridge, UK.

Kalnay, E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woollen, Y. Zhu, M. Chelliah, W. Ebisuzaki, W. Higgins, J. Janowiak, K.C. Mo, C. Ropelewski, J. Wang, A. Leetmaa, R. Reynolds, R. Jenne, and D. Joseph. 1996. The NCEP/NCAR 40-year reanalysis project. Bull. Am. Meteorol. Soc. 77: 437-471.

Kite, G. W. 1988. Frequency and risk analyses in hydrology, Water resources publications, Littleton, Colorado, U.S.A.

Lake, P.S. 2003. Ecological effects of perturbation by drought in flowing waters. Freshwater Biology 48: 1161-1172.

Lee, R. M., and J. N. Rinne. 1980. Critical thermal maximum of five trout species in the southwestern United States. Trans. Am. Fish. Soc. 190:632-635.

MacKay, M. D., R. E. Stewart, and G. Bergeron. 1998. Downscaling the hydrological cycle in the Mackenzie Basin with the Canadian Regional Climate Model. Atmosphere-Ocean 36: 179-211.

Madsen, H., P.F. Rasmussen and D. Rosbjerg. 1997. Comparison of annual maximum series and partial duration series methods for modeling extreme hydrologic events. Water Resources Research, 33(4): 747-757.

Manabe, S., and R. T. Wetherald. 1987. Large-scale changes of soil wetness induced by an increase in atmospheric carbon dioxide. J. Atmos. Sci. 44:1211-1235.

McCarthy, J. J., O. F. Canziana, N. A. Leary, D. J. Dokken, and K. S. White. 2001. Climate Change 2001: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, Cambridge, UK.

Minns, C.K., R.G. Randall, E.M.P. Chadwick, J.E. Moore, and R. green. 1995. Potential of climate change on the habitat and population dynamics of juvenile Atlantic salmon (Salmo salar) in Eastern Canada. p.699-708 in R.J. Beamish, editor. Climate change and northern fish populations. Canadian Special Publication of Fisheries and Aquatic Sciences, 121.

Nagao, M. and M. Kadoya. 1971. Two-variate exponential distribution and its numerical table for engineering application. Bull. Dis. Prev. Res. Institut, Kyoto University, Vol. 20, Part 3, No. 178, March, pp.183-215.

Natural Resources Canada. 2002. Climate change impacts and adaptation: a Canadian perspective. Water Resources. Climate Change Impacts and Adaptation Directorate, Ottawa, Ontario. 16 pp.

New Brunswick Department of the Environment and Local Government. 2003 (Unpublished report). Withdrawal water use in New Brunswick. 118p. (copies can be obtained from the New Brunswick Department of the Environment and Local Government, Sciences and Reporting Branch, P.O. Box 6000, Fredericton, New Brunswick, E3B 5H1).

Nicholls, N., G.V. Gruza, J. Jouzel, T.R. Karl, L.A. Ogallo, and D.E. Parker. 1996. Observed climate variability and change. Pages 132-192 *in* J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Katenberg, and K. Maskell, editors. Climate Change 1995, the science of climate change. Cambridge University Press, Cambridge, UK.

North, M. 1980. Time-dependent stochastic model of floods. ASCE Journal of the Hydrological Division, U.S.A., 106(5):649-665.

Panel on Reconciling Temperature Observations. 2000. Reconciling observations of global temperature change. Climate Research Committee, Board on Atmospheric Sciences and

Climate, Commission on Geosciences, Environment, and Resources, National Research Council, National Academy Press, Washington, D.C.

Parks Canada. 1999. Air quality, climate change and Canada's national parks. Parks Canada, Natural Resources Branch, Air Issues Bulletin No. 100, Ottawa.

Phillips, D. 1990. The Climate of Canada. Canada Communications Group-Publishing, Ottaw, ON. 176 pp.

Postel, S. L., G. C. Daily, and P. R. Ehrlich. 1996. Human appropriation of renewable fresh water. Science 271: 785-788.

Postel, S.L., J.I. Morrison and P.H. Gleick. 1998. Allocating fresh water to aquatic ecosystems: the case of the Colorado River delta. Water International 23:119-125.

Riley Environment Limited. 2003. Developing adaptation strategies for water resources management in New Brunswick under a changing climate. 22p.

Rosbjerg, D., H. Madsen and P.F. Rasmussen. 1992. Prediction in partial duration series with generalized Pareto-distribution exceedances. Water Resources Research, 28: 3001-3010.

Savoie, N., N. El-Jabi, F. Ashkar, and D. Caissie. 2004. Low flow characterization in New Brunswick using the Deficit Below Threshold approach. Can. Tech. Rep. Fish. Aquat. Sci. 2545: 48p.

Swansburg, E., G. Chaput, D. Moore, D. Caissie, and N. El-Jabi. 2002. Size variability of juvenile Atlantic salmon: links to environmental conditions. J. Fish. Biol. 61: 661-683.

Swansburg, E., N. El-Jabi, D. Caissie, and G. Chaput. 2004. Hydrometeorological trends in the Miramichi River, Canada: implications for Atlantic salmon growth. N. Am. J. Fish. Manage. 24: 561-576.

Todorovic, P. 1978. Stochastic models of floods. Water Resources Research. 14: 345-356.

Université de Moncton. 1994. Atlantic Canada Flow Analysis Version 1.0, software prepared by École de génie, Université de Moncton for Fisheries and Oceans Canada, Gulf Region.

Vincent, L. A. 1998. A technique for the identification of inhomogeneities in Canadian temperature series. J. Clim. 11: 1094-1104.

von Storch, H. 1995. Inconsistencies at the interface of climate impact studies and global climate research. Meteorol. Zeitschrift 4 NF: 72–80.

von Storch, H. 1999. The global and regional climate system. In H. von Storch and G. Flöser (editors). Anthropogenic Climate Change, Springer Verlag. pp. 3-36.

Wang, X. L., and H.-R. Cho. 1997. Spatial-temporal structures of trend and oscillatory variabilities in precipitation over Northern Eurasia. Journal of Climate 10: 2285-2298.

Wigley, T. M. L., P. D. Jones, K. R. Briffa, and G. Smith. 1990. Obtaining sub-gridscale information from coarse-resolution general circulation model output. J. Geophys. Res. 95: 1943-1953.

Wilby, R. L. 1998. Statistical downscaling of daily precipitation using daily airflow and seasonal teleconnection indices. Clim. Res. 10: 163-178.

Wilby, R. L., C. W. Dawson, and E. M. Barrows. 2002. SDSM – a decision support tool for the assessment of regional climate change impacts. Environ. Model. Software 17: 147-159.

Xu, C.-Y. 1999. From GCMs to river flow: a review of downscaling methods and hydrologic modelling approaches. Prog. Phys. Geogr. 23: 229-249.

Zelenhasic, E. and A. Salvai. 1987. A method of streamflow drought analysis. Water Resources Research, 23(1): 156-168.

Zhang, X., L. A. Vincent, W. D. Hogg, and A. Niitsoo. 2000. Temperature and precipitation trends in Canada during the 20th century. Atmosphere-Ocean 38: 395-429.

Table 1. Selected hydrometric stations.

River	ID	Latitude, Longitude	Drainage Area (km^2)	Analysis Period
1. Saint John R. at Fort Kent	01AD002	47 15 N, 68 35 W	14700	1927-1999
2. St. Francis R. at outlet of Glacier Lake	01AD003	47 12 N, 68 57 W	1350	1952-1999
3. Fish R. near Fort Kent	01AE001	47 14 N, 68 35 W	2260	1981-1999
4. Grande R. at Violette Bridge	01AF007	47 15 N, 67 55 W	339	1977-1999
5. Meduxnekeag R. near Belleville	01AJ003	46 13 N, 67 44 W	1210	1968-1999
6. Big Presque Isle Stream at Tracey Mills	01AJ004	46 26 N, 67 45 W	484	1968-1999
7. Becaguimec Stream at Coldstream	01AJ010	46 20 N, 67 28 W	350	1974-1999
8. Shogomoc Stream near TCH	01AK001	45 57 N, 67 19 W	234	1919-1940, 1944-1999
9. Middle Branch Nashwaaksis Stream near Sandwith’s Farm	01AK006	46 05 N, 66 44 W	5.7	1967-1999
10. Nackawic Stream	01AK007	46 03 N, 67 14 W	240	1968-1999
11. Nashwaak R. at Durham Bridge	01AL002	46 08 N, 66 37 W	1450	1962-1999
12. Narrows Mountain Bk. near Narrows Mountain	01AL004	46 17 N, 67 01 W	3.89	1972-1999
13. North Branch Oromocto R. at Tracy	01AM001	45 40 N, 66 41 W	557	1963-1999
14. Salmon R. at Castaway	01AN002	46 17 N, 65 43 W	1050	1974-1999
15. Canaan R. at East Canaan	01AP002	46 04 N, 65 22 W	668	1926-1999, 1963-1999
16. Kennebecasis R. at Apohaqui	01AP004	45 42 N, 65 36 W	1100	1962-1999
17. Lepreau R. at Lepreau	01AQ001	45 10 N, 66 28 W	239	1919-1999
18. Restigouche R. below Kedgwick R.	01BC001	47 40 N, 67 29 W	3160	1963-1999
19. Upsalquitch R. at Upsalquitch	01BE001	47 50 N, 66 53 W	2270	1919-1932, 1944-1999
20. Jacquet R. near Durham Centre	01BJ003	47 54 N, 66 02 W	510	1965-1999
21. Restigouche R., Rafting Ground Bk.	01BJ007	47 54 N, 66 57 W	7740	1969-1999
22. Middle R. near Bathurst	01BJ010	47 37 N, 65 43 W	217	1982-1999
23. R. Caraquet at Burnsville	01BL002	47 42 N, 65 09 W	173	1970-1999
24. Big Tracadie R. at Murchy Bridge Crossing	01BL003	47 26 N, 65 06 W	383	1971-1999
25. SW Miramichi R. at Blackville	01BO001	46 44 N, 65 50 W	5050	1919-1932, 1962-1999
26. Little SW Miramichi R. at Lyttleton	01BP001	46 56 N, 65 54 W	1340	1952-1999
27. NW Miramichi R. at Trout Bk.	01BQ001	47 06 N, 65 50 W	948	1962-1999
28. Coal Branch R. at Beersville	01BS001	46 27 N, 65 04 W	166	1965-1999
29. Petitcodiac R. near Petitcodiac	01BU002	45 57 N, 65 10 W	391	1962-1999
30. Turtle Creek at Turtle Creek	01BU003	45 57 N, 64 52 W	129	1963-1999
31. Point Wolfe R. at Fundy National Park	01BV006	45 34 N, 65 01 W	130	1965-1999

Table 2. Low flow (m^3/s), 1-day duration, for return periods of 2, 10, 20, and 50 years as determined by the Type III Extremal (Weibull) distribution function using the annual minimum series method.

	Return Period			
Station	2 years	10 years	20 years	50 years
01AD002	31.5	18.4	15.5	12.9
01AD003	3.36	2.30	2.12	1.97
01AE001	6.39	3.81	2.94	1.92
01AF007	0.585	0.337	0.280	0.226
01AJ003	1.33	0.453	0.324	0.228
01AJ004	0.802	0.339	0.234	0.134
01AJ010	0.505	0.257	0.197	0.139
01AK001	0.263	0.079	0.057	0.042
01AK006	0.001	-	-	-
01AK007	0.066	0.014	0.006	0.000
01AL002	3.78	2.71	2.57	2.48
01AL004	0.007	0.003	0.003	0.002
01AM001	0.374	0.043	0.011	-
01AN002	1.95	1.234	1.125	1.042
01AP002	0.438	0.181	0.145	0.118
01AP004	2.64	1.54	1.29	1.05
01AQ001	0.503	0.138	0.063	-
01BC001	9.72	5.52	4.23	2.76
01BE001	5.70	3.92	3.58	3.28
01BJ003	0.999	0.609	0.525	0.448
01BJ007	22.9	14.5	12.5	10.7
01BJ010	0.254	0.125	0.105	0.090
01BL002	0.676	0.459	0.403	0.344
01BL003	1.46	1.01	0.952	0.908
01BO001	18.5	13.9	13.3	12.8
01BP001	5.48	3.59	3.17	2.77
01BQ001	2.67	1.86	1.69	1.55
01BS001	0.214	0.112	0.091	0.073
01BU002	0.398	0.186	0.147	0.114
01BU003	0.321	0.210	0.186	0.164
01BV006	0.329	0.145	0.116	0.094

Table 3. Low flow (m^3/s), 7-day duration, for return periods of 2, 10, 20, and 50 years as determined by the Type III Extremal (Weibull) distribution function using the annual minimum series method.

	Return Period			
Station	2 years	10 years	20 years	50 years
01AD002	32.9	18.7	15.7	12.9
01AD003	3.51	2.41	2.21	2.05
01AE001	6.76	3.96	3.09	2.10
01AF007	0.615	0.343	0.284	0.229
01AJ003	1.60	0.549	0.377	0.243
01AJ004	0.936	0.439	0.326	0.218
01AJ010	0.588	0.323	0.267	0.217
01AK001	0.309	0.097	0.069	0.049
01AK006	0.002	-	-	-
01AK007	0.092	0.021	0.010	0.000
01AL002	4.22	2.87	2.68	2.56
01AL004	0.009	0.004	0.003	0.002
01AM001	0.446	0.047	0.004	-
01AN002	2.13	1.30	1.16	1.04
01AP002	0.546	0.199	0.144	0.102
01AP004	2.93	1.68	1.38	1.09
01AQ001	0.584	0.171	0.091	0.022
01BC001	9.96	6.98	6.36	5.80
01BE001	6.01	4.03	3.63	3.28
01BJ003	1.06	0.649	0.557	0.471
01BJ007	23.9	15.3	13.4	11.5
01BJ010	0.286	0.147	0.123	0.103
01BL002	0.705	0.476	0.418	0.361
01BL003	1.504	1.048	0.99	0.95
01BO001	19.8	14.5	13.7	13.1
01BP001	5.78	3.84	3.43	3.05
01BQ001	2.81	1.96	1.79	1.65
01BS001	0.241	0.135	0.115	0.098
01BU002	0.458	0.220	0.174	0.133
01BU003	0.350	0.230	0.206	0.185
01BV006	0.391	0.174	0.137	0.107

Table 4. Low flow (m^3/s), 14-day duration for return periods of 2, 10, 20, and 50 years as determined by the Type III Extremal (Weibull) distribution function using the annual minimum series method.

	Return Period			
Station	2 years	10 years	20 years	50 years
01AD002	34.8	19.2	15.9	12.9
01AD003	3.66	2.49	2.28	2.12
01AE001	7.19	4.26	3.34	2.27
01AF007	0.659	0.378	0.316	0.258
01AJ003	1.82	0.694	0.525	0.4
01AJ004	1.06	0.498	0.366	0.24
01AJ010	0.689	0.399	0.339	0.287
01AK001	0.358	0.109	0.072	0.046
01AK006	0.003	-	-	-
01AK007	0.119	0.031	0.016	0.004
01AL002	4.65	3.08	2.86	2.70
01AL004	0.010	0.005	0.004	0.003
01AM001	0.537	0.049	-	-
01AN002	2.315	1.339	1.16	1.011
01AP002	0.600	0.249	0.208	0.182
01AP004	3.21	1.80	1.51	1.25
01AQ001	0.678	0.198	0.107	0.030
01BC001	10.38	7.22	6.56	5.97
01BE001	6.26	4.12	3.70	3.32
01BJ003	1.12	0.673	0.572	0.476
01BJ007	24.8	15.9	14.0	12.2
01BJ010	0.323	0.164	0.132	0.105
01BL002	0.741	0.500	0.442	0.384
01BL003	1.56	1.09	1.031	0.991
01BO001	21.2	15.1	14.1	13.4
01BP001	6.12	4.06	3.62	3.22
01BQ001	3.04	2.08	1.87	1.69
01BS001	0.260	0.152	0.134	0.120
01BU002	0.524	0.254	0.203	0.159
01BU003	0.367	0.246	0.224	0.206
01BV006	0.464	0.200	0.153	0.114

Table 5. Threshold values and number of low flow events for hydrometric stations.

River	ID	Threshold Value (Q_R) (m^3/s)	Number of events
1. Saint John R. at Fort Kent	01AD002	92.94	178
2. St. Francis R. at outlet of Glacier Lake	01AD003	7.733	110
3. Fish R. near Fort Kent	01AE001	13.24	42
4. Grande R. at Violette Bridge	01AF007	2.153	90
5. Meduxnekeag R. near Belleville	01AJ003	4.191	82
6. Big Presque Isle Stream at Tracey Mills	01AJ004	2.167	89
7. Becaguimec Stream at Coldstream	01AJ010	1.440	108
8. Shogomoc Stream near TCH	01AK001	0.588	115
9. Middle Branch Nashwaaksis Stream near Sandwith's Farm	01AK006	0.011	80
10. Nackawic Stream	01AK007	0.344	83
11. Nashwaak R. at Durham Bridge	01AL002	8.581	100
12. Narrows Mountain Bk. near Narrows Mountain	01AL004	0.018	73
13. North Branch Oromocto R. at Tracy	01AM001	1.312	55
14. Salmon R. at Castaway	01AN002	4.210	67
15. Canaan R. at East Canaan	01AP002	1.098	100
16. Kennebecasis R. at Apohaqui	01AP004	4.720	80
17. Lepreau R. at Lepreau	01AQ001	1.183	156
18. Restigouche R. below Kedgwick R.	01BC001	25.01	95
19. Upsalquitch R. at Upsalquitch	01BE001	13.88	162
20. Jacquet R. near Durham Centre	01BJ003	2.483	86
21. Restigouche R., Rafting Ground Bk.	01BJ007	61.66	78
22. Middle R. near Bathurst	01BJ010	0.849	59
23. R. Caraquet at Burnsville	01BL002	1.439	82
24. Big Tracadie R. at Murchy Bridge Crossing	01BL003	3.041	64
25. SW Miramichi R. at Blackville	01BO001	38.45	173
26. Little SW Miramichi R. at Lyttleton	01BP001	11.95	162
27. NW Miramichi R. at Trout Bk.	01BQ001	6.396	128
28. Coal Branch R. at Beersville	01BS001	0.472	76
29. Petitcodiac R. near Petitcodiac	01BU002	0.899	86
30. Turtle Creek at Turtle Creek	01BU003	0.516	64
31. Point Wolfe R. at Fundy National Park	01BV006	1.169	103

Table 6. Best fitted distribution for volume, duration and intensity.

	Pareto	Exponential	Weibull	none
Volume	25	1	4	1
Duration	21	4	5	1
Intensity	0	0	29	2

Table 7. Best fitted distribution for the largest volume, largest duration and largest intensity in a one year period.

	Pareto	Exponential	Weibull	none
Largest volume	4	0	26	1
Largest duration	2	1	28	0
Largest intensity	0	0	28	3

Table 8. Volume (m^3/s*days) of low flow events at recurrence periods of 2, 10, 20 and 50 years using the Deficit Below Threshold method.

ID	Recurrence Period (yrs.)			
	2	10	20	50
01AD002	2222	7510	10428	15234
01AD003	146	498	650	857
01AE001	186	527	672	872
01AF007	102	214	259	318
01AJ003	55.4	191	253	340
01AJ004	27.0	86.1	119	173
01AJ010	17.2	43.3	56.0	75.5
01AK001	6.0	21.1	26.8	34.2
01AK007	8.6	20.4	25.2	31.5
01AL002	112	280	342	419
01AM001	20.2	72.1	88.9	109
01AN002	58.2	167	208	261
01AP002	11.6	44.1	57.4	75.1
01AP004	37.0	133	184	269
01BC001	625	1724	2165	2747
01BE001	327	1040	1349	1770
01BJ003	19.8	57.9	72.1	90.4
01BJ007	1734	4290	5234	6437
01BJ010	22.9	57.0	70.2	87.4
01BL002	28.6	84.2	108	139
01BL003	53.8	160	203	260
01BO001	587	1389	1691	2078
01BP001	238	594	735	919
01BQ001	119	309	386	488
01BS001	4.1	17.1	24.0	34.5
01BU002	9.7	34.4	44.7	58.5
01BU003	4.1	13.7	16.9	21.0
01BV006	20.4	55.5	69.1	86.8

Table 9. Duration (days) of low flow events at recurrence periods of 2, 10, 20 and 50 years using the Deficit Below Threshold method.

ID	Recurrence Period (yrs.)			
	2	10	20	50
01AD002	60	136	166	203
01AD003	57	142	176	220
01AE001	53	93	105	119
01AF007	83	152	178	211
01AJ003	37	88	107	131
01AJ004	42	99	120	147
01AJ010	35	67	79	94
01AK001	28	88	107	130
01AK007	41	83	99	120
01AL002	44	90	105	123
01AM001	32	87	103	122
01AN002	40	93	112	135
01AP002	28	81	101	126
01AP004	35	90	109	133
01AQ001	30	79	95	115
01BC001	68	150	181	219
01BE001	73	177	215	265
01BJ003	65	137	162	193
01BJ007	75	144	166	193
01BJ010	67	135	159	189
01BL002	65	149	181	221
01BL003	64	133	156	184
01BO001	52	102	120	141
01BP001	59	124	147	177
01BQ001	56	114	135	161
01BS001	33	90	113	143
01BU002	32	87	108	134
01BU003	35	94	114	138
01BV006	41	93	111	134

Table 10. Low flow (m^3/s) at recurrence periods of 2, 10, 20 and 50 years using the Deficit Below Threshold method.

ID	Ref.Value Qr (m^3/s)	Recurrence Period (yrs.)			
		2	10	20	50
01AD002	92.9	34.8	18.2	13.9	9.23
01AE001	13.2	6.71	3.73	2.93	2.03
01AF007	2.15	0.17	0.00	0.00	0.00
01AJ003	4.19	1.50	0.43	0.15	0.00
01AJ004	2.17	0.93	0.30	0.12	0.00
01AJ010	1.44	0.52	0.22	0.13	0.03
01AK001	0.59	0.31	0.10	0.04	0.00
01AK007	0.34	0.06	0.00	0.00	0.00
01AL002	8.58	4.32	2.51	2.01	1.44
01AL004	0.02	0.01	0.00	0.00	0.00
01AM001	1.31	0.48	0.01	0.00	0.00
01AN002	4.21	2.15	1.18	0.92	0.61
01AP002	1.10	0.48	0.18	0.10	0.02
01AP004	4.72	2.82	1.65	1.32	0.93
01BC001	25.0	10.8	5.61	4.19	2.58
01BE001	13.9	6.33	3.55	2.84	2.05
01BJ003	2.48	1.75	1.37	1.26	1.14
01BJ007	61.7	26.7	14.5	11.2	7.56
01BJ010	0.85	0.32	0.12	0.06	0.00
01BL002	1.44	0.74	0.47	0.39	0.31
01BL003	3.04	1.64	1.05	0.90	0.72
01BO001	38.5	18.9	9.15	6.30	3.02
01BP001	12.0	5.50	3.13	2.45	1.68
01BQ001	6.40	3.00	1.74	1.38	0.98
01BS001	0.47	0.22	0.11	0.09	0.05
01BU002	0.90	0.41	0.21	0.15	0.09
01BU003	0.52	0.33	0.25	0.23	0.20

Table 11. Low flow (m^3/s) conditioned by a 7-day duration for recurrence intervals of 2, 10, 20 and 50 years using the Deficit Below Threshold method.

Station	Ref. Value Q_R (m^3/s)	Recurrence Period (yrs)			
		2	10	20	50
01AF007	2.15	1.27	0.94	0.86	0.76
01AJ003	4.19	2.76	2.00	1.79	1.55
01AJ010	1.44	1.00	0.79	0.73	0.67
01AK001	0.59	0.43	0.35	0.33	0.30
01AK007	0.34	0.20	0.13	0.11	0.09
01AL002	8.58	6.48	5.26	4.91	4.52
01AN002	4.21	3.19	2.64	2.48	2.30
01AP002	1.10	0.75	0.57	0.52	0.46
01AP004	4.72	3.70	3.12	2.95	2.77
01AQ001	1.18	0.83	0.65	0.61	0.55
01BL002	1.44	1.11	0.94	0.89	0.84
01BP001	12.0	9.10	7.52	7.12	6.37
01BS001	0.47	0.32	0.24	0.22	0.20
01BU002	0.90	0.61	0.48	0.45	0.41
01BV006	1.17	0.83	0.67	0.62	0.57

Table 12. Low flow (m^3/s) conditioned by a 14-day duration of for recurrence intervals of 2, 10, 20 and 50 years using the Deficit Below Threshold method

Station	Ref. Value	Recurrence Period (yrs)			
	Q_R (m^3/s)	2	10	20	50
01AD002	92.9	53.1	38.3	34.3	30.1
01AD003	7.73	5.76	4.72	4.43	4.12
01AE001	13.2	9.76	7.43	7.09	6.46
01AF007	2.15	1.09	0.55	0.44	0.30
01AJ003	4.19	2.43	1.67	1.46	1.23
01AJ004	2.17	1.42	1.03	0.92	0.81
01AJ010	1.44	0.86	0.65	0.59	0.53
01AK001	0.59	0.38	0.30	0.28	0.26
01AK007	0.34	0.17	0.10	0.08	0.05
01AL002	8.58	6.00	4.75	4.41	4.03
01AM001	1.31	0.68	0.48	0.43	0.37
01AN002	4.21	2.91	2.35	2.20	2.02
01AP002	1.10	0.66	0.48	0.43	0.37
01AP004	4.72	3.41	2.82	2.66	2.47
01AQ001	1.18	0.71	0.54	0.49	0.43
01BC001	25.0	17.2	14.4	13.6	12.8
01BE001	13.9	9.66	7.60	7.04	6.42
01BJ003	2.48	1.69	1.37	1.29	1.20
01BJ007	61.7	43.3	36.2	34.3	32.2
01BJ010	0.85	0.53	0.36	0.31	0.26
01BL002	1.44	1.05	0.88	0.83	0.78
01BL003	3.04	2.30	1.94	1.84	1.73
01BO001	38.5	28.1	22.7	21.2	19.4
01BP001	11.9	8.42	6.86	6.42	5.96
01BQ001	6.40	4.52	3.58	3.32	3.03
01BS001	0.47	0.29	0.22	0.20	0.17
01BU002	0.90	0.54	0.42	0.39	0.35
01BU003	0.52	0.38	0.32	0.31	0.29
01BV006	1.17	0.72	0.56	0.51	0.46

Table 13. Linear regression analysis of 1, 7, and 14-day low flows for return periods of 2, 10, 20, and 50 years, as a function of basin drainage area ($\mathrm{Log}\ (LF_{t,d}) = a_1 + b_1\ \mathrm{Log}\ (DA)$)using the annual minimum series method.

Period	a_1	b_1	R^2	p
1 day				
2 years	-3.036	1.121	0.909	0.001
10 years	-3.472	1.185	0.850	0.001
20 years	-3.593	1.200	0.827	0.001
50 years	-3.705	1.208	0.795	0.001
7 days				
2 years	-2.923	1.097	0.920	0.001
10 years	-3.397	1.172	0.864	0.001
20 years	-3.562	1.201	0.835	0.001
50 years	-3.804	1.250	0.779	0.001
14 days				
2 years	-2.978	1.121	0.897	0.001
10 years	-3.629	1.243	0.835	0.001
20 years	-3.832	1.283	0.811	0.001
50 years	-4.023	1.324	0.730	0.001

Table 14. Multiple regression analysis of 1, 7, and 14-day low flows for return periods of 2, 10, 20, and 50 years, as a function of basin drainage area, and average annual precipitation ($\mathrm{Log}\ (LF_{t,d}) = a_2 + b_2\ \mathrm{Log}\ (DA) + c_2\ \mathrm{Log}\ (PREC)$) using the annual minimum series method.

Period	a_2	b_2	c_2	R^2	p
1 dayr					
2 years	-0.885	1.079	-0.672	0.939	0.001
10 years	-0.360	1.125	-0.973	0.896	0.001
20 years	-0.476	0.074	-1.032	0.878	0.001
50 years	-0.459	1.130	-1.000	0.851	0.001
7 days					
2 years	-2.417	1.059	-0.130	0.945	0.001
10 years	0.668	1.107	-1.283	0.906	0.001
20 years	2.764	1.123	-2.020	0.889	0.001
50 years	8.144	1.136	-3.849	0.859	0.001
14 days					
2 years	-3.073	1.069	0.084	0.924	0.001
10 years	-1.161	1.134	-0.711	0.866	0.001
20 years	0.563	1.153	-1.328	0.845	0.001
50 years	5.852	1.157	-3.110	0.784	0.001

Table 15. Linear regression analysis of volume, duration and low flow at recurrence intervals of 2, 10, 20, and 50 years and basin drainage area upstream of the gauging station ($Y = \alpha + \beta DA$) using the Deficit Below Threshold method.

Period	α	β	R^2	p
		Volume (m^3/s*days)		
2 years	-45.17	0.166	0.943	<0.001
10 years	-192.3	0.515	0.970	<0.001
20 years	-292.3	0.694	0.968	<0.001
50 years	-473.7	0.978	0.957	<0.001
		Duration (days)		
2 years	46.32	0.0018	0.109	0.080
10 years	105.1	0.0030	0.100	0.095
20 years	126.0	0.0036	0.097	0.100
50 years	152.3	0.0042	0.089	0.115
		Low flow (m^3/s)		
2 years	0.192	0.0027	0.945	<0.001
10 years	0.126	0.0014	0.941	<0.001
20 years	0.098	0.0011	0.939	<0.001
50 years	0.072	0.0007	0.929	<0.001

Table 16. Linear regression analysis of volume, duration and low flow (logarithmic scale)at recurrence intervals of 2, 10, 20, and 50 years and basin drainage area (logarithmic scale) upstream of the gauging station ($\log Y = a_1 + b_1 \log DA$) using the Deficit Below Threshold method.

Period	a_1	b_1	R^2	p
		Volume (m^3/s*days)		
2 years	-1.865	1.255	0.818	<0.001
10 years	-1.348	1.239	0.853	<0.001
20 years	-1.249	1.242	0.858	<0.001
50 years	-1.151	1.246	0.862	<0.001
		Duration (days)		
2 years	1.357	0.110	0.168	0.027
10 years	1.823	0.072	0.123	0.063
20 years	1.914	0.068	0.110	0.079
50 years	2.008	0.063	0.093	0.107
		Low flow (m^3/s)		
2 years	-3.407	1.238	0.843	<0.001
10 years	-3.566	1.191	0.680	<0.001
20 years	-3.610	1.174	0.729	<0.001
50 years	-3.397	1.070	0.618	<0.001

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Table 17. Linear regression analysis of low flow conditioned by 7- and 14-day durations at recurrence intervals of 2, 10, 20, and 50 years and basin drainage area upstream of the gauging station ($Y = \alpha + \beta DA$) using the Deficit Below Threshold method.

Period	α	β	R^2	p
	>Low Flow (m^3/s) conditioned by 7- day duration			
2 years	-0.584	0.0046	0.735	<0.001
10 years	-0.498	0.0037	0.718	<0.001
20 years	-0.474	0.0035	0.709	<0.001
50 years	-0.446	0.0032	0.700	<0.001
	Low Flow (m^3/s) conditioned by 14- day duration			
2 years	0.138	0.0042	0.939	<0.001
10 years	0.299	0.0032	0.898	<0.001
20 years	0.351	0.0029	0.880	<0.001
50 years	0.384	0.0026	0.858	<0.001

Table 18. Linear regression analysis of low flow conditioned by 7- and 14-day durations (logarithmic scale) at recurrence intervals of 2, 10, 20, and 50 years and basin drainage area (logarithmic scale)upstream of the gauging station ($\log Y = a_1 + b_1 \log DA$) using the Deficit Below Threshold method.

Period	a_1	b_1	R^2	p
	Low Flow (m^3/s) conditioned by 7- day duration			
2 years	-2.714	1.062	0.673	<0.001
10 years	-2.861	1.078	0.645	<0.001
20 years	-2.913	1.084	0.633	<0.001
50 years	-2.981	1.093	0.616	0.001
	Low Flow (m^3/s) conditioned by 14- day duration			
2 years	-3.013	1.174	0.879	<0.001
10 years	-3.190	1.194	0.858	<0.001
20 years	-3.256	1.204	0.847	<0.001
50 years	-3.351	1.219	0.830	<0.001

Table 19. Location and length of air temperature and precipitation time series at meteorological stations in New Brunswick.

Meteorological Station	ID	Latitude, Longitude	Air Temperature Series	Precipitation Series
Aroostook	8100300	46º 48' N; 67º 43' W	1913-1999 (87 yrs.)	1929-2000 (72 yrs.)
Charlo Airport	8100880	47º 59' N; 66º 20' W	1945-1999 (55 yrs.)	1966-2000 (35 yrs.)
Chatham Airport	8101000	47º 01' N; 65º 27' W	1895-1999 (105 yrs.)	1943-2000 (58 yrs.)
Doaktown[1]	8101200	46º 33' N; 66º 09' W	1952-1999 (48 yrs.)	1934-2000 (67 yrs.)
Fredericton Airport	8101500	45º 52' N; 66º 32' W	1895-1999 (105 yrs.)	1951-2000 (50 yrs.)
Moncton Airport	8103200	46º 06' N; 64º 47' W	1895-1999 (105 yrs.)	1939-2000 (62 yrs.)
Saint John Airport	8104900	45º 19' N; 65º 53' W	1895-1999 (105 yrs.)	1946-2000 (55 yrs.)

[1] Data was not "homogenised" to remove non-climatic inconsistencies

Table 20. Location, drainage area (km^2), and period of record at selected hydrometric stations in New Brunswick.

Hydrometric Station	ID	Latitude, Longitude	Drainage Area (km^2)[1]	Period of Record
Saint John R. at Fort Kent	01AD002	47° 15' N, 68° 36' W	14,700	1927-99 (73 yrs.)
Nashwaak R. at Durham Bridge	01AL002	46° 08' N, 66° 37' W	1,450	1962-99 (38 yrs.)
Canaan R. at East Canaan	01AP002	46° 04' N, 65° 22' W	668	1926-40, 1963-99 (52 yrs.)
Kennebecasis R. at Apohaqui	01AP004	45° 42' N, 65° 36' W	1,100	1962-99 (38 yrs.)
Restigouche R. below Kedgwick R.	01BC001	47° 40' N, 67° 29' W	3,160	1963-99 (37 yrs.)
SW Miramichi R. at Blackville	01BO001	46° 44' N, 65° 50' W	5,050	1919-32, 1962-99 (52 yrs.)
NW Miramichi R. at Trout Bk.	01BQ001	47° 06' N, 65° 50' W	948	1962-99 (38 yrs.)

[1] Drainage area upstream of gauging station

Table 21. Abbreviations and descriptions of environmental parameters related to air temperature, precipitation, and discharge.

Parameter	Description
Air Temperature (°C)	
A_{max}	Maximum daily air temperature
A_{min}	Minimum daily air temperature
$A_{max5\%}$, $A_{min5\%}$	5th percentile (extreme low) of daily air temperature (maximum and minimum) distributions
$A_{max95\%}$, $A_{min95\%}$	95th percentile (extreme high) of daily air temperature (maximum and minimum) distributions
Precipitation (mm)	
P_{total}	Total precipitation (mm)
P_{freq}	Frequency of precipitation (number of days)
P_{mean}	Mean total precipitation falling per precipitation event (mm/day)
Discharge (m^3/s)	
Q	Mean daily discharge
$Q_{5\%}$	5th percentile (extreme low) of daily discharge distribution
$Q_{95\%}$	95th percentile (extreme high) of daily discharge distribution
Q50	Median August discharge

Table 22. Trends in mean and extreme (5th and 95th percentiles) maximum air temperature at meteorological stations in New Brunswick, as determined by linear regression analysis.

	Aroostook	Charlo	Chatham	Doaktown	Fredericton	Moncton	Saint John
				Average Maximum Air Temperature (°C/dec.)			
Winter	-[1]	-0.3 °C/dec.	-	-	-	-	-
Spring	-	-	-	-	-	-	+0.1 °C/dec.
Summer	-	-	-	+0.4 °C/dec.	+0.1 °C/dec.	+0.1 °C/dec.	+0.3 °C/dec.
Autumn	-	-0.3 °C/dec.	-	-	-	-	-
				Extreme (5th Percentile) Maximum Air Temperature (°C/dec.)			
Winter	-	-	-	-0.8 °C/dec.	-	-	-
Spring	-	-	-	-	-	-	-
Summer	-	-	-	-	-	-	+0.1 °C/dec.
Autumn	-	-0.4 °C/dec.	-	-0.4 °C/dec.	-	-	-
				Extreme (95th Percentile) Maximum Air Temperature (°C/dec.)			
Winter	-	-	+0.1 °C/dec.	-	-	-	-
Spring	-	-	-	+0.9 °C/dec.	-	-	+0.2 °C/dec.
Summer	-	-	-	+0.6 °C/dec.	+0.1 °C/dec.	-	+0.3 °C/dec.
Autumn	-	-	-	+0.4 °C/dec.	-	-	+0.1 °C/dec.

[1] Trend was not statistically significant (p<0.05)

Table 23. Trends in mean and extreme (5th and 95th percentiles) minimum air temperature at meteorological stations in New Brunswick, as determined by linear regression analysis.

	Aroostook	Charlo	Chatham	Doaktown	Fredericton	Moncton	Saint John
Minimum Air Temperature							
Winter	+0.3 °C/dec.	-	+0.3 °C/dec.	-	+0.2 °C/dec.	+0.3 °C/dec.	+0.2 °C/dec.
Spring	+0.3 °C/dec.	+0.3 °C/dec.	+0.1 °C/dec.	+0.4 °C/dec.	+0.1 °C/dec.	+0.1 °C/dec.	+0.1 °C/dec.
Summer	-[1]	+0.3 °C/dec.	+0.1 °C/dec.	+0.5 °C/dec.	+0.1 °C/dec.	+0.1 °C/dec.	+0.1 °C/dec.
Autumn	+0.1 °C/dec.	-	+0.1 °C/dec.	+0.2 °C/dec.	+0.1 °C/dec.	+0.1 °C/dec.	+0.1 °C/dec.
Extreme (5th Percentile) Minimum Air Temperature (°C/dec.)							
Winter	-	-	+0.5 °C/dec.	-	+0.3 °C/dec.	+0.3 °C/dec.	-
Spring	-	-	+0.4 °C/dec.	-	-	-	-
Summer	-	+0.2 °C/dec.	+0.1 °C/dec.	+0.5 °C/dec.	-	+0.2 °C/dec.	-
Autumn	-	-0.5 °C/dec.	-	-	-	-	-
Extreme (95th Percentile) Minimum Air Temperature (°C/dec.)							
Winter	-	-	+0.2 °C/dec.	-	+0.2 °C/dec.	+0.2 °C/dec.	+0.3 °C/dec.
Spring	-	-		+0.7 °C/dec.	-	-	+0.2 °C/dec.
Summer	-	+0.2 °C/dec.	+0.1 °C/dec.	+0.3 °C/dec.	+0.1 °C/dec.	-	+0.2 °C/dec.
Autumn	-	-0.5 °C/dec.	+0.1 °C/dec.	-	-	-	+0.2 °C/dec.

[1] Trend was not statistically significant ($p<0.05$)

Table 24. Trends in total precipitation, frequency of precipitation, and average precipitation per event at meteorological stations in New Brunswick, as determined by linear regression analysis (1929-2000).

	Aroostook	Charlo	Chatham	Doaktown	Fredericton	Moncton	Saint John
Total Precipitation (mm)							
Winter	-[1]	-	-	+16 mm/dec.	-	+11 mm/dec.	-17 mm/dec.
Spring	-	-	-	+26 mm/dec.	-	-	-
Summer	-	-	-	+20 mm/dec.	-	-	-
Autumn	-	-	-	+14 mm/dec.	-	-	-
Frequency of Precipitation (days)							
Winter	-	-	-	+2.6 d/dec.	-		-
Spring	+1.2 d/dec.	-	+1.4 d/dec.	+4.2 d/dec.	-	+1.5 d/dec.	-
Summer	-	-	+1.2 d/dec.	+2.6 d/dec.	-	+1.4 d/dec.	-
Autumn	-	-	-	+2.8 d/dec.	-	+1.0 d/dec.	-
Precipitation per Event (mm/day)							
Winter	-	-	-	-	-	-	-0.5 mm/d/dec.
Spring	-	-	-	-	-	-	-
Summer	-	-	-	-	-	-	-
Autumn	-	-	-0.3 mm/d/dec.	-0.3 mm/d/dec.	-	-	-

[1] Trend was not statistically significant ($p<0.05$)

Table 25. Location and average (± 1 standard error) climatic conditions (1961-1990) at meteorological stations in New Brunswick.

Meteorological Station	ID[1]	Latitude, Longitude	Mean Annual Temperature (ºC)	Mean Annual Precipitation (mm)
Charlo Airport[2]	8100880	47º 59’ N; 66º 20’ W	3.4 ± 0.1	1053 ± 32
Chatham Airport	8101000	47º 01’ N; 65º 27’ W	5.0 ± 0.1	1087 ± 32
Aroostook	8100300	46º 48’ N; 67º 43’ W	4.0 ± 0.1	1103 ± 30
Doaktown[3]	8101200	46º 33’ N; 66º 09’ W	4.7 ± 0.2	1072 ± 27
Moncton Airport	8103200	46º 06’ N; 64º 47’ W	5.3 ± 0.1	1227 ± 34
Fredericton Airport	8101500	45º 52’ N; 66º 32’ W	5.6 ± 0.1	1133 ± 32
Saint John Airport	8104900	45º 19’ N; 65º 53’ W	5.2 ± 0.1	1433 ± 40

[1] Climate ID assigned by the Meteorological Service of Canada
[2] Precipitation time series extends from 1966-1990
[3] Data was not homogenised to remove non-climatic inconsistencies

Table 26. Location, drainage area (km^2), and average (± 1 standard error) annual discharge (1961-1990) at hydrometric stations in New Brunswick.

Hydrometric Station	ID[1]	Latitude, Longitude	Drainage Area (km^2)	Mean Annual Discharge (m^3/s)
Restigouche R. below Kedgwick R.[2]	01BC001	47º 40’ N; 67º 29’ W	3,160	65.7 ± 2.6
Saint John R. at Fort Kent	01AD002	47º 15’ N; 68º 36’ W	14,700	279.3 ± 11.9
NW Miramichi R. at Trout Bk.[3]	01BQ001	47º 06’ N; 65º 50’ W	948	20.9 ± 1.0
SW Miramichi R. at Blackville[3]	01BO001	46º 44’ N; 65º 50’ W	5,050	116.4 ± 4.9
Nashwaak R. at Durham Bridge[3]	01AL002	46º 08’ N; 66º 37’ W	1,450	35.0 ± 1.6
Canaan R. at East Canaan[2]	01AP002	46º 04’ N; 65º 22’ W	668	13.2 ± 0.7
Kennebecasis R. at Apohaqui[3]	01AP004	45º 42’ N; 65º 36’ W	1,100	25.0 ± 1.2

[1] Station ID assigned by the Water Survey of Canada
[2] Precipitation time series extends from 1963-1990
[3] Precipitation time series extends from 1962-1990

Table 27. Surface and upper-atmospheric predictor variables (500 and 850 hectopascals [hPa]) obtained from the National Center for Environmental Prediction / National Center for Atmospheric Research (NCEP/NCAR) Reanalysis (Kalnay et al. 1996) and the Canadian Global Coupled Model (CGCM) for use in statistical downscaling.

Predictor Variable	Abbreviation
Mean temperature at 2 m (ºC)	T
Mean sea level pressure (hPa)	mslp
500 hPa Geopotential height (m)	H_{500}
850 hPa Geopotential height (m)	H_{850}
Near surface specific humidity (g/kg)	q
Specific humidity at 500 hPa height (g/kg)	q_{500}
Specific humidity at 850 hPa height (g/kg)	q_{850}
Geostrophic airflow velocity[1] (hPa)	F_s, F_{500}, F_{850}
Vorticity[1] (hPa)	Z_s, Z_{500}, Z_{850}
Zonal velocity component[1]	U_s, U_{500}, U_{850}
Meridional velocity component[1]	V_s, V_{500}, V_{850}
Wind direction[1]	W_s, W_{500}, W_{850}
Divergence[1] (hPa)	D_s, D_{500}, D_{850}

[1] Secondary (airflow) variables derived from pressure fields (surface, geopotential height fields of 500 and 850 hPa) (Jones et al. 1993)

Table 28. Predictor variables selected in the calibration and validation of daily maximum and minimum air temperature models (1961-1990), as derived from statistical downscaling of the Canadian Global Coupled Model (CGCM1-GA1).

Meteorological Station	Predictors	Maximum Temperature		Minimum Temperature	
		r^2	Standard Error	r^2	Standard Error
Charlo	$T, T_{i-1}, Z_s, U_s, U_{850}$	0.759	2.996	0.753	2.888
Chatham	$T, T_{i-1}, Z_{850}, U_s, H_{500}$	0.744	3.149	0.740	3.018
Aroostook	$T, T_{i-1}, Z_s, Z_{850}, q_{850}$	0.809	2.757	0.815	3.057
Doaktown	$T, T_{i-1}, Z_{850}, V_{850}, q_{850}$	0.783	2.968	0.761	3.363
Moncton	$T, T_{i-1}, Z_{850}, \mathrm{mslp}, H_{500}$	0.764	2.975	0.778	2.701
Fredericton	$T, T_{i-1}, U_s, q, q_{850}$	0.821	2.651	0.804	2.714
Saint John	$T, T_{i-1}, D_s, H_{500}, q_{850}$	0.759	2.594	0.707	3.075

Table 29. Predictor variables selected in the calibration and validation of daily precipitation models (1961-1990), as derived from statistical downscaling of the Canadian Global Coupled Model (CGCM1-GA1).

Meteorological Station	Predictors	r^2	Standard Error
Charlo	$q_{500}, U_s, V_s, U_{850}, Z_s$	0.127	0.430
Chatham	$q_{500}, U_s, V_s, q_{850}, D_s$	0.134	0.446
Aroostook	$q_{500}, U_s, V_{850}, q, D_s$	0.082	0.406
Doaktown	$q_{500}, U_s, V_{850}, Z_{500}, T$	0.075	0.421
Moncton	$q_{500}, U_s, V_s, q, H_{500}$	0.143	0.456
Fredericton	$q_{500}, U_s, V_{850}, Z_{500}, H_{500}$	0.137	0.448
Saint John	$q_{500}, U_s, V_{850}, Z_{500}, H_{500}$	0.114	0.496

Table 30. Predictor variables selected in the calibration and validation of daily discharge models (1961-1990), as derived from statistical downscaling of the Canadian Global Coupled Model (CGCM1-GA1).

Hydrometric Station	Predictors	r^2	Standard Error
Saint John R. at For Kent	q, q_{850}, T, V_s, Z_s	0.336	1.995
Nashwaak R. at Durham Bridge	q, q_{850}, T, V_{850}, H_{500}	0.341	2.037
Canaan R. at East Canaan	q, q_{850}, T, V_s, V_{850}	0.344	2.618
Kennebecasis R. at Apohaqui	q, q_{850}, T, V_s, V_{850}	0.352	2.056
Restigouche R. below Kedgwick R.	q, q_{850}, T, V_{500}, Z_s	0.324	1.919
SW Miramichi R. at Blackville	q, q_{850}, T, V_{850}, Z_{850}	0.354	1.879
NW Miramichi R. at Trout Bk.	q, q_{850}, T, H_{500}, Z_s	0.337	2.018

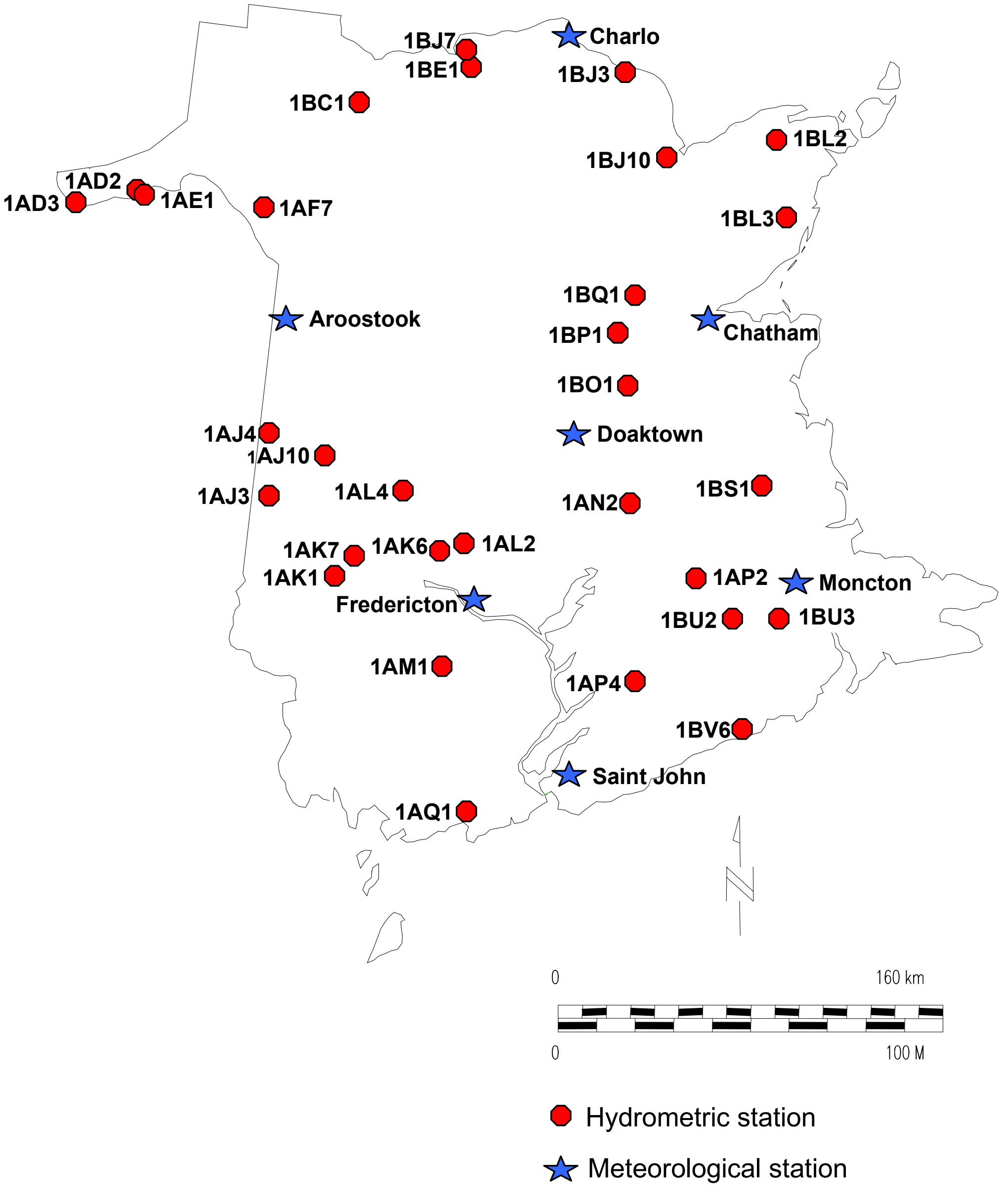

Figure 1. Location of selected hydrometric and meteorological stations in New Brunswick.

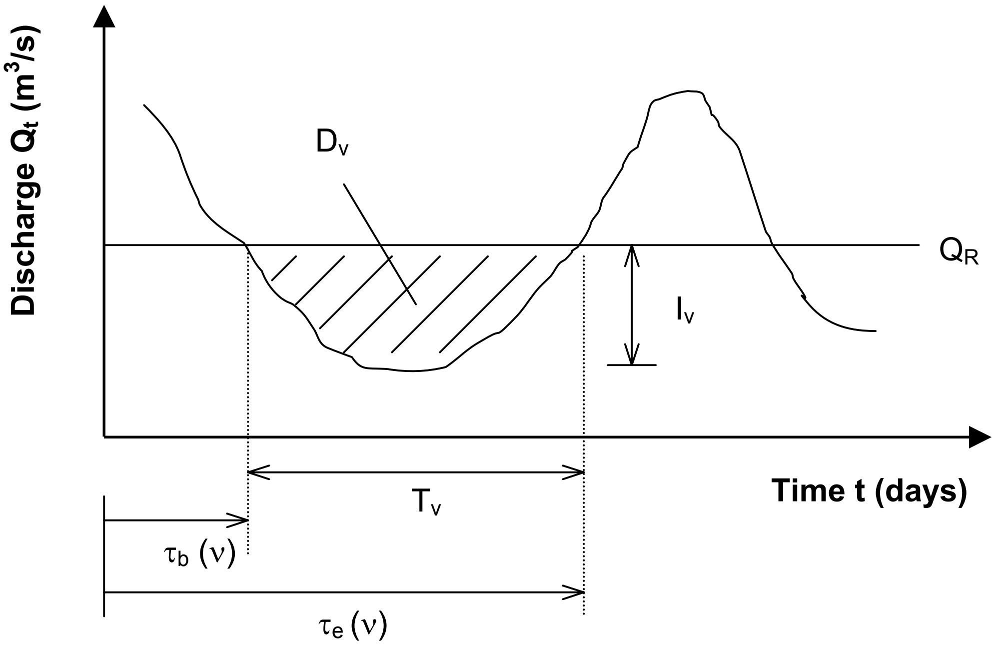

Figure 2. Hydrograph representing low flow event characteristics.

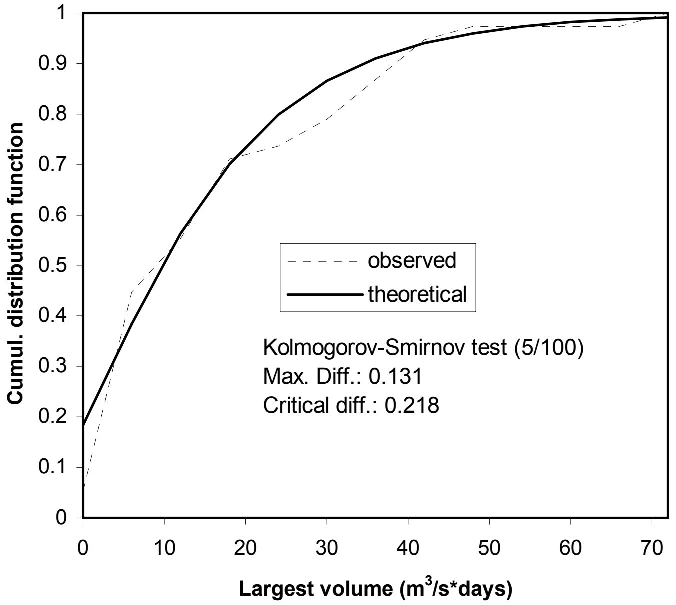

Figure 3. Theoretical (Weibull) and observed largest volume distribution for station 01BU002.

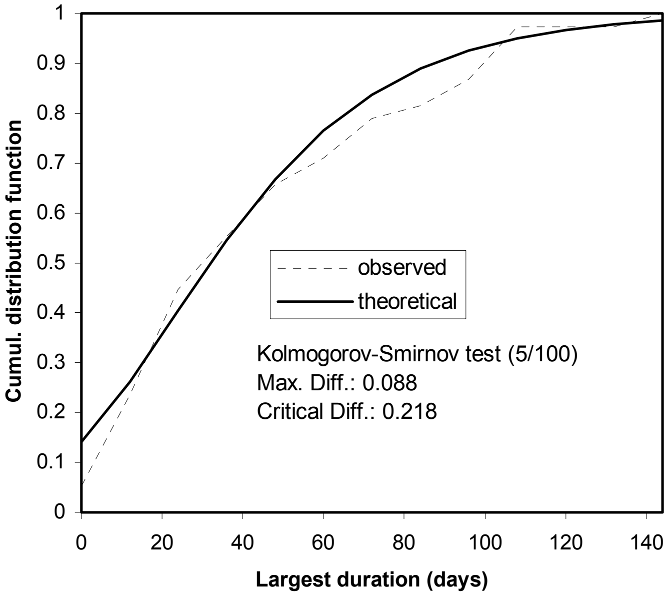

Figure 4. Theoretical (Weibull) and observed largest duration distribution for station 01BU002.

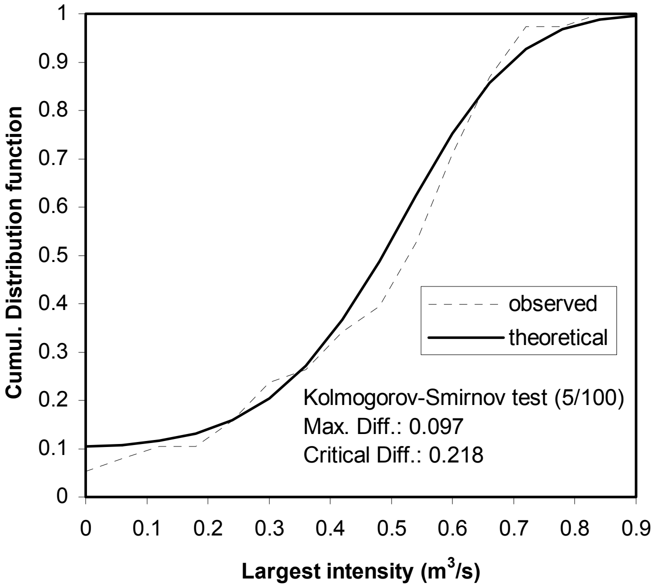

Figure 5. Theoretical (Weibull) and observed largest intensity distribution for station 01BU002.

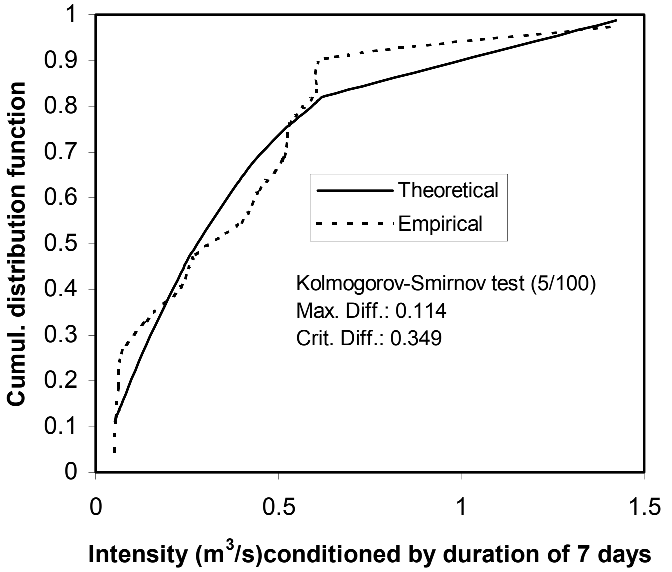

Figure 6. Theoretical (Weibull) and empirical distribution of the intensity (m^3/s) conditioned by a duration of 7 days for station 01BJ003.

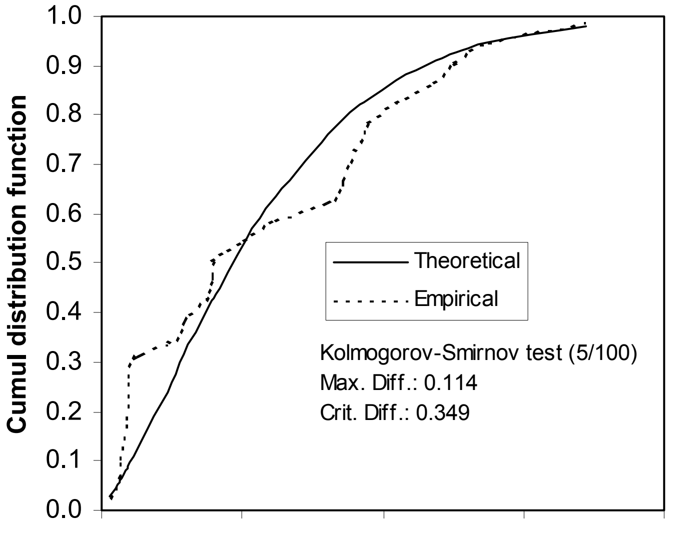

Figure 7. Theoretical (Weibull) and empirical distribution of the intensity (m^3/s) conditioned by a duration of 14 days for station 01BJ003.

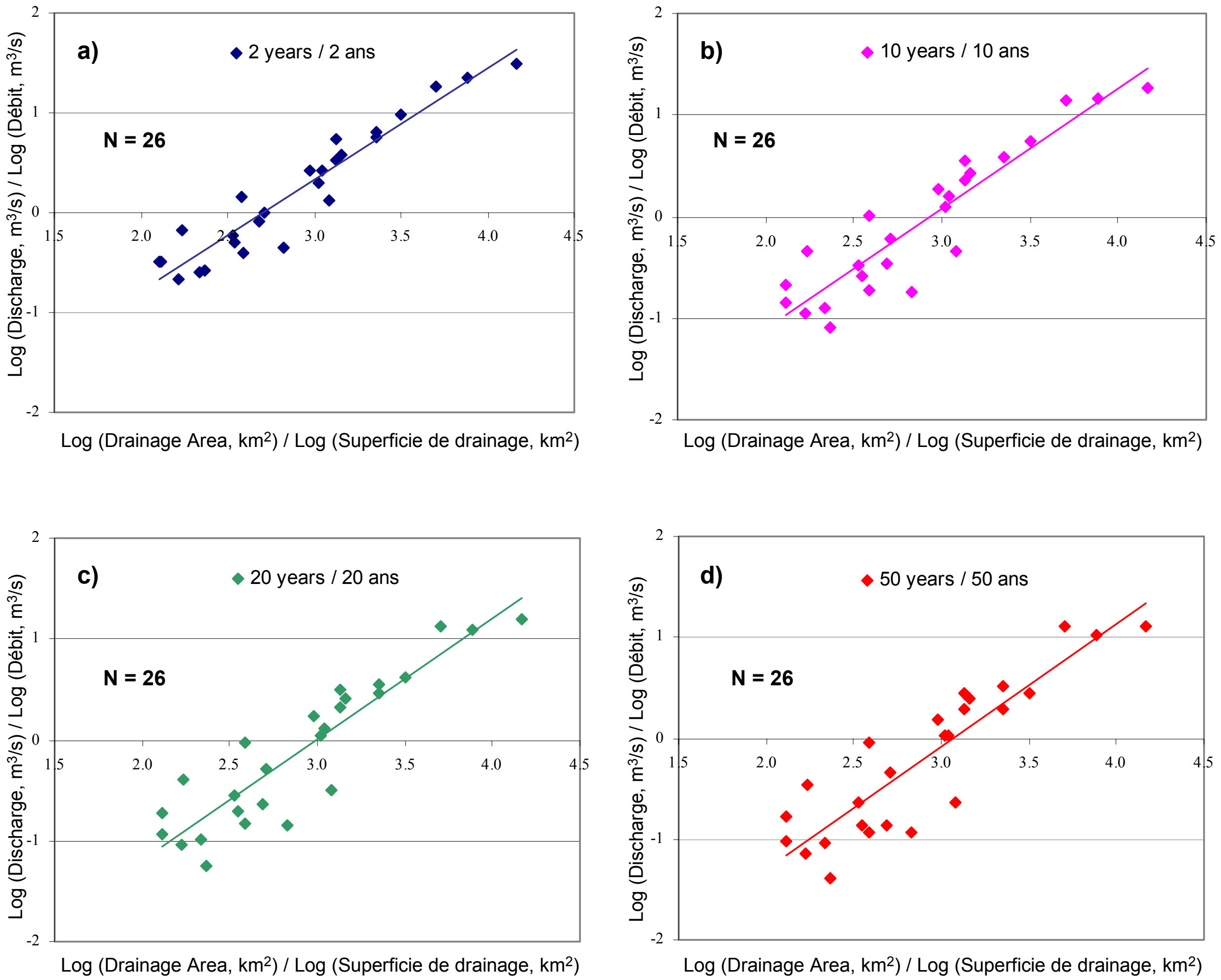

Figure 8. Regression analysis of 1-day low flow for return periods of 2, 10, 20, and 50 years (Log (Discharge, m^3/s) vs. Log (Drainage area, km^2))using the annual minimum series method. Equations are applicable to basins with a drainage area from 129 km^2 to 14 700 km^2. N = number of analysed stations.

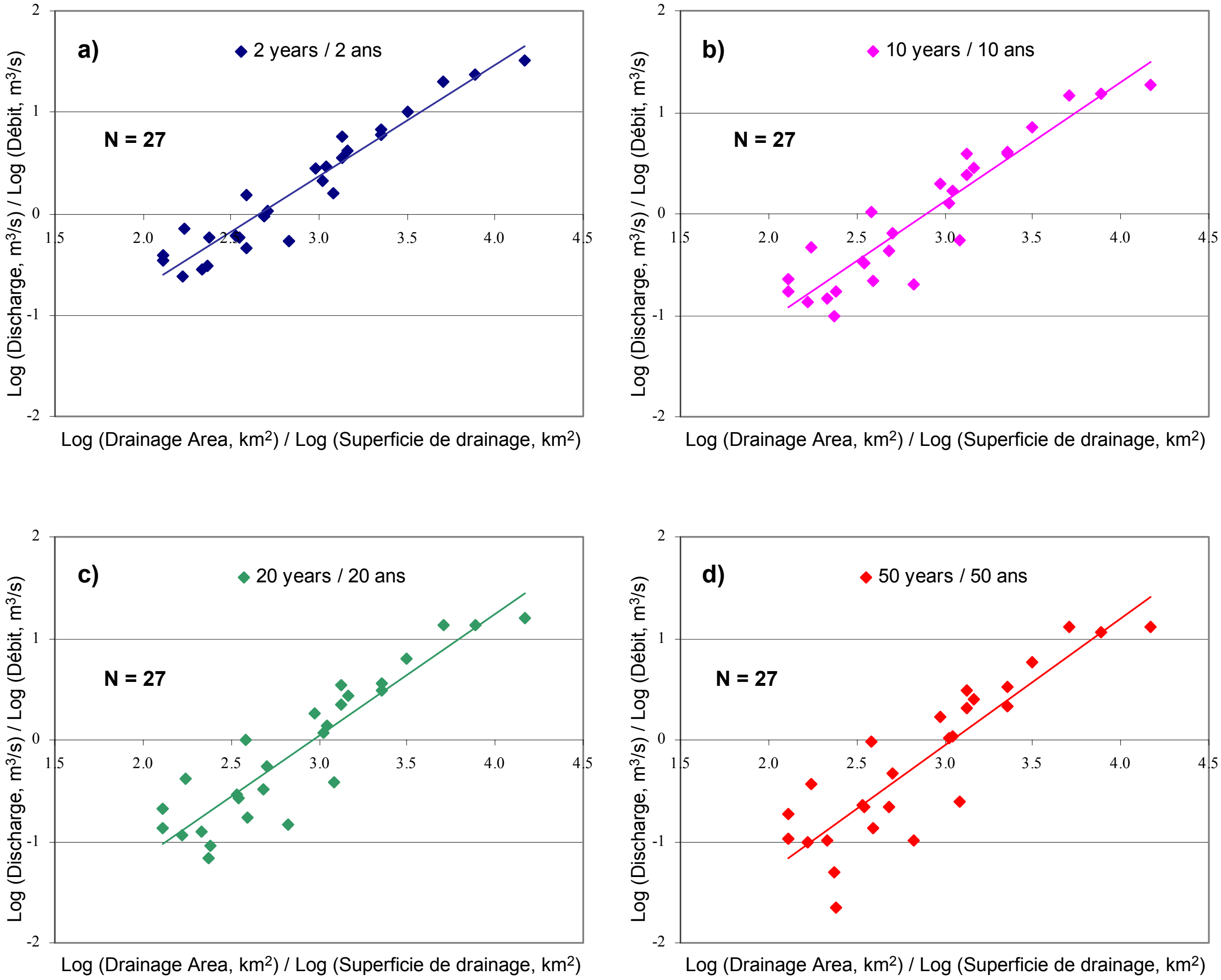

Figure 9. Regression analysis of 7-day low flow for return periods of 2, 10, 20, and 50 years (Log (Discharge, m^3/s) vs. Log (Drainage area, km^2)) using the annual minimum series method. Equations are applicable to basins with a drainage area from 129 km^2 to 14 700 km^2. N = number of analysed stations.

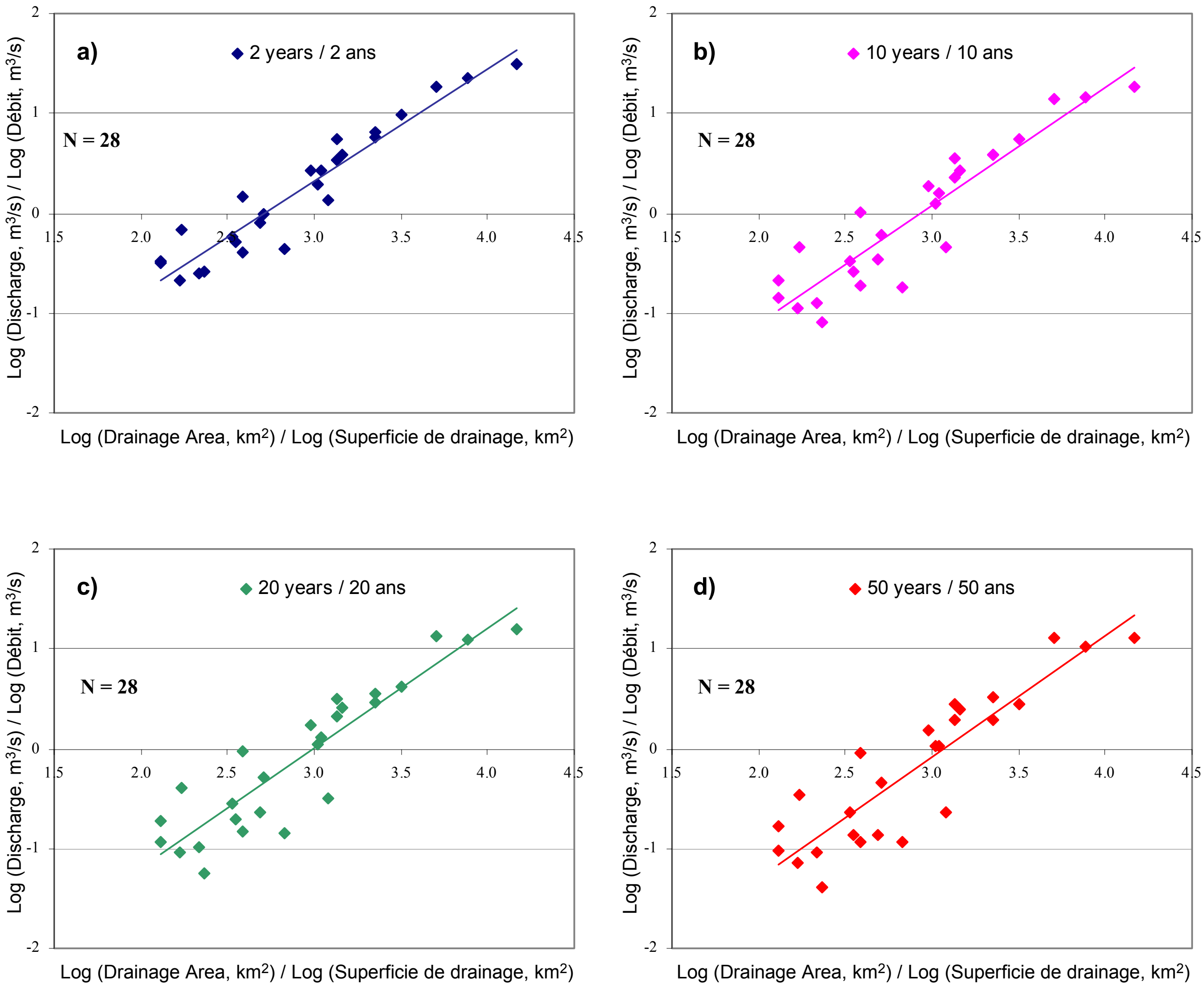

Figure 10. Regression analysis of 14-day low flow for return periods of 2, 10, 20, and 50 years (Log (Discharge, m^3/s) vs. Log (Drainage area, km^2)) using the annual minimum series method. Equations are applicable to basins with drainage area from 129 km^2 to 14 700 km^2. N = number of analysed stations.

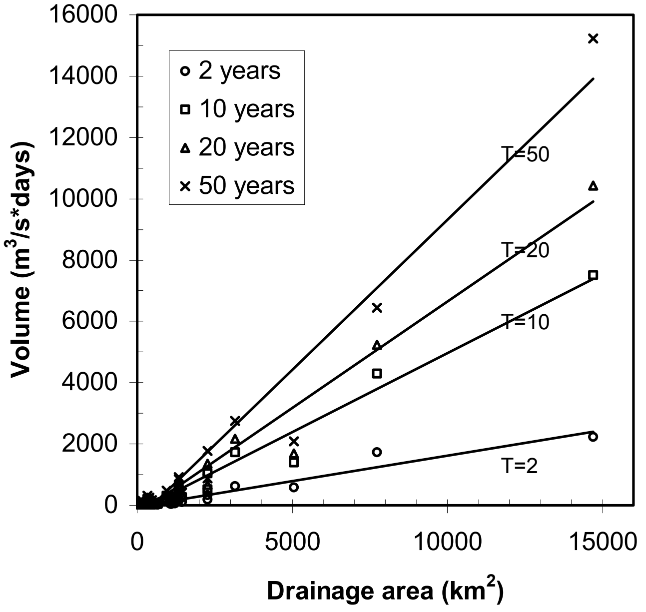

Figure 11. Regionalization of low flow volumes in N.B (28 stations).

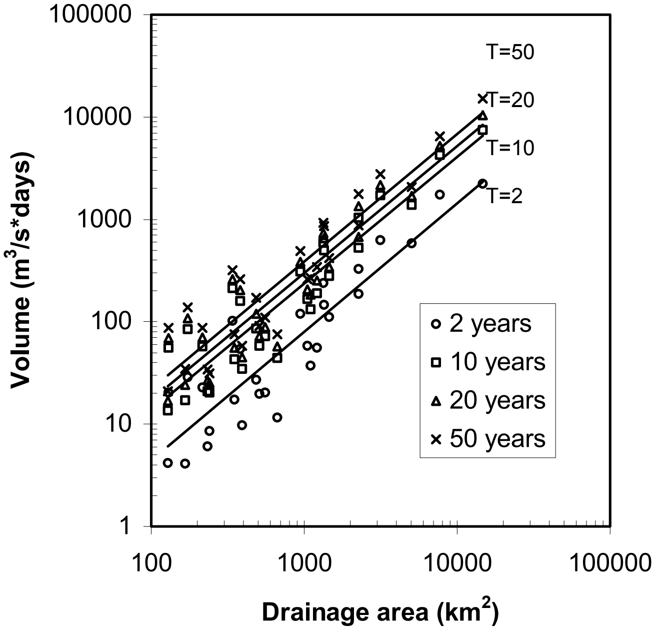

Figure 12. Regionalization of low flow volumes (logarithmic scale) in N.B (28 stations).

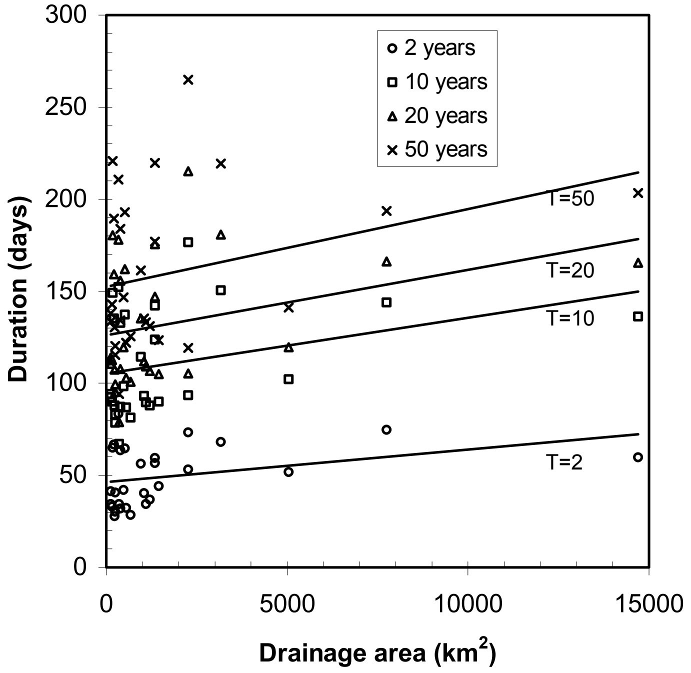

Figure 13. Regionalization of low flow durations in N.B (29 stations).

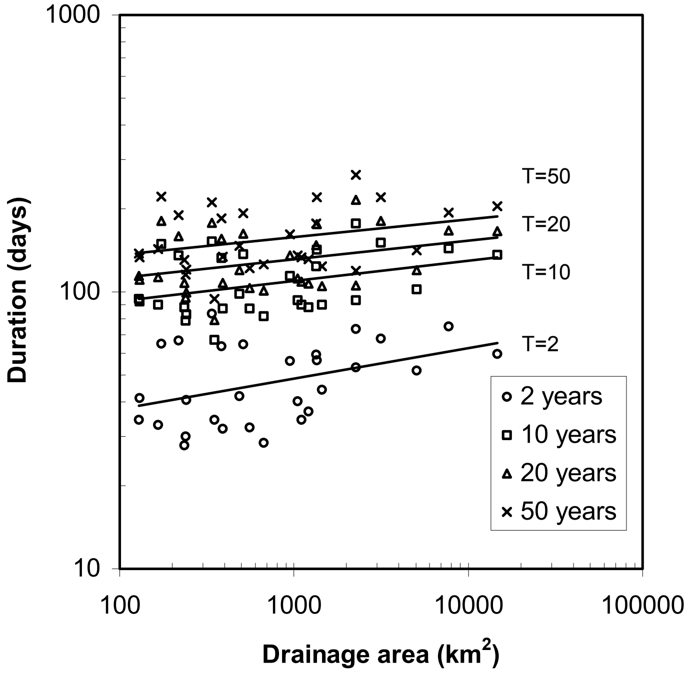

Figure 14. Regionalization of low flow durations (logarithmic scale) in N.B (29 stations).

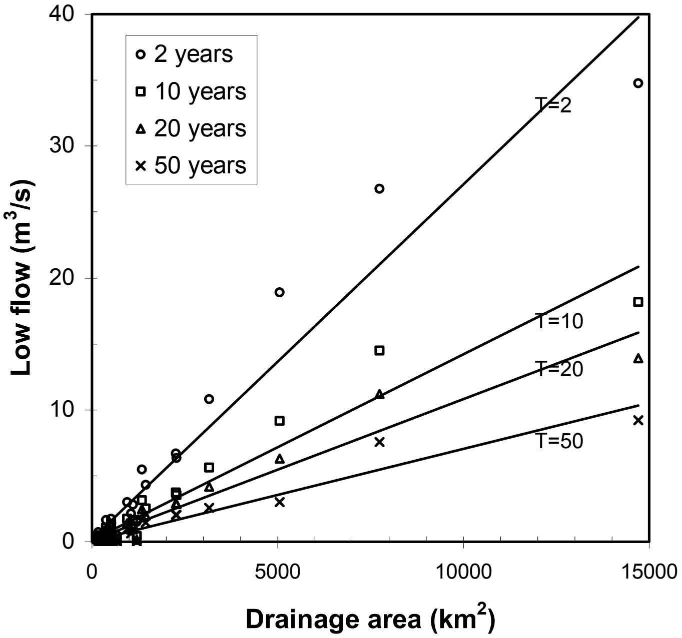

Figure 15. Regionalization of low flow in N.B (26 stations).

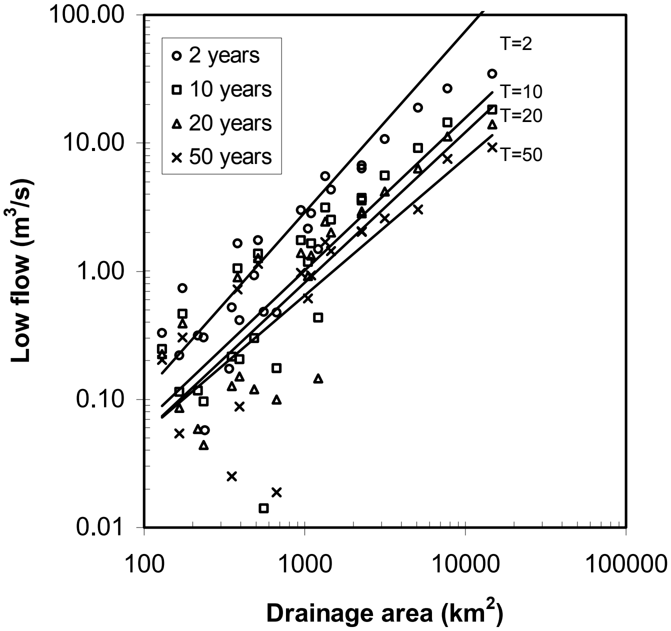

Figure 16. Regionalization of low flow (logarithmic scale) in N.B (26 stations).

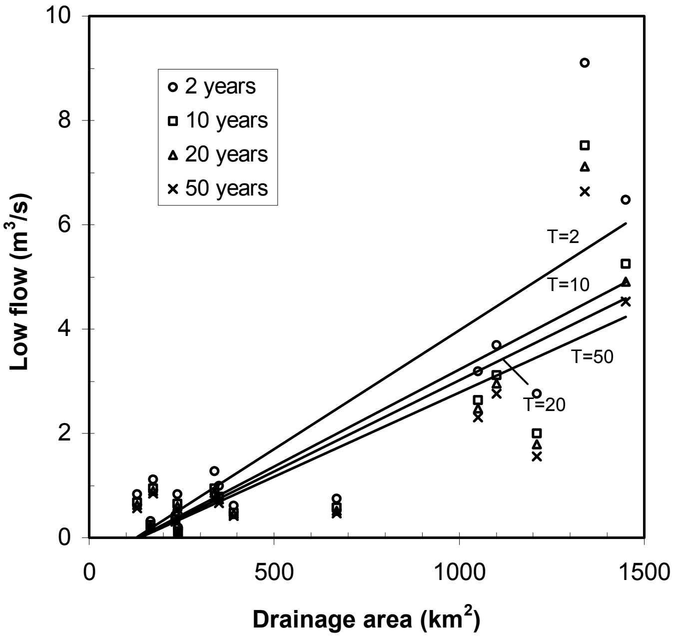

Figure 17. Regionalization of low flow conditioned by a 7-day duration in N.B (15 stations).

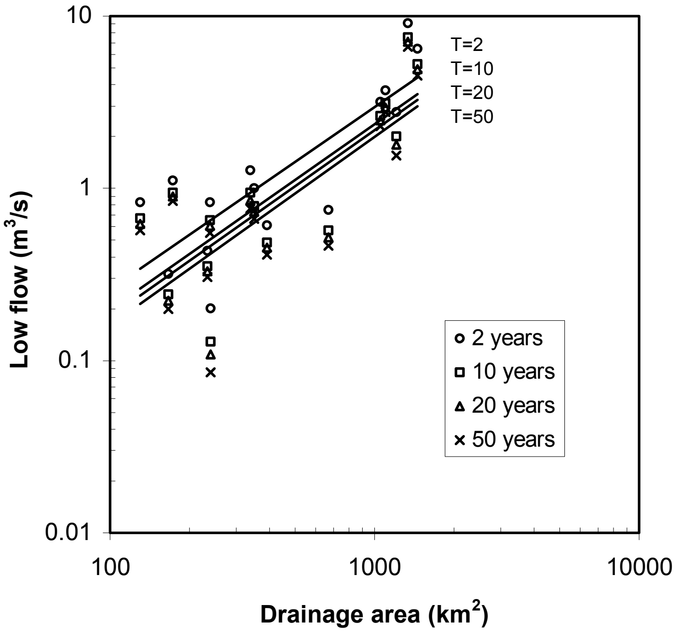

Figure 18. Regionalization of low flow conditioned by a 7-day duration (logarithmic scale) in N.B (15 stations).

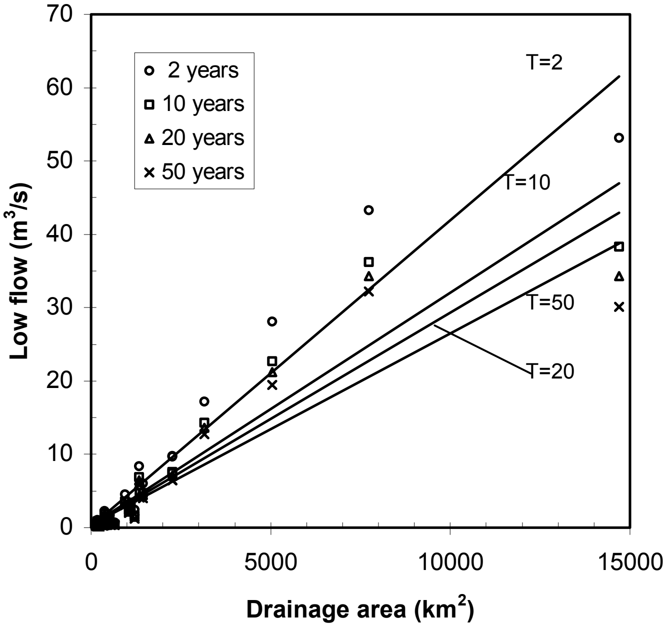

Figure 19. Regionalization of low flow conditioned by a 14-day duration in N.B (29 stations).

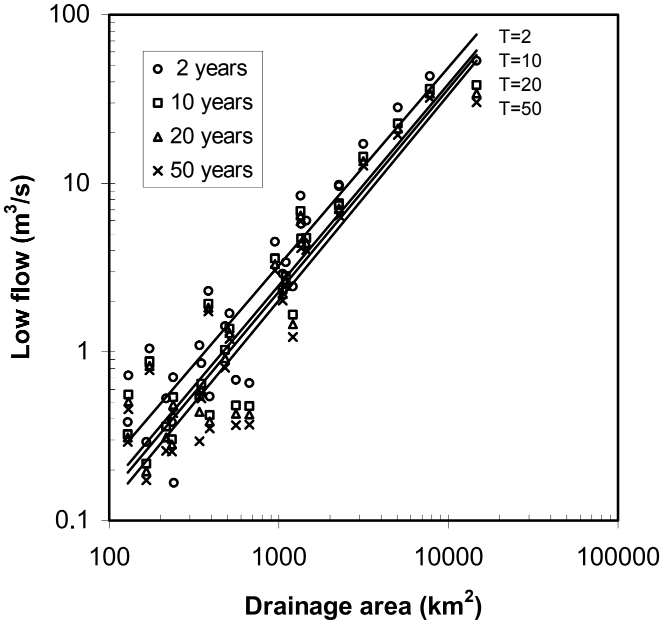

Figure 20. Regionalization of low flow conditioned by a 14-day duration (logarithmic scale) in N.B (29 stations).

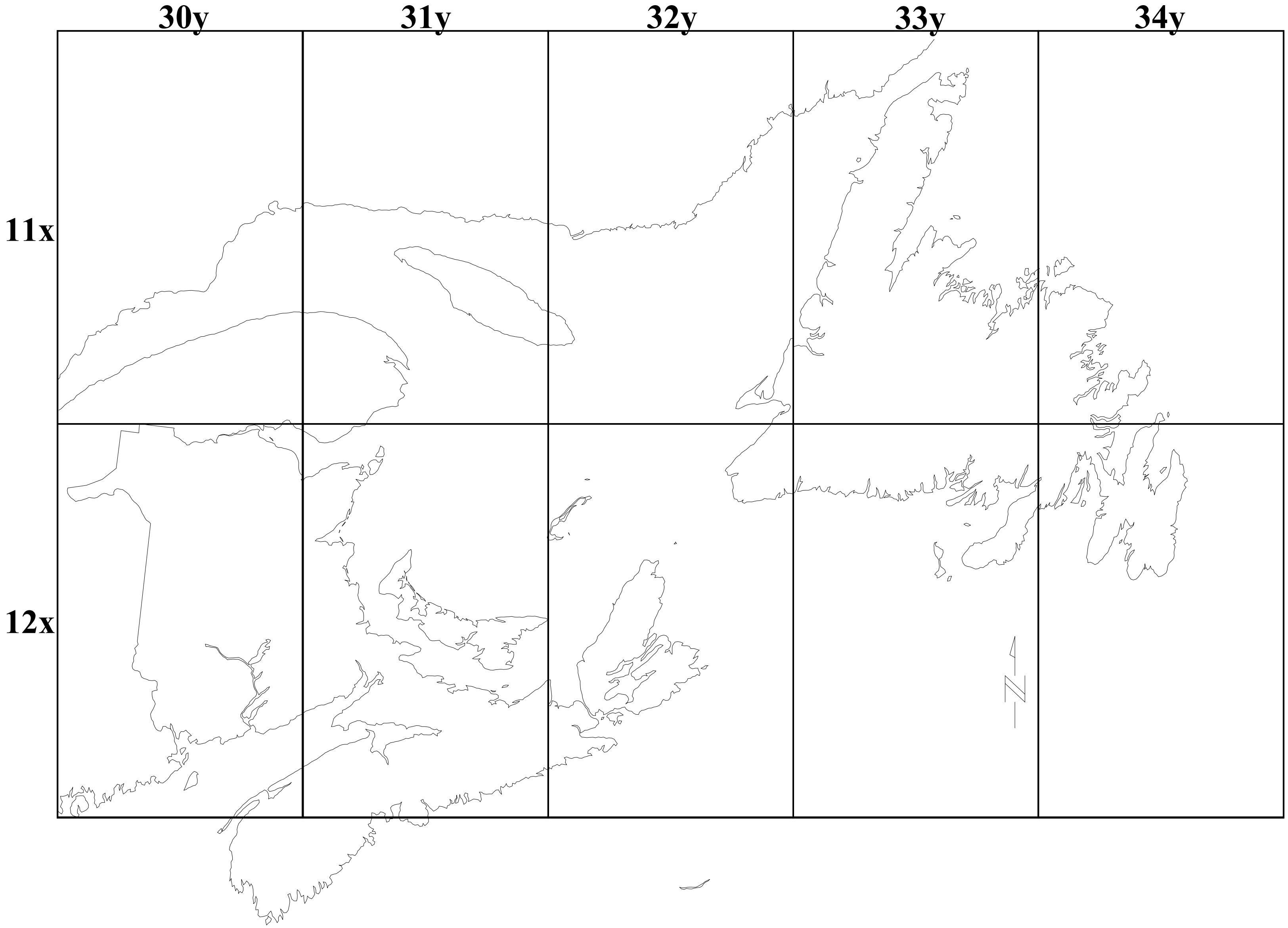

Figure 21. Canadian Global Climate Model (CGCM) grid (3.75° latitude x 3.75° longitude) superimposed over Atlantic Canada.

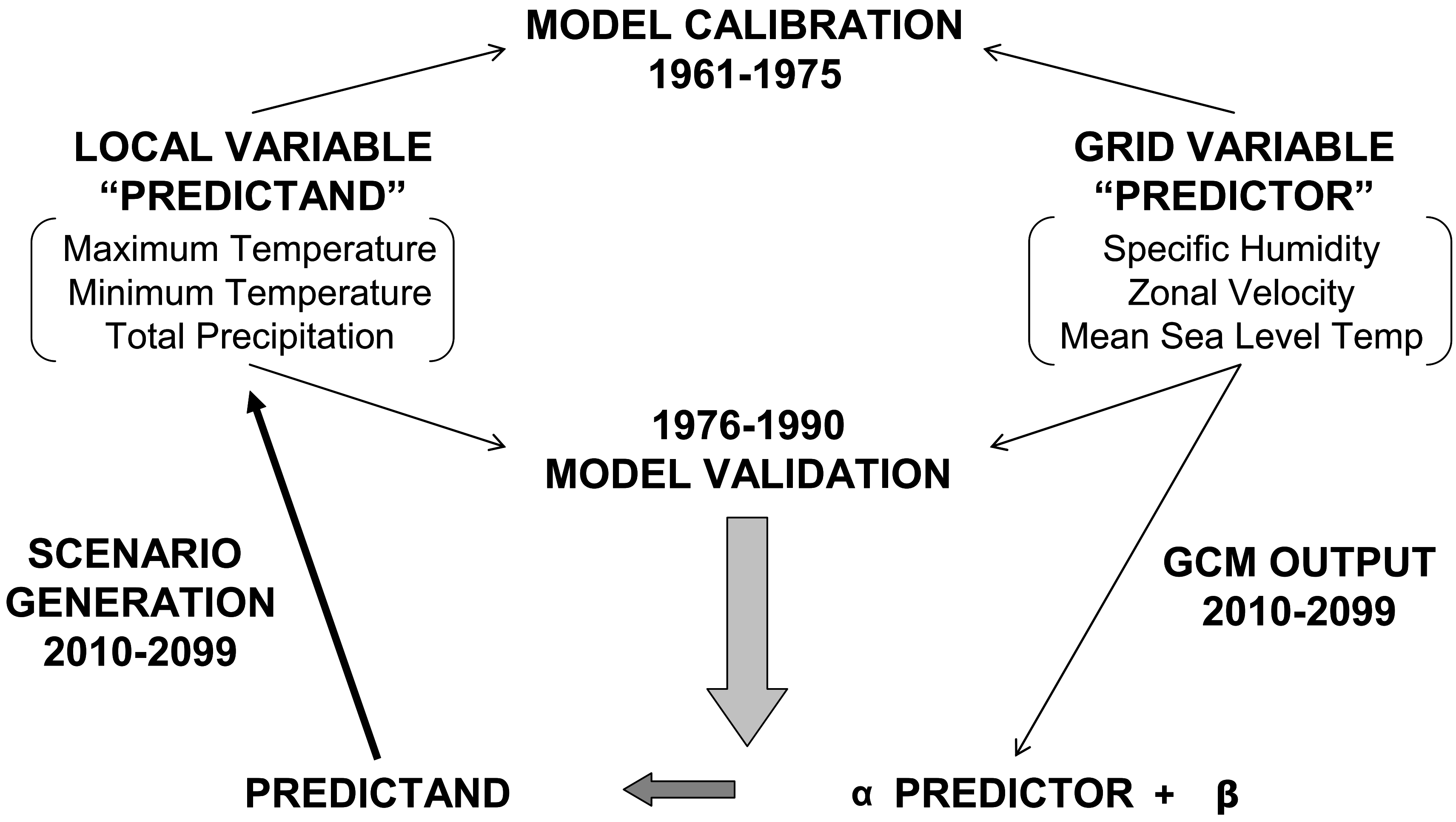

Figure 22. Statistical downscaling of Global Circulation Model (GCM) output to site-specific climate scenarios.

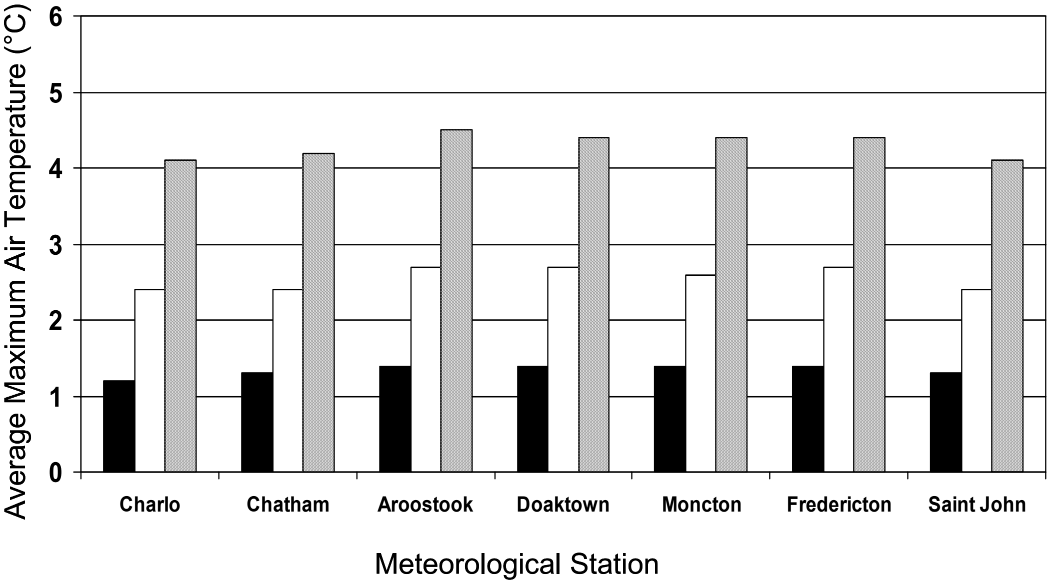

Figure 23. Change in mean annual maximum air temperature (ºC) in New Brunswick from current climate conditions (1961-1990) to 2020s (black), 2050s (white), and 2080s (hatched) as derived from statistical downscaling of the Canadian Global Coupled Model (CGCM1-GA1).

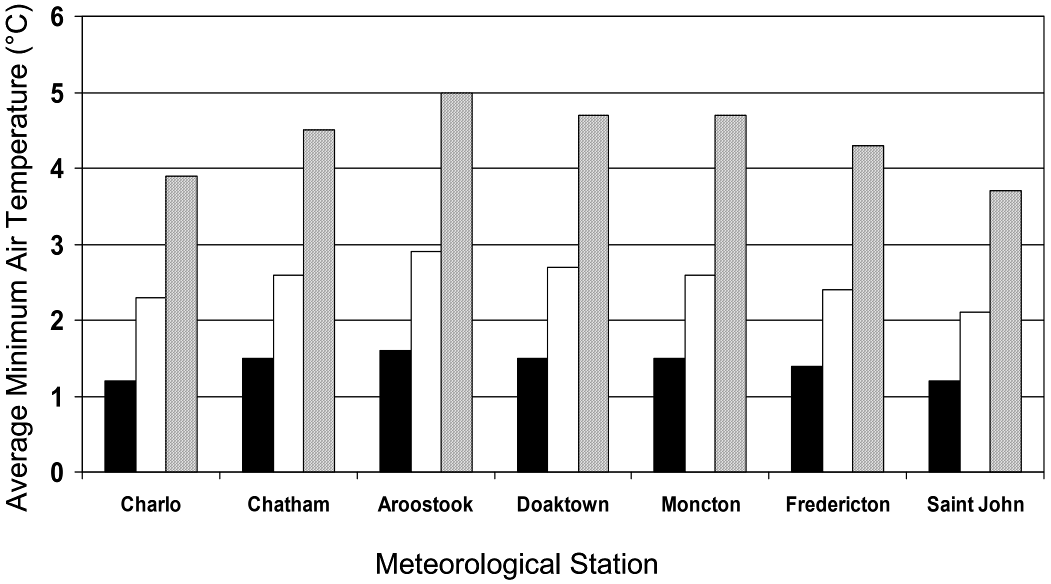

Figure 24. Change in mean annual minimum air temperature (ºC) in New Brunswick from current climate conditions (1961-1990) to 2020s (black), 2050s (white), and 2080s (hatched) as derived from statistical downscaling of the Canadian Global Coupled Model (CGCM1-GA1).

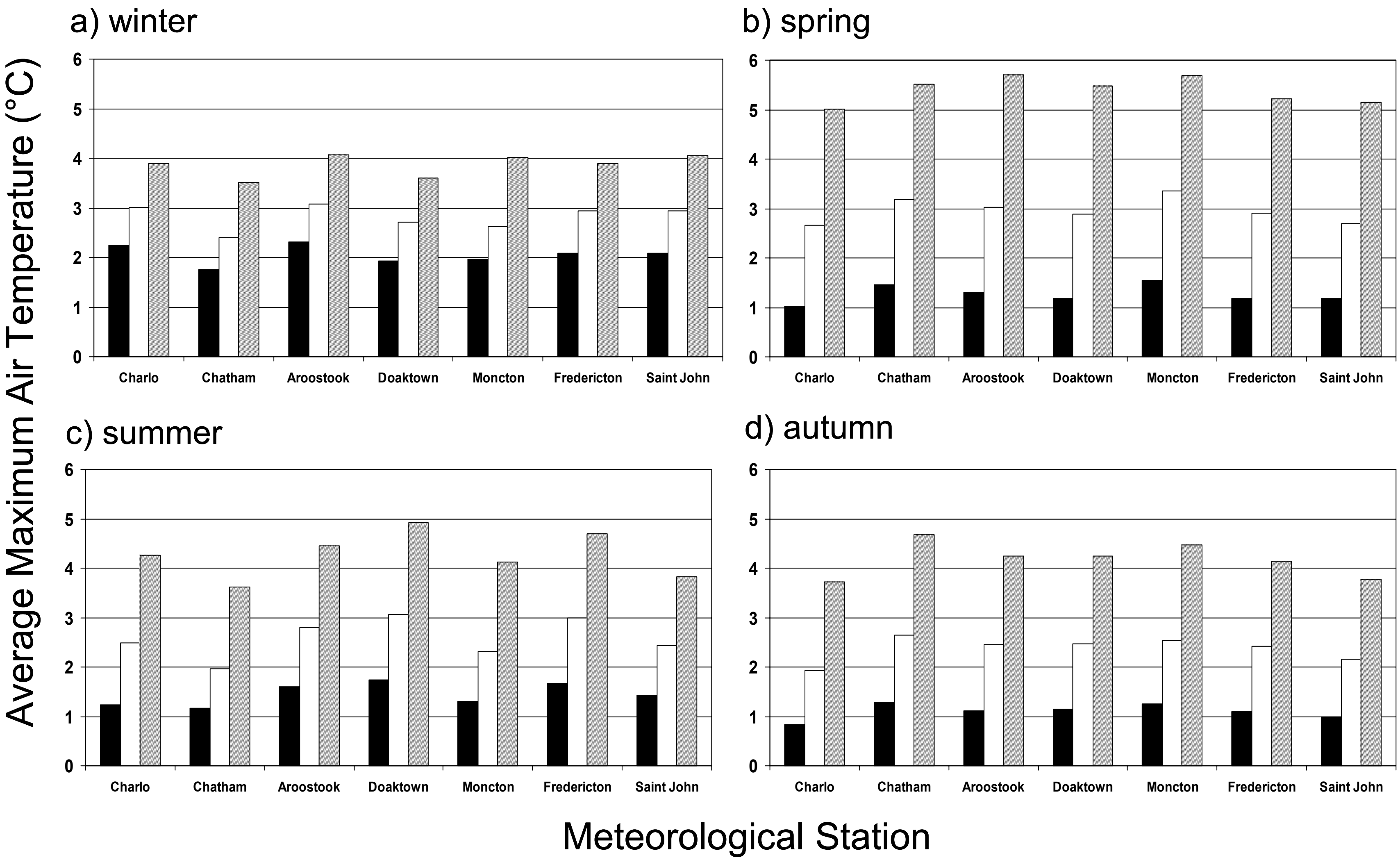

Figure 25. Change in mean winter (a), spring (b), summer (c), and autumn (d) maximum air temperature (ºC) in New Brunswick from current climate conditions (1961-1990) to 2020s (black), 2050s (white), and 2080s (hatched) as derived from statistical downscaling of the Canadian Global Coupled Model (CGCM1-GA1).

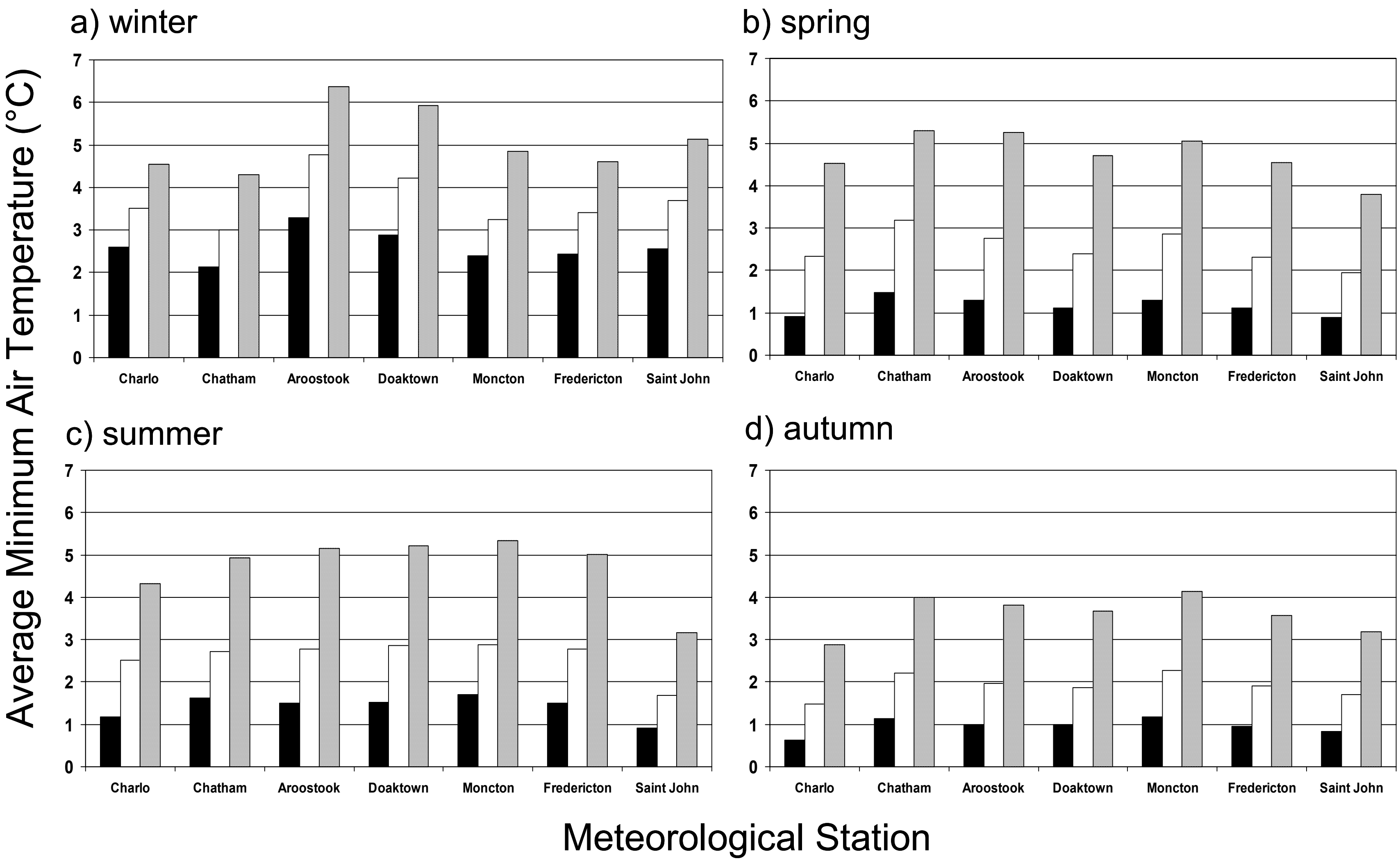

Figure 26. Change in mean winter (a), spring (b), summer (c), and autumn (d) minimum air temperature (ºC) in New Brunswick from current climate conditions (1961-1990) to 2020s (black), 2050s (white), and 2080s (hatched) as derived from statistical downscaling of the Canadian Global Coupled Model (CGCM1-GA1).

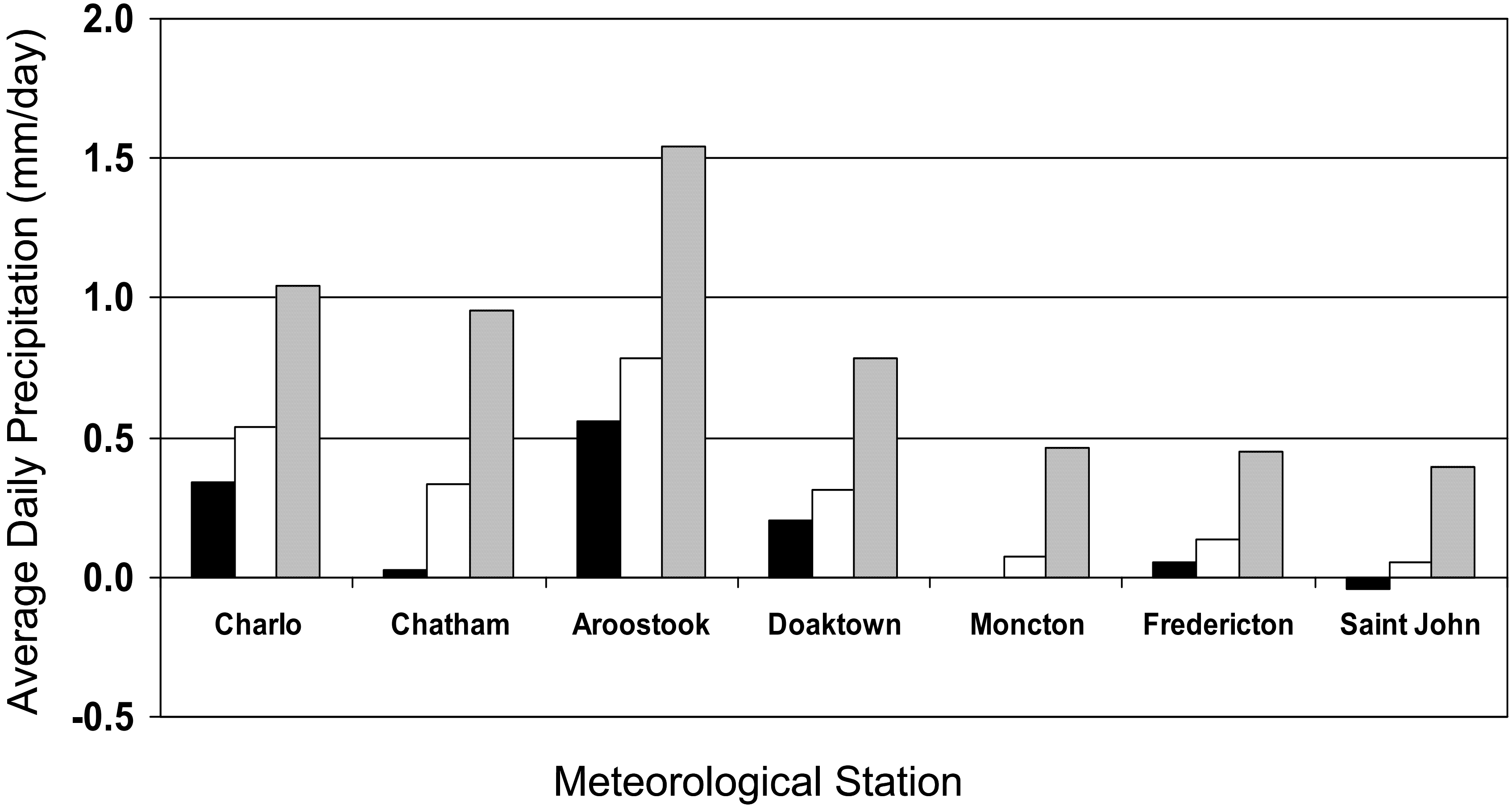

Figure 27. Change in mean daily precipitation (mm/day) in New Brunswick from current climate conditions (1961-1990) to 2020s (black), 2050s (white), and 2080s (hatched) as derived from statistical downscaling of the Canadian Global Coupled Model (CGCM1-GA1).

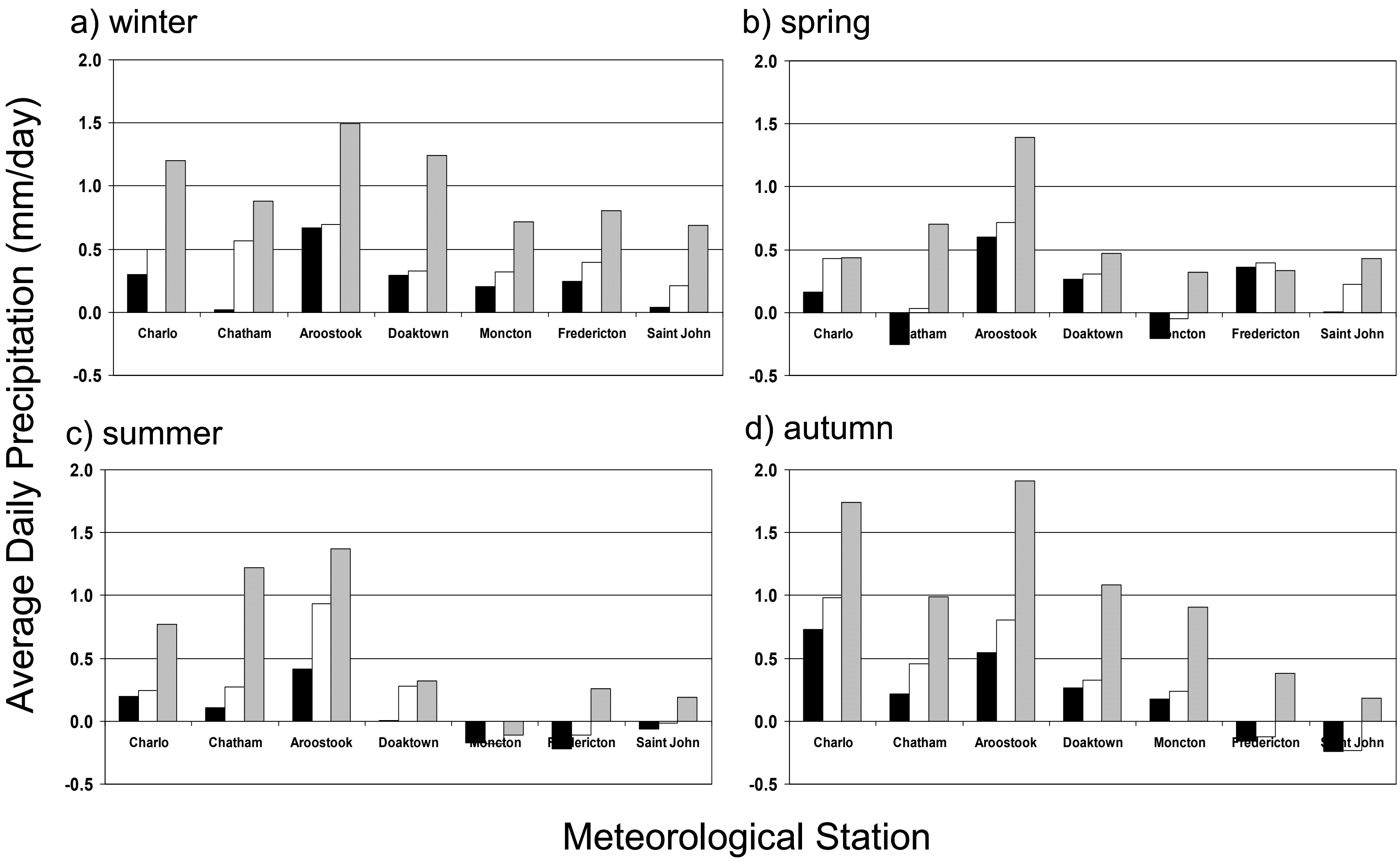

Figure 28. Change in mean daily winter (a), spring (b), summer (c), and autumn (d) precipitation (mm/day) in New Brunswick from current climate conditions (1961-1990) to 2020s (black), 2050s (white), and 2080s (hatched) as derived from statistical downscaling of the Canadian Global Coupled Model (CGCM1-GA1).

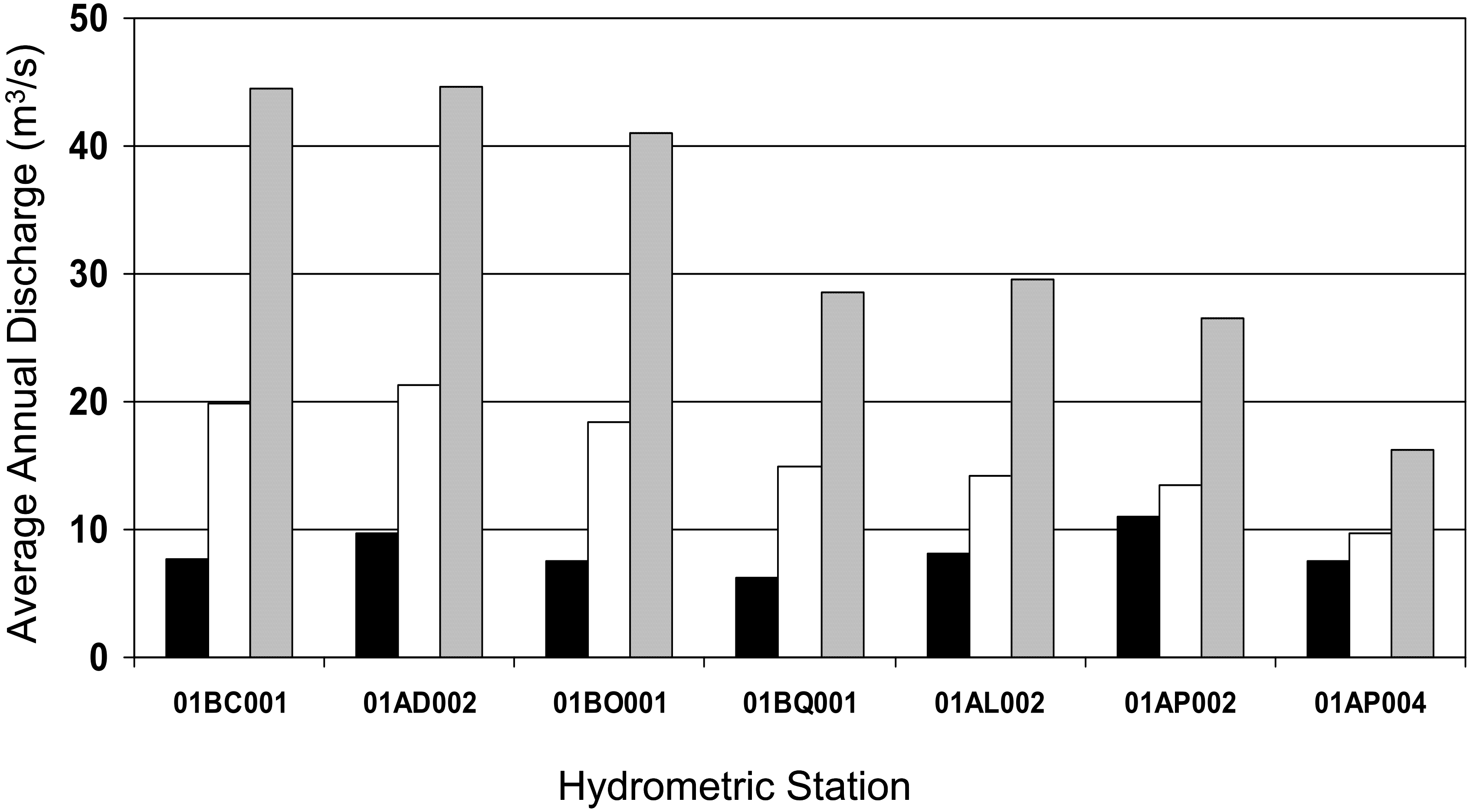

Figure 29. Change in mean annual discharge (m^3/s) in New Brunswick from current climate conditions (1961-1990) to 2020s (black), 2050s (white), and 2080s (hatched) as derived from statistical downscaling of the Canadian Global Coupled Model (CGCM1-GA1).

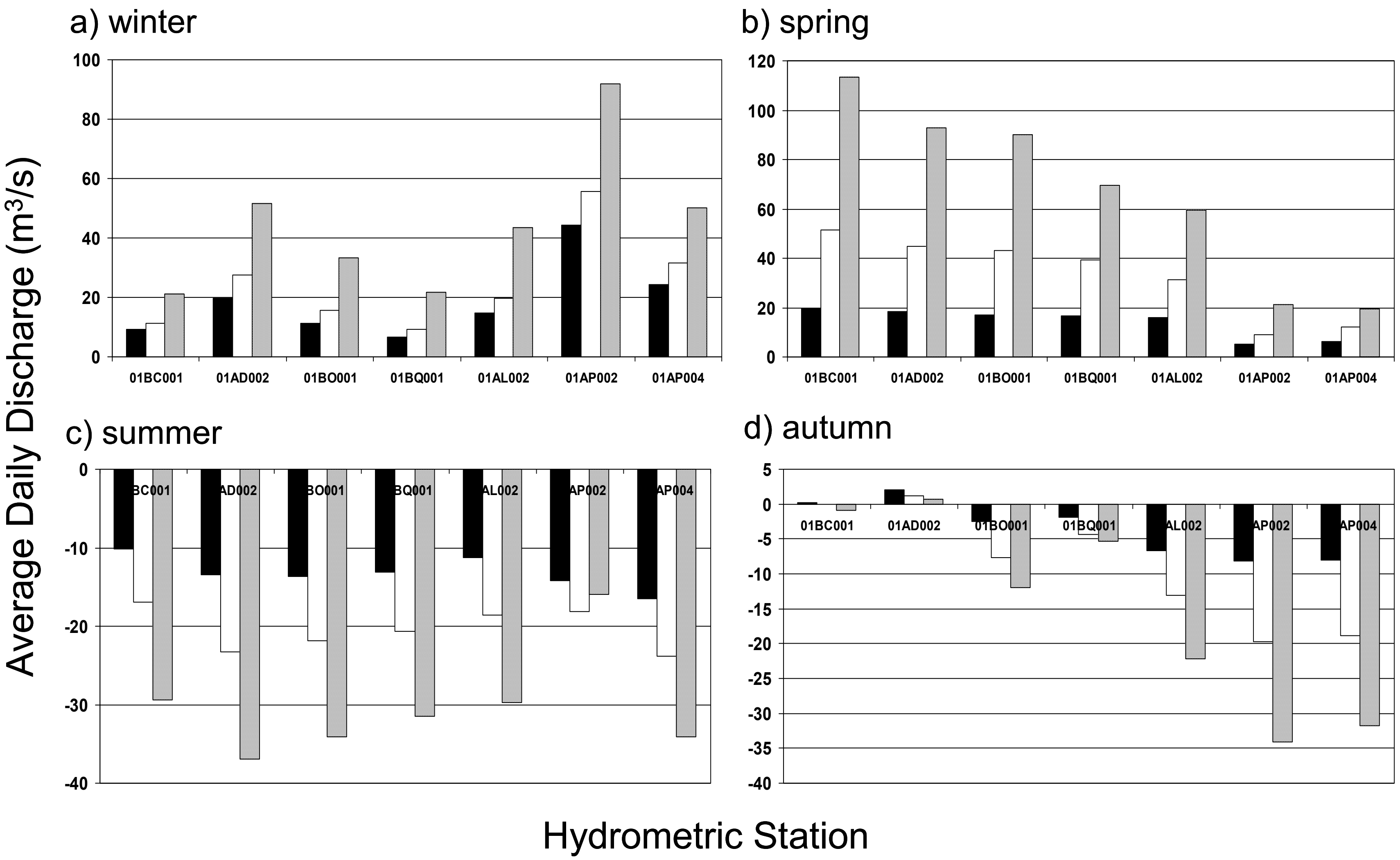

Figure 30. Change in mean daily winter (a), spring (b), summer (c), and autumn (d) discharge (m^3/s) in New Brunswick from current climate conditions (1961-1990) to 2020s (black), 2050s (white), and 2080s (hatched) as derived from statistical downscaling of the Canadian Global Coupled Model (CGCM1-GA1).