Floods and droughts under different climate change scenarios in New Brunswick

N. Turkkan, N. El-Jabi and D. Caissie

Fisheries and Oceans Canada
Oceans and Science Branch
Diadromous Fish Section
343 Université Avenue
Moncton, NB
E1C 9B6

2011

Canadian Technical Report of Fisheries and Aquatic Sciences 2928

Fisheries and Oceans Canada Pêches et Océans Canada

Canada

Canadian Technical Report of Fisheries and Aquatic Sciences

Technical reports contain scientific and technical information that contributes to existing knowledge but which is not normally appropriate for primary literature. Technical reports are directed primarily toward a worldwide audience and have an international distribution. No restriction is placed on subject matter and the series reflects the broad interests and policies of Fisheries and Oceans, namely, fisheries and aquatic sciences.

Technical reports may be cited as full publications. The correct citation appears above the abstract of each report. Each report is abstracted in the data base *Aquatic Sciences and Fisheries Abstracts*.

Technical reports are produced regionally but are numbered nationally. Requests for individual reports will be filled by the issuing establishment listed on the front cover and title page.

Numbers 1-456 in this series were issued as Technical Reports of the Fisheries Research Board of Canada. Numbers 457-714 were issued as Department of the Environment, Fisheries and Marine Service, Research and Development Directorate Technical Reports. Numbers 715-924 were issued as Department of Fisheries and Environment, Fisheries and Marine Service Technical Reports. The current series name was changed with report number 925.

Rapport technique canadien des sciences halieutiques et aquatiques

Les rapports techniques contiennent des renseignements scientifiques et techniques qui constituent une contribution aux connaissances actuelles, mais qui ne sont pas normalement appropriés pour la publication dans un journal scientifique. Les rapports techniques sont destinés essentiellement à un public international et ils sont distribués à cet échelon. II n'y a aucune restriction quant au sujet; de fait, la série reflète la vaste gamme des intérêts et des politiques de Pêches et Océans Canada, c'est-à-dire les sciences halieutiques et aquatiques.

Les rapports techniques peuvent être cités comme des publications à part entière. Le titre exact figure au-dessus du résumé de chaque rapport. Les rapports techniques sont résumés dans la base de données *Résumés des sciences aquatiques et halieutiques*.

Les rapports techniques sont produits à l'échelon régional, mais numérotés à l'échelon national. Les demandes de rapports seront satisfaites par l'établissement auteur dont le nom figure sur la couverture et la page du titre.

Les numéros 1 à 456 de cette série ont été publiés à titre de Rapports techniques de l'Office des recherches sur les pêcheries du Canada. Les numéros 457 à 714 sont parus à titre de Rapports techniques de la Direction générale de la recherche et du développe-ment, Service des pêches et de la mer, ministère de l'Environnement. Les numéros 715 à 924 ont été publiés à titre de Rapports techniques du Service des pêches et de la mer, ministère des Pêches et de l'Environnement. Le nom actuel de la série a été établi lors de la parution du numéro 925.

Canadian Technical Report of
Fisheries and Aquatic Sciences 2928

2011

Floods and droughts under different climate change scenarios In New Brunswick

by

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

Fisheries and Oceans Canada
Oceans and Science Branch
Diadromous Fish Section
343 Université Avenue
Moncton, NB
E1C 9B6

[1.] Université de Moncton, Faculty of Engineering, Moncton, NB, E1A 3E9

Cat. No. Fs. 97-6/2928E ISSN 0706-6457 (printed version)
Cat. No. F597-6/2928E-PDF ISNN 1488-5379 (on-line version)

Correct citation for this publication:

Turkkan, N., N. El-Jabi and D. Caissie. 2011. Floods and droughts under different climate change scenarios in New Brunswick. Can. Tech. Rep. Fish. Aquat. Sci. 2928: xii + 55p.

Funding and partners of the present study

New Nouveau Brunswick
CANADA

NEW BRUNSWICK ENVIRONMENTAL TRUST FUND

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

UNIVERSITÉ DE MONCTON
EDMUNDSTON MONCTON SHIPPAGAN

Daniel Caissie
Department of Fisheries & Oceans
Moncton, NB

Pêches et Océans Canada
Fisheries and Oceans Canada

2011

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS AND SYMBOLS

ANN	Artificial neural network
CCCma	Canadian Centre for Climate Modelling and Analysis
CGCM	Coupled global climate model
IDW	Inverse distance weighting method
IPCC	Intergovernmental Panel on Climate Change
GCM	General Circulation Model
GEV	Generalized extreme value distribution
RCI	Regional climate index
SRES	Special Report on Emissions Scenarios

$F(x)$	Cumulative function
k	GEV shape parameter
P	Precipitation
P_{fact}	Precipitation ratio
P_{new}	Future precipitation
P_{obs}	Observed precipitation
Qave	Mean flow
Qmax	High flow
Qmin	Low flow
Q_T	Discharge at return period T
R^2	Coefficient of determination
RCI_D	Regional climate index for drought
RCI_F	Regional climate index for flood
T	Return period
T_{delta}	Temperature change
T_{new}	Future temperature
T_{obs}	Observed temperature
Tmax	Maximum temperature
Tmin	Minimum temperature
x	Variable in a function or a site
μ	GEV location parameter
σ	GEV scale parameter

ABSTRACT

Turkkan, N., N. El-Jabi and D. Caissie. 2011. Floods and droughts under different climate change scenarios in New Brunswick. Can. Tech. Rep. Fish. Aquat. Sci. 2928: xii + 55p.

The present work analyzes the impact of climate change on the discharge regimes of several catchments in New Brunswick. The hydrological responses of seven catchments to two climate scenarios were simulated using artificial neural network (ANN) models. Future climate data were extracted from the Canadian Coupled General Climate Model (CGCM3.1) under the greenhouse gas emission scenarios B1 and A2 defined by the Intergovernmental Panel on Climate Change (IPCC, Alcamo et al., 1994). The climate variables (temperature and precipitation) were computed using the delta change approach. Using the ANN, future river discharge was predicted for selected hydrometric stations. Then, a frequency analysis was carried out using the generalized extreme value (GEV) distribution function. For the period 2010-2100, average temperatures are projected to increase between 4.7°C and 4.8°C for the studied sites in New Brunswick. As for precipitation, the mean annual precipitation showed an increase of 9-12% compared to current conditions. The increase in high flows for low return floods (e.g., 2-year) was generally higher than higher return floods (e.g. 100-year). Depending on the scenario and the time slice used, the increase in low return floods was about 30% and about 15% for higher return floods. Low flows showed increases of about 10% for low return droughts and about 20% for higher return droughts. An important part of the design process when using frequency analysis under climate scenarios is the estimation of future floods and droughts at a given site for a specific return period. This was done through the application of regional regression equations that links floods and droughts to their frequency under future climate scenarios B1 and A2. To accomplish this, an index, called the regional climate index (RCI), was introduced.

RÉSUMÉ

Turkkan, N., N. El-Jabi and D. Caissie. 2011. Floods and droughts under different climate change scenarios in New Brunswick. Can. Tech. Rep. Fish. Aquat. Sci. 2928: xii + 55p.

L'objectif de cette étude a été d'étudier l'influence du changement climatique sur les débits de crue et d'étiages au Nouveau-Brunswick, en se basant sur un modèle canadien du climat et les réseaux de neurones artificiels (RNA). Les données, provenant d'une simulation de la troisième génération du modèle couplé climatique global (MCCG3.1), ont été utilisées avec les RNA multicouches pour estimer les débits extrêmes dans le contexte actuel et dans le contexte climatique sous les familles de scénarios B1 et A2. La régionalisation des données (températures et précipitations) a été accomplie en utilisant la méthode des deltas. La loi GEV (« Generalized Extreme Value ») a été utilisée pour estimer la fréquence de ces débits extrêmes. Pour la période 2010-2100, des augmentations de température de 4.7 °C à 4.8 °C sont prévues pour les sites étudiés au Nouveau-Brunswick. Quant aux précipitations, les moyennes annuelles ont montré une augmentation de 9 % à 12 % par rapport aux conditions actuelles. L'augmentation des débits de crues pour des périodes de récurrence faible (p. ex., 2 ans) était généralement plus élevée que l'augmentation des débits de crue pour des périodes de récurrence élevée (p. ex., 100 ans). En fonction du scénario et de la période, l'analyse fréquentielle des débits de crue montre une augmentation de 30 % pour les périodes de récurrence faible et 15 % pour les périodes de récurrence élevée. Les débits d'étiage montrent une augmentation de 10% pour les périodes de récurrence faible et 20 % pour les périodes de récurrence élevée. De plus, un indice régional de climat (RCI) a été développé pour faciliter le processus de design. Cet indice permet de relier les crues et les étiages à leurs fréquences selon les scénarios B1 et A2.

1. Introduction

There is currently a broad scientific consensus that the global climate is changing in ways that are likely to have a profound impact on human society and the natural environment over the coming decades. Climate change and its impacts on a global scale are the focus of intense, broad-based international research efforts in the natural and social sciences. However, understanding the nature and potential consequences of climate change at regional scales remains a challenge. For example, in some regions, changes in the frequency and magnitude of extreme weather events may have more substantial and widespread impacts on the environment and human activities than changes in the average climate.

A number of extreme events (with significant impacts on the environment and socio-economic activities) have been observed during the last decade, including severe floods and droughts as well as extreme heat around the world. These events have caused serious risks to the health of human populations as well as to ecosystems and have had severe economic consequences in many sectors, including agriculture and water resources. As such, it is important

- to improve our ability to manage extreme climatic risks,
- to assess the consequences of extreme events over the next decades, and
- to develop new tools and design criteria to more accurately assess the impact of extremes on water resources and river discharge (e.g. floods and droughts).

Improved knowledge and assessment tools will assist policy-makers in formulating more robust policies to mitigate climate change and to develop climate change adaptation strategies.

The objectives of the present study are:

- to carry out a modeling of river discharge of both floods and droughts using the Artificial Neural Network (ANN) approach to predict future river discharge in New Brunswick under different climate change scenarios, and

- to carry out high and low flow frequency analyses using predicted discharge to determine the level of expected changes in flows for design purposes.

These targeted objectives will help improve the management of risks associated with climate change and will contribute towards a review of current criteria and procedures for the design of hydraulic structures and water resources infrastructure.

2. Data and methodology

2.1 Site description

New Brunswick lies on Canada’s Atlantic coast, and is bordered by the ocean on its southern shore (Bay of Fundy) and northern and eastern shores (Gulf of St. Lawrence). 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 in the form of snow. Precipitation tends to be highest in southern parts of the province whereas the northern part of New Brunswick receives relatively higher amounts of precipitation in the form of snow due to colder winters.

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

2.2 Global climate model

General Circulation Models or Global Climate Models (GCMs) are based on mathematical representations of atmosphere, ocean, ice cap as well as land-surface processes. These models are considered to be the only credible tools currently available for simulating the response of the global climate system to increasing greenhouse gas concentrations.

However, researchers must use scenarios to foresee potential future climates. Multiple scenarios (storylines) have been developed by the Intergovernmental Panel on Climate Change (IPCC) and reflect a variety of CO_2 emission scenarios over the next 100 years.

Global climate models were developed to simulate the present climate and to project potential future climates. While the complexity of the global climate system is well captured by these models, they are unable to represent local scale features and processes due to their coarse spatial resolution. Large geographic areas (e.g. 50,000 to 300,000 km^2) represent the basic unit of GCMs. The Canadian Global Coupled Model (CGCM 3.1 / T63), for example, corresponds to geographic areas represented by a grid of approximately 2.81° latitude by 2.81° longitude (~ 60,000 km^2). By comparison, New Brunswick has a total area of 72,908 km^2. Limited spatial resolution over GCM output results in the simplification and homogenization of climatic conditions of large geographic areas, thus contributing to the loss of local climate characteristics. At odds with GCM resolution is the fact that most researchers are focusing on the impacts of climate change primarily at local and regional scales rather than focusing on large or global-scale changes (Xu, 1999).

Given the coarse spatial resolution of GCMs, methods to derive more detailed regional and site-specific scenarios for climate studies have emerged in recent years. For example, spatial downscaling has been developed. This approach uses data from the GCM output and involves the development of significant relationships between local and large scale climate patterns. Downscaling approaches include empirical / statistical and statistical / dynamical methods (e.g. transfer functions, weather typing, and stochastic weather generators). Typically, these techniques are computationally inexpensive, and can easily be applied to output from different GCM experiments. However, spatial downscaling assumes that the relationships between local and large-scale climate will remain valid under future climate conditions.

The climate model used in the present study is the latest Canadian coupled global climate model CGCM3.1/T63. The time-slice simulations follow IPCC "observed 20th century" 20C3M scenario for years 1961-2000 and the Special Report on Emissions Scenarios (SRES) B1 and A2 (see Figure 1) for years 2000-2100 over the Gaussian 128x64 grid (Figure 2). The B1 storyline and scenario family describes a convergent world with low population growth and rapid changes in economic structures towards a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives. The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in high population growth. Economic development is primarily regionally oriented and per capita economic growth and technological changes are more fragmented and slower than in other storylines (i.e., B1). Figure 1 shows the time evolution of the CO_2 concentrations and globally averaged sulphate aerosol loadings scaled to year 2000 for different scenarios including the 20C3M, SRES B1 and SRES A2 and the so-called "Committed" scenario in which the greenhouse gas concentrations and aerosol loadings were held fixed at the year 2000 level.

2.3 Data collection

Streamflow data constitute the basis of information used by hydrologists to make predictions of high and low flow events and their corresponding frequencies. The probabilistic approach is useful in frequency analysis due to the random nature of such events and the flexibility of this approach in characterizing extreme events. Such analysis of hydrologic data can be carried out, among others, following the annual series approach or the partial duration series approach. The annual series approach is widely used in flood and low flow frequency analyses, and it will be used in this study.

Daily maximum and minimum air temperatures and total precipitation data from seven meteorological stations in New Brunswick were obtained from Environment Canada's National Climate Data Archive (Figure 3, Table 1). Air temperature data were available from dates going back as far as 1895 for some stations whereas precipitation data goes back to 1929 (Aroostook).

Daily discharge (m^3/s) data from seven hydrometric stations in New Brunswick was obtained from Environment Canada's National Water Data Archive (HYDAT CD-ROM) (Figure 3, Table 2). Basin size analysed in New Brunswick ranged between 668 km^2 (Canaan River) to 14,700 km^2 (Saint John River).

Simulated monthly maximum and minimum air temperatures and total precipitation for the period 1961-2100 were obtained from CCCma, Canadian Centre for Climate Modelling and Analysis. The atmosphere model output is provided on a 128 x 64 Gaussian grid (Figure 2). Figure 3 shows the sub-region occupied by New Brunswick.

2.4 Data processing

Observed (historical) data:

Daily values of temperatures, precipitations and discharges were converted to monthly mean values. Input with any missing data (temperatures, precipitation or discharge) was ignored during ANN simulations.

Simulated data:

When using simulated data from the CCCma model, an inverse distance weighting (IDW) method was used to compute data corresponding to each meteorological site. These data, at the selected site, were computed from the known values at four grid points surrounding the site (Figure 4). The IDW method is a multivariate interpolation, a process of assigning values to unknown points by using values from usually scattered sets of known points. Distances for the computation are provided for each station as shown within the Table, see bottom of Figure 4.

The interpolated data were then downscaled using the delta change approach (Prudhomme et al. 2002). This approach to downscaling of CGMs for hydrological modeling is one of the simpler statistical downscaling techniques. Fowler et al. (2007) noted that if reproducing the mean characteristics are the main objectives, then simple statistical downscaling methods can perform as well as more sophisticated approaches. Changes in mean climate are applied as follows:

Temperatures

$$T_{new} = T_{obs} + T_{delta} \tag{1}$$

Precipitation

$$P_{new} = P_{obs} \times P_{fact} \tag{2}$$

where T_{delta} is the difference between the CGM simulated mean temperature (from the future time period) and the historic mean temperature (1970-99). P_{fact} is the ratio of the CGM simulated mean precipitation from the future time period relative to the historic period.

2.5 Hydrological modelling using artificial neural networks

Neural networks are based on a schematic representation of neurons in the brain. It is hypothesized from biological observations that neurons are part of a structured network. Neurons are organized in layers, and an exchange of information occurs between layers. The simulation problem consists in finding a satisfactory relationship between a set of neurons representing input data and the associated known input. In general, the network is composed of an input layer of neurons to receive the input data, a hidden layer of neurons and an output layer of neurons to produce an appropriate response to the given input. The neurons in the hidden layer are connected to those of the input layer as well as to those of the output layer. The evolution of the network is characterized by a training process which consists of modifying the connection weights in some orderly fashion using a learning method.

ANN approaches have been successfully used in water resources in a wide variety of applications (Govindaraju 2000a and 2000b). River flow and groundwater level forecasting and sediment estimation are a few examples. Also, predicting conductivity and acidity of streams are some of the time series successfully modeled using this technique (Bastarache et al. 1997).

The architecture and data structure of the ANN used in this study are shown in Figure 5. It is characterized by:

- Learning algorithm : back propagation with Levenberg-Marquardt method
- Training data : 85% of data
- Testing data : 15% of data
- Hidden layer : 8 to 12 neurons

It was observed that the extreme discharge events were better predicted using an Ln-Ln regression model. Therefore, average monthly discharge, Qave, was simulated first (see Figure 5) with input parameters (Month, Tmin, Tmax and Precipitation). Once the Qave was predicted, then regression equations (Figures 6 and 7) were used to link maximum daily flows (Qmax) and minimum daily flows (Qmin) during each month.

2.6 Analysis of model results

The performance of the network is presented in Table 3. This table shows that the Network had an R^2 ranging between 0.69 and 0.79. High flow predictions (Figure 6) showed higher R^2 (0.85-0.92) than low flow predictions (Figure 7) (0.66-0.82). Using the results from the Doaktown site (SW Miramichi River) as an example, Figure 8 shows how well the ANN model coupled with an Ln-Ln model simulated monthly Qave, Qmax and Qmin between 1985 and 1990 compared to observed discharge values when using historical input data (precipitation and temperature). A visual inspection also confirmed that the simulated discharges coincided fairly well with the observed discharges. It should be noted that input data consisted of local historical observations at the Doaktown station. As such, the ANN model and regression equations were effective in predicting the different flow components using historical data. However, some uncertainties exist in estimating hydrological responses. They come from the CGM with additional uncertainties linked to the local scale patterns in downscaling of temperature and precipitation. The downscaling problem was addressed here using the straightforward delta change approach which eliminates some of the modeling bias.

3. Results and discussion

3.1 Future climate change projections

Figures 9 to 15 and Tables 4 to 6, in annual means, summarize the major changes in temperatures, precipitation and average flows throughout the province of New Brunswick for the periods 2010-39, 2040-69 and 2070-2099 compared to 1970-99, using emission scenarios B1 and A2. In Figures 9 to 15, the shaded areas indicate the difference between the two scenarios in the estimated air temperatures, precipitation and mean flows produced by the two CGM scenarios (A1 and B2).

Again using the Doaktown site as an example, the annual maximum air temperature shows a significant increase for the period 2070-2099 compared to current climate conditions (1970-1999), with an increase of approximately 2.7 °C (B1) and 4.6 °C (A2) (Figure 12b). In terms of mean air temperature, the current air temperature will undergo an increase of 1.2°C (2010-39), 2.2°C (2040-69) and 2.9°C (2070-99) under scenario B1 and 1.2°C (2010-39), 2.9°C (2040-69) and 5.0°C (2070-99) under scenario A2. Similar increases (between 1.2°C and 5.3°C) are projected for all sites in New Brunswick (Table 4 to 6). As for precipitation, the mean annual precipitation is projected to increase significantly compared to current climate conditions (Figure 12c). This figure shows that precipitation will most likely increase from approximately 1140 mm annually to 1200 mm annually (B1 scenario) and to 1440 mm annually (A2 scenario) within the next hundred years. For the Doaktown area, this represents an increase in precipitation of 5.1% (B1) and 14.6% (A2) compared to current conditions. Other sites show similar increases depending on the time slice and climate scenario used.

3.2 Floods and droughts

The discharge event of different recurrence intervals were computed using the generalized extreme value (GEV) distribution. The cumulative function has the form:

$$F(x) = \exp(-(1+kz)^{-1/k}) \qquad z \equiv \frac{x-\mu}{\sigma} \tag{3}$$

where *k* is the shape parameter, σ is the scale parameter and μ is the location parameter. The inverse function may be written as:

$$x = \mu + \frac{\sigma}{k}\left[(-\mathrm{Ln}(F))^{-k} - 1\right] \tag{4}$$

where *x* represents discharge and *F(x)* the cumulative frequency. The cumulative frequency is also a function of the recurrence interval or return period.

The *T* year return period for high flow is estimated by:

$$T = \frac{1}{1 - F(x)} \tag{5}$$

and the low flow by:

$$T = \frac{1}{F(x)} \tag{6}$$

The parameters of the GEV for both high and low flows were estimated by the method of L-moments and the goodness of fit was assessed by the Anderson-Darling statistics. In addition, the return periods for high (and low flows) were based on the maximum (and minimum) daily flows recorded each year. As such this flow could occur during any time or season of the year.

Figures 16 to 22 and Figures 23 to 29 illustrate the return periods for high and low flows for the selected rivers in New Brunswick. The flood and drought frequency data used in these figures are given in Tables 7 to 20. The frequency of high and low flow events was calculated based on present day data for the period 1970-1999 and also using future climate information for the period 2010-2099, under climate scenarios B1 and A2. With these projected high or low flow frequency calculations, it is possible to assess the suitability of current design criteria for dealing with future scenarios under climate change.

Using the Doaktown site (Figure 19), results show that a 30-year high flow event for the Southwest Miramichi River could potentially become a more dominant high flow event at the end of the century with a flow 11% higher than current flow using scenario A2, thus representing a flow with a much lower recurrence interval. Figure 19 also shows that a 30-year event would be closer to a 10-year event in the future depending on the slice of 30 years used. Changes pertaining to low flows were small for the Southwest Miramichi River for all time slices (Figure 26).

The analysis shows that, for all the sites under investigation, the intensity and frequency of discharges will most likely increase in severity. The increase in high flows for lower return periods (e.g., 2-year) was generally close to 32% (2010-2039, B1 scenario) and for higher return periods (e.g., 100-year) close to 21% (2070-99, A2 scenario). For low return periods, low flows showed increases of 8% (2010-2039, B1 scenario) and for higher return periods, 25% (2070-2099, A2 scenario).

3.3 Regional Climate Index (RCI)

An important part of the design process using frequency analysis is the estimation of future change in floods or droughts under climate scenarios at a given site for a specific return period or recurrence interval. This is carried out through the application of regional regression models linking floods and droughts to their frequency in the future under climate scenarios B1 and A2. To accomplish this, an index called Regional Climate Index (RCI) was introduced. This index was calculated by dividing future flows by historical flow values while maintaining the same characteristic parameters. RCI can be expressed as follows:

For floods

$$RCI_F = Q_{F,T}^{x,ts,sc} \;/\; Q_{F,T}^{x,2010} \tag{7}$$

For droughts

$$RCI_D = Q_{D,T}^{x,ts,sc} \;/\; Q_{D,T}^{x,2010} \tag{8}$$

where $Q_{F,T}^{x,ts,sc}$ and $Q_{D,T}^{x,ts,sc}$ are the high or low flow discharges at a site *x*, in time slice *ts* (2010-39, 2040-69 or 2070-99), under scenario *sc* (B1 or A2), at return period *T*. $Q_{F,T}^{x,2010}$ and $Q_{D,T}^{x,2010}$ are the present time discharges at the same site *x*. RCI_F and RCI_D are the regional climate index equations for floods and droughts defined as the mean ratio of discharges from the future time period relative to the historic period and are given in Tables 21-22 and also plotted in Figures 30-31.

The evaluation of different RCIs was achieved through regression analysis using existing and simulated floods (and low flows) as presented previously. In all cases, the coefficient of determination, R^2, was about 0.99. Figures 30 and 31 show the variation of RCI for floods and droughts of different return periods for both scenarios B1 and A2 and for the different time periods. The future high and low discharges in New Brunswick may therefore be estimated by:

For floods

$$Q_{F,T}^{x,ts,sc} = Q_{F,T}^{x,2010} \times RCI_F(T) \tag{10}$$

For droughts

$$Q_{D,T}^{x,ts,sc} = Q_{D,T}^{x,2010} \times RCI_D(T) \tag{11}$$

Again using the Doaktown site as an example, a 30-year high flow event for the Southwest Miramichi River in the 2050s under A2 scenario may be computed using Figure 30. The actual flood flow for the Southwest Miramichi River being 1750 m^3/s, then the flood flow in the 2050s will be 1750 x 1.22 = 2135 m^3/s.

4. Conclusions

The present study analyzes the impact of climate change on the discharge regimes of several catchments in New Brunswick. The hydrological responses of seven catchments to two emission scenarios were simulated using artificial neural network (ANN). It was observed that air temperature in New Brunswick will increase by as much as 5.2 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) and Houghton et al. (2001) for the Atlantic Provinces. As for precipitation, the mean annual precipitation showed an increase of 9-12% compared to current conditions. The frequency analyses show that flood magnitude would most likely increase by 11% to 21% towards the end of the century, depending on the emission scenario used. In terms of low flows, the model is predicting an increase of 20% to 26% towards the end of the century. This increase in low flow is most likely linked to the increase in precipitation in the future. Finally, future high and low flows were estimated by the introduction of a Regional Climate Index (RCI) in New Brunswick. These RCIs can be calculated based on the results of a regression analysis using existing and simulated data, as presented previously. The RCIs for floods and droughts were defined as the mean ratio of future discharge relative to the historic flows.

Climate change will undoubtedly alter floods and droughts in New Brunswick. The success of industries (e.g., agriculture, forestry, fisheries and others) are intrinsically linked to the climate, making New Brunswick particularly vulnerable to the impacts of climate change. These industries (among others) will be significantly affected by a warmer, wetter climate during some seasons (e.g., winter). Adaptation will be essential in maintaining the viability of some industries within the province. Regionally, water resources in northern New Brunswick may be more plentiful during some seasons, especially during winter, perhaps meeting increasing water demand in some of these areas. In New Brunswick, precipitation amounts are projected to increase by close to 10%, and demand for water is also projected to increase as a function of population growth, particularly in the south (e.g. Moncton-Dieppe-Riverview). In this region, meeting future water demand may be more difficult because of the current population growth, which is among the highest in the province. The agricultural industry may be vulnerable under climate change. This may have an impact on irrigation and water withdrawals (during some seasons), although low flows are projected to be less severe than current conditions. Climate change will potentially increase the conflict between water withdrawal and aquatic resources 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.

Acknowledgements

This study was funded by the New Brunswick Environmental Trust Fund. The authors remain thankful to M. Darryl Pupek for his helpful comments. The CGCM3.1 atmospheric data were generated and supplied by the Ouranos Climate Simulation Team via CCCma's data distribution Web page.

References

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

Bastarache D., El-Jabi N, Turkkan N, Clair TA (1997) Predicting Conductivity and Acidity for Two Small Streams Using Learning Networks. Canadian Journal of Civil Engineering, 24, 1030-1039.

Fowler, H. and Kilsby, C., (2007) Using regional climate model data to simulate historical and future river flows in northwest England. Climatic Change, 80(3): 337-367.

Govindaraju RS (2000a) Artificial neural networks in hydrology. I: Preliminary concepts. Journal of Hydrologic Engineering 5(2): 115-123.

Govindaraju RS (2000b) Artificial neural networks in hydrology. II: Hydrologic application. Journal of Hydrologic Engineering 5(2): 124-137.

Houghton JT, Ding D, Griggs J, Noguer M, van der Linden PJz, Xiaosu D (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.

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

Prudhomme C, Reynard N, Crooks S (2002) Downscaling from global climate models for flood frequency analysis: where are we now? Hydrol Process 16:1137–1150

Xu, C.-Y. (1999) From GCMs to river flow: a review of downscaling methods and hydrologic modelling approaches. Progress in Physical Geography 23: 229-249.

Table 1 – Meteorological stations

Meteor. station	Latitude, Longitude	Temperatures	Precipitation
Aroostook	46º 48’ N; 67º 43’ W	1913-1999	1929-2005
Charlo Airport	47º 59’ N; 66º 20’ W	1945-1999	1966-2005
Chatham Airport	47º 01’ N; 65º 27’ W	1895-1999	1943-2005
Doaktown	46º 33’ N; 66º 09’ W	1952-1999	1934-2005
Fredericton Airport	45º 52’ N; 66º 32’ W	1895-1999	1951-2005
Moncton Airport	46º 06’ N; 64º 47’ W	1895-1999	1939-2005
Saint John Airport	45º 19’ N; 65º 53’ W	1895-1999	1946-2005

Table 2 – Hydrometric stations

Hydrometric station	ID	Latitude, Longitude	Drainage Area (km^2)	Period of record
Saint John R. at Fort Kent	1AD2	47° 15’ N, 68° 36’ W	14,700	1927-05
Nashwaak R. at Durham Br.	1AL2	46° 08’ N, 66° 37’ W	1,450	1962-05
Canaan R. at East Canaan	1AP2	46° 04’ N, 65° 22’ W	668	1926-40, 1963-05
Kennebecasis R. at Apohaqui	1AP4	45° 42’ N, 65° 36’ W	1,100	1961-05
Restigouche River	1BC1	47° 40’ N, 67° 29’ W	3,160	1963-05
SW Miramichi R. at Blackville	1BO1	46° 44’ N, 65° 50’ W	5,050	1919-32, 1962-05
NW Miramichi R. at Trout Bk.	1BQ1	47° 06’ N, 65° 50’ W	948	1962-05

Table 3 – ANN Model results

Location	R^2
Aroostook (Saint John R.)	0.79
Charlo (Restigouche R.)	0.79
Chatham (NW Miramichi R.)	0.76
Doaktown (SW Miramichi R.)	0.78
Fredericton (Nashwaak R.)	0.75
Moncton (Canaan R.)	0.71
Saint John (Kennebecasis R.)	0.69

Table 4 – Mean air temperature increase (°C)

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

Table 5 – Mean precipitation increase (%)

	Scenario B1			Scenario A2		
	2010-39	2040-69	2070-99	2010-39	2040-69	2070-99
Aroostook	2.2	6.3	5.6	4.2	8.0	15.4
Charlo	2.5	7.1	5.6	3.4	8.4	16.6
Chatham	2.3	7.1	5.6	4.5	8.4	15.2
Doaktown	2.1	6.5	5.1	4.4	8.1	14.6
Fredericton	2.3	6.6	5.3	4.8	7.7	14.7
Moncton	3.1	8.0	6.1	6.9	9.0	13.6
Saint John	2.8	7.0	5.6	5.1	7.9	14.7

Table 6 – Mean flow increase (%)

	Scenario B1			Scenario A2		
	2010-39	2040-69	2070-99	2010-39	2040-69	2070-99
Saint John River	3.8	8.8	11.3	4.6	13.4	26.6
Restigouche River	3.8	6.0	6.7	3.9	7.2	11.0
NW Miramichi River	0.2	1.7	1.0	0.7	1.9	4.0
SW Miramichi River	4.7	10.2	11.4	5.6	13.6	22.6
Nashwaak River	1.3	3.2	2.9	2.2	3.9	8.4
Canaan River	4.4	10.4	11.9	8.1	14.1	24.4
Kennebecasis R.	3.5	7.6	7.3	5.5	9.4	15.5

Table 7 – Flood frequency data for Saint John River
(T in years, discharge in m^3/s)

T	Scenario B1			Scenario A2		
	2010-39	2040-69	2070-99	2010-39	2040-69	2070-99
2	2907	3065	3144	2933	3211	3632
3	3330	3510	3601	3359	3677	4160
5	3753	3957	4059	3786	4145	4689
6	3886	4097	4203	3920	4292	4855
8	4082	4304	4415	4118	4508	5100
10	4224	4453	4568	4261	4665	5277
15	4462	4704	4826	4501	4928	5575
20	4618	4869	4994	4659	5100	5770
30	4823	5084	5215	4865	5326	6025
40	4958	5227	5362	5001	5475	6194
50	5057	5332	5469	5102	5585	6318
60	5136	5414	5554	5181	5671	6416
70	5200	5482	5623	5245	5742	6496
100	5341	5630	5775	5387	5898	6672

Table 8 – Drought frequency data for Saint John River
(T in years, discharge in m^3/s)

T	Scenario B1			Scenario A2		
	2010-39	2040-69	2070-99	2010-39	2040-69	2070-99
2	41.2	42.6	43.3	41.5	43.9	47.5
3	36.3	37.5	38.1	36.5	38.6	41.7
5	31.7	32.8	33.3	31.9	33.8	36.5
6	30.4	31.4	31.9	30.5	32.3	35.0
8	28.4	29.4	29.9	28.6	30.3	32.7
10	27.1	28.0	28.5	27.2	28.8	31.2
15	24.8	25.7	26.1	25.0	26.4	28.6
20	23.4	24.2	24.6	23.5	24.9	26.9
30	21.6	22.3	22.6	21.7	22.9	24.8
40	20.3	21.0	21.4	20.4	21.6	23.4
50	19.4	20.1	20.4	19.5	20.7	22.4
60	18.7	19.4	19.7	18.8	20.0	21.6
70	18.2	18.8	19.1	18.3	19.3	20.9
100	16.9	17.5	17.8	17.0	18.0	19.4

Table 9 – Flood frequency data for Restigouche River
(T in years, discharge in m^3/s)

T	Scenario B1			Scenario A2		
	2010-39	2040-69	2070-99	2010-39	2040-69	2070-99
2	688	705	710	689	714	744
3	785	804	810	786	815	849
5	895	917	924	896	930	968
6	933	956	964	934	969	1009
8	992	1017	1025	994	1030	1073
10	1038	1064	1072	1039	1078	1122
15	1120	1148	1157	1122	1163	1211
20	1179	1208	1218	1180	1224	1275
30	1262	1293	1303	1264	1310	1365
40	1322	1354	1365	1323	1372	1429
50	1368	1402	1413	1370	1420	1479
60	1406	1441	1452	1408	1460	1520
70	1439	1474	1486	1440	1494	1555
100	1514	1552	1564	1516	1572	1637

Table 10 – Drought frequency data for Restigouche River
(T in years, discharge in m^3/s)

T	Scenario B1			Scenario A2		
	2010-39	2040-69	2070-99	2010-39	2040-69	2070-99
2	10.6	10.7	10.8	10.6	10.8	11.0
3	9.7	9.8	9.8	9.7	9.9	10.1
5	8.9	9.0	9.0	8.9	9.0	9.3
6	8.6	8.7	8.8	8.6	8.8	9.0
8	8.3	8.4	8.5	8.3	8.5	8.7
10	8.1	8.2	8.2	8.1	8.2	8.4
15	7.7	7.8	7.8	7.7	7.9	8.1
20	7.5	7.6	7.6	7.5	7.6	7.8
30	7.2	7.3	7.3	7.2	7.3	7.5
40	7.0	7.1	7.1	7.0	7.1	7.3
50	6.8	6.9	7.0	6.8	7.0	7.1
60	6.7	6.8	6.9	6.7	6.9	7.0
70	6.6	6.7	6.8	6.6	6.8	6.9
100	6.4	6.5	6.6	6.4	6.6	6.7

Table 11 – Flood frequency data for NW Miramichi River
(T in years, discharge in m^3/s)

T	Scenario B1			Scenario A2		
	2010-39	2040-69	2070-99	2010-39	2040-69	2070-99
2	312	323	340	315	338	371
3	356	368	385	359	382	416
5	400	413	430	403	427	462
6	413	428	445	417	441	477
8	434	449	466	437	462	498
10	449	464	481	452	477	513
15	474	490	507	478	503	540
20	490	507	524	494	519	557
30	512	529	546	516	541	579
40	526	544	561	531	556	594
50	537	555	572	541	567	605
60	545	564	581	550	575	614
70	552	571	588	557	582	621
100	567	586	603	572	598	636

Table 12 – Drought frequency data for NW Miramichi River
(T in years, discharge in m^3/s)

T	Scenario B1			Scenario A2		
	2010-39	2040-69	2070-99	2010-39	2040-69	2070-99
2	2.6	2.7	2.7	2.6	2.7	2.7
3	2.4	2.4	2.4	2.4	2.4	2.5
5	2.2	2.2	2.2	2.2	2.2	2.2
6	2.1	2.1	2.1	2.1	2.1	2.2
8	2.0	2.0	2.0	2.0	2.1	2.1
10	2.0	2.0	2.0	2.0	2.0	2.0
15	1.9	1.9	1.9	1.9	1.9	1.9
20	1.8	1.8	1.8	1.8	1.8	1.9
30	1.7	1.7	1.7	1.7	1.8	1.8
40	1.7	1.7	1.7	1.7	1.7	1.7
50	1.6	1.7	1.7	1.6	1.7	1.7
60	1.6	1.6	1.6	1.6	1.6	1.7
70	1.6	1.6	1.6	1.6	1.6	1.6
100	1.5	1.6	1.5	1.5	1.6	1.6

Table 13 – Flood frequency data for SW Miramichi River
(T in years, discharge in m^3/s)

T	Scenario B1			Scenario A2		
	2010-39	2040-69	2070-99	2010-39	2040-69	2070-99
2	1121	1188	1202	1132	1229	1338
3	1240	1314	1330	1252	1359	1480
5	1356	1436	1454	1369	1486	1618
6	1392	1474	1492	1405	1525	1661
8	1443	1528	1547	1457	1581	1722
10	1480	1567	1586	1494	1622	1766
15	1540	1631	1651	1555	1688	1839
20	1579	1673	1693	1595	1731	1885
30	1629	1726	1747	1645	1785	1945
40	1662	1760	1781	1678	1821	1983
50	1685	1785	1807	1702	1847	2011
60	1704	1804	1826	1720	1867	2033
70	1718	1820	1842	1735	1883	2051
100	1751	1854	1877	1767	1918	2089

Table 14 – Drought frequency data for SW Miramichi River
(T in years, discharge in m^3/s)

T	Scenario B1			Scenario A2		
	2010-39	2040-69	2070-99	2010-39	2040-69	2070-99
2	20.7	21.5	21.6	20.8	21.9	23.1
3	18.9	19.6	19.7	19.0	20.0	21.1
5	17.3	18.0	18.1	17.5	18.4	19.4
6	16.9	17.5	17.7	17.0	17.9	18.9
8	16.3	16.9	17.0	16.4	17.2	18.2
10	15.9	16.4	16.6	15.9	16.8	17.7
15	15.2	15.7	15.8	15.3	16.1	16.9
20	14.7	15.3	15.4	14.8	15.6	16.4
30	14.2	14.7	14.8	14.3	15.0	15.8
40	13.8	14.3	14.4	13.9	14.6	15.4
50	13.6	14.1	14.2	13.6	14.4	15.1
60	13.4	13.9	14.0	13.4	14.2	14.9
70	13.2	13.7	13.8	13.3	14.0	14.7
100	12.8	13.3	13.4	12.9	13.6	14.3

Table 15 – Flood frequency data for Nashwaak River
(T in years, discharge in m^3/s)

T	Scenario B1			Scenario A2		
	2010-39	2040-69	2070-99	2010-39	2040-69	2070-99
2	541	574	594	573	582	643
3	596	633	653	626	643	702
5	651	692	713	679	705	762
6	669	711	732	696	724	780
8	695	738	760	721	753	808
10	713	758	780	739	773	828
15	745	792	814	770	809	862
20	766	814	837	790	832	884
30	793	843	866	816	862	913
40	811	863	886	833	882	932
50	825	877	900	846	897	947
60	835	888	911	856	909	958
70	844	897	921	865	918	967
100	863	918	941	883	939	987

Table 16 – Drought frequency data for Nashwaak River
(T in years, discharge in m^3/s)

T	Scenario B1			Scenario A2		
	2010-39	2040-69	2070-99	2010-39	2040-69	2070-99
2	4.3	4.4	4.4	4.3	4.4	4.5
3	3.8	3.9	3.9	3.8	3.9	4.0
5	3.4	3.5	3.5	3.4	3.5	3.6
6	3.3	3.3	3.3	3.3	3.4	3.5
8	3.2	3.2	3.2	3.2	3.2	3.3
10	3.1	3.1	3.1	3.1	3.1	3.2
15	2.9	2.9	2.9	2.9	2.9	3.0
20	2.8	2.8	2.8	2.8	2.8	2.9
30	2.7	2.7	2.7	2.7	2.7	2.8
40	2.6	2.6	2.6	2.6	2.6	2.7
50	2.5	2.6	2.6	2.6	2.6	2.7
60	2.5	2.5	2.5	2.5	2.5	2.6
70	2.5	2.5	2.5	2.5	2.5	2.6
100	2.4	2.4	2.4	2.4	2.4	2.5

Table 17 – Flood frequency data for Canaan River
(T in years, discharge in m^3/s)

T	Scenario B1			Scenario A2		
	2010-39	2040-69	2070-99	2010-39	2040-69	2070-99
2	177	188	191	184	195	214
3	202	214	218	210	222	244
5	226	240	243	234	248	273
6	233	248	251	242	257	282
8	244	259	262	253	268	294
10	251	267	270	261	276	303
15	263	279	284	273	290	318
20	271	288	292	281	298	327
30	281	298	302	291	309	339
40	287	305	309	298	316	347
50	291	310	314	303	321	352
60	295	313	318	306	325	356
70	298	316	321	309	328	360
100	304	323	328	316	334	367

Table 18 – Drought frequency data for Canaan River
(T in years, discharge in m^3/s)

T	Scenario B1			Scenario A2		
	2010-39	2040-69	2070-99	2010-39	2040-69	2070-99
2	0.5	0.6	0.6	0.5	0.6	0.6
3	0.4	0.4	0.4	0.4	0.4	0.5
5	0.3	0.3	0.3	0.3	0.3	0.4
6	0.3	0.3	0.3	0.3	0.3	0.3
8	0.3	0.3	0.3	0.3	0.3	0.3
10	0.2	0.3	0.3	0.3	0.3	0.3
15	0.2	0.2	0.2	0.2	0.2	0.2
20	0.2	0.2	0.2	0.2	0.2	0.2
30	0.2	0.2	0.2	0.2	0.2	0.2
40	0.1	0.1	0.1	0.1	0.2	0.2
50	0.1	0.1	0.1	0.1	0.1	0.1
60	0.1	0.1	0.1	0.1	0.1	0.1
70	0.1	0.1	0.1	0.1	0.1	0.1
100	0.1	0.1	0.1	0.1	0.1	0.1

Table 19 – Flood frequency data for Kennebecasis River

(T in years, discharge in m^3/s)

T	Scenario B1			Scenario A2		
	2010-39	2040-69	2070-99	2010-39	2040-69	2070-99
2	301	311	311	304	326	353
3	343	355	354	348	368	395
5	386	399	398	391	412	438
6	399	413	412	405	425	452
8	419	433	432	425	446	472
10	433	448	447	440	460	486
15	457	473	472	464	485	511
20	473	489	488	481	501	527
30	494	511	510	502	522	548
40	508	525	524	516	536	562
50	518	536	534	526	547	572
60	526	544	543	535	555	581
70	533	551	550	541	562	587
100	547	566	565	556	576	602

Table 20 – Drought frequency data for Kennebecasis River

(T in years, discharge in m^3/s)

T	Scenario B1			Scenario A2		
	2010-39	2040-69	2070-99	2010-39	2040-69	2070-99
2	2.7	2.8	2.8	2.7	2.8	2.9
3	2.4	2.4	2.4	2.4	2.5	2.6
5	2.1	2.1	2.1	2.1	2.2	2.3
6	2.0	2.1	2.1	2.0	2.1	2.2
8	1.9	2.0	2.0	1.9	2.0	2.1
10	1.8	1.9	1.9	1.9	1.9	2.0
15	1.7	1.8	1.8	1.7	1.8	1.9
20	1.6	1.7	1.7	1.7	1.7	1.8
30	1.6	1.6	1.6	1.6	1.6	1.7
40	1.5	1.5	1.5	1.5	1.6	1.6
50	1.5	1.5	1.5	1.5	1.5	1.6
60	1.4	1.5	1.5	1.4	1.5	1.5
70	1.4	1.4	1.4	1.4	1.5	1.5
100	1.3	1.4	1.4	1.4	1.4	1.4

Table 21 – Regional climate index equations for floods

Time slice	Scenario B1	Scenario A2
2010-39	$RCI_F(T) = -0.0727\,\mathrm{Ln}(T) + 1.379$	$RCI_F(T) = -0.0756\,\mathrm{Ln}(T) + 1.4075$
2040-69	$RCI_F(T) = -0.0759\,\mathrm{Ln}(T) + 1.4442$	$RCI_F(T) = -0.0795\,\mathrm{Ln}(T) + 1.4909$
2070-99	$RCI_F(T) = -0.0794\,\mathrm{Ln}(T) + 1.4766$	$RCI_F(T) = -0.0907\,\mathrm{Ln}(T) + 1.6263$

Table 22 – Regional climate index equations for droughts

Time slice	Scenario B1	Scenario A2
2010-39	$RCI_D(T) = 0.01\,\mathrm{Ln}(T) + 1.0763$	$RCI_D(T) = 0.0191\,\mathrm{Ln}(T) + 1.0867$
2040-69	$RCI_D(T) = 0.0194\,\mathrm{Ln}(T) + 1.105$	$RCI_D(T) = 0.0195\,\mathrm{Ln}(T) + 1.1219$
2070-99	$RCI_D(T) = 0.0193\,\mathrm{Ln}(T) + 1.1103$	$RCI_D(T) = 0.0194\,\mathrm{Ln}(T) + 1.745$

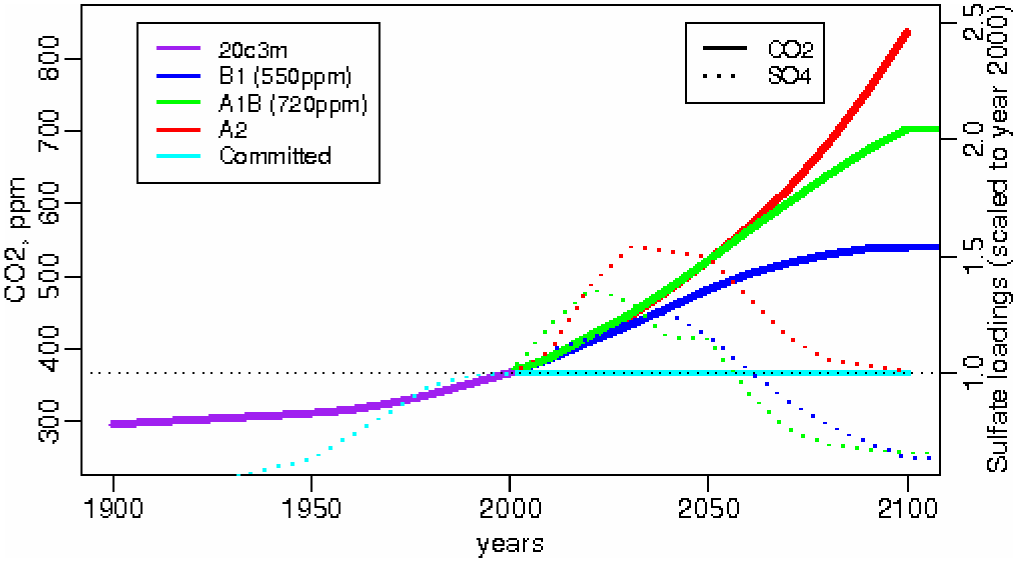


Figure 1 - Time evolution of the CO_2 concentrations (solid line curves) and globally averaged sulphate aerosol loadings scaled to year 2000 (dotted line curves) as prescribed in the IPCC 20-th century 20C3M (purple), SRES B1 (blue) and A2 (red) experiment

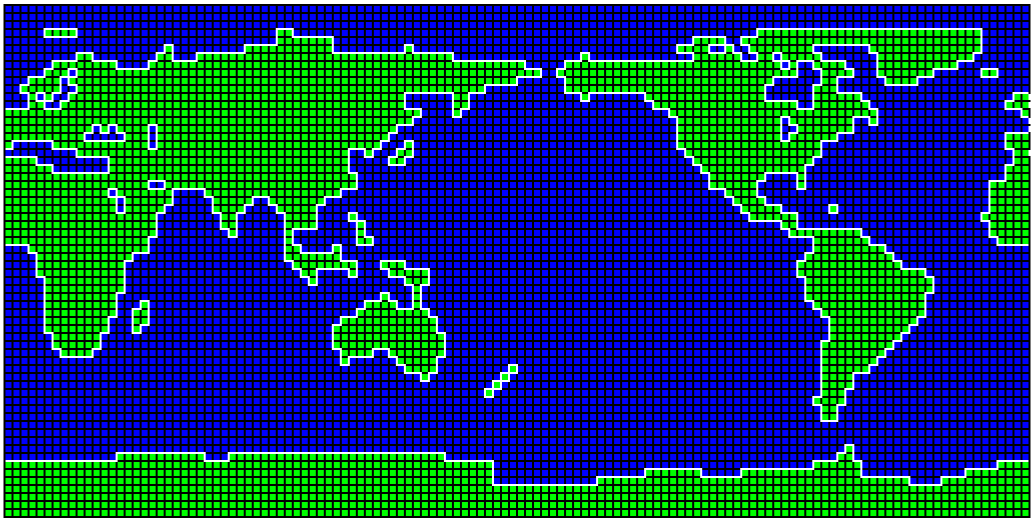


Figure 2 – 128 x 64 Gaussian grid (grid box size ~ 2.81° lat x 2.81° long)

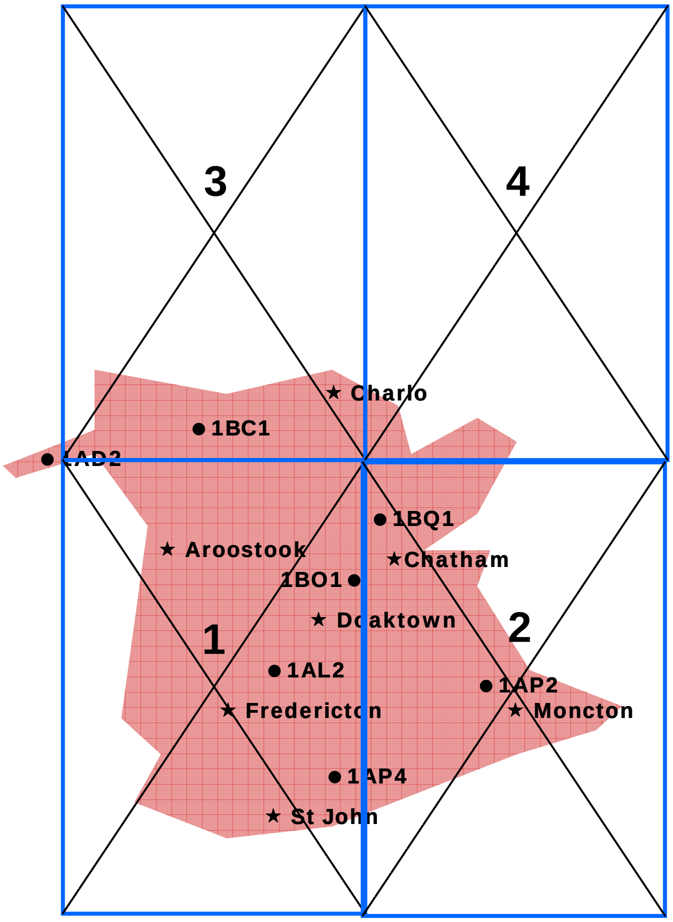
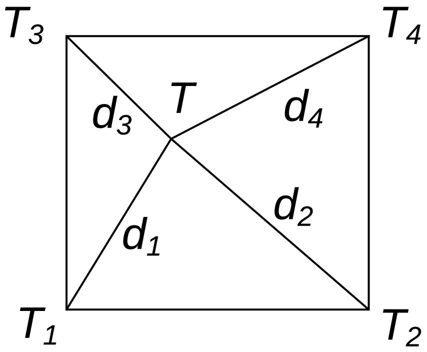


Figure 3 – Subarea corresponding to New Brunswick: 4 grid boxes
(Box size ~200x300 km, • hydrometric station, ★meteorological station)
(1→67.5° W 46.04°N, 2→64.69°W 46.04°N, 3→67.5°W 48.84°N, 4→64.69°W 48.84°N)

$$T = \frac{\sum_{i=1}^{4} \frac{T_i}{d_i}}{\sum_{j=1}^{4} \frac{1}{d_j}}$$



- *T :* Interpolated value (Tmin, Tmax ou P)
- T_i : Known values on grid points
- d_i : Given distances from T to each grid point

Location	d_1 (km)	d_2 (km)	d_3 (km)	d_4 (km)
Aroostook	86	247	227	320
Charlo	234	248	130	153
Chatham	200	123	254	210
Doaktown	118	126	274	277
Fredericton	77	143	338	358
Moncton	210	10	367	305
Saint John	149	122	410	402

Figure 4 – Inverse distance weighting (IDW) method and the corresponding distances

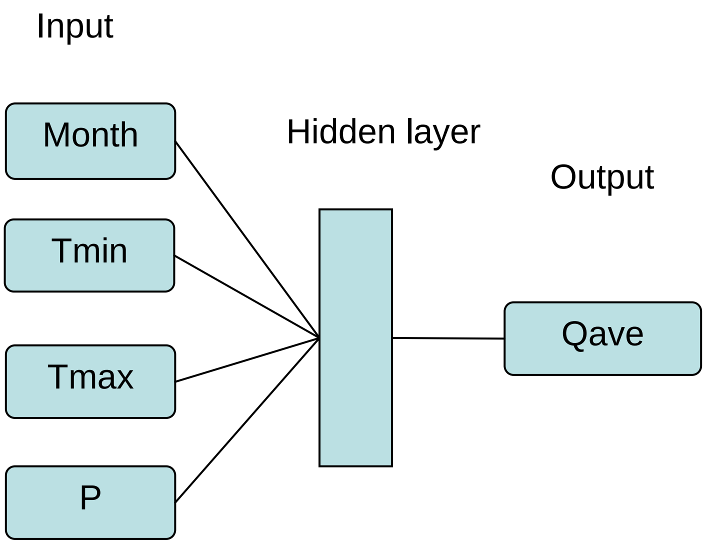


Figure 5 – ANN architecture and the input data structure used in the study

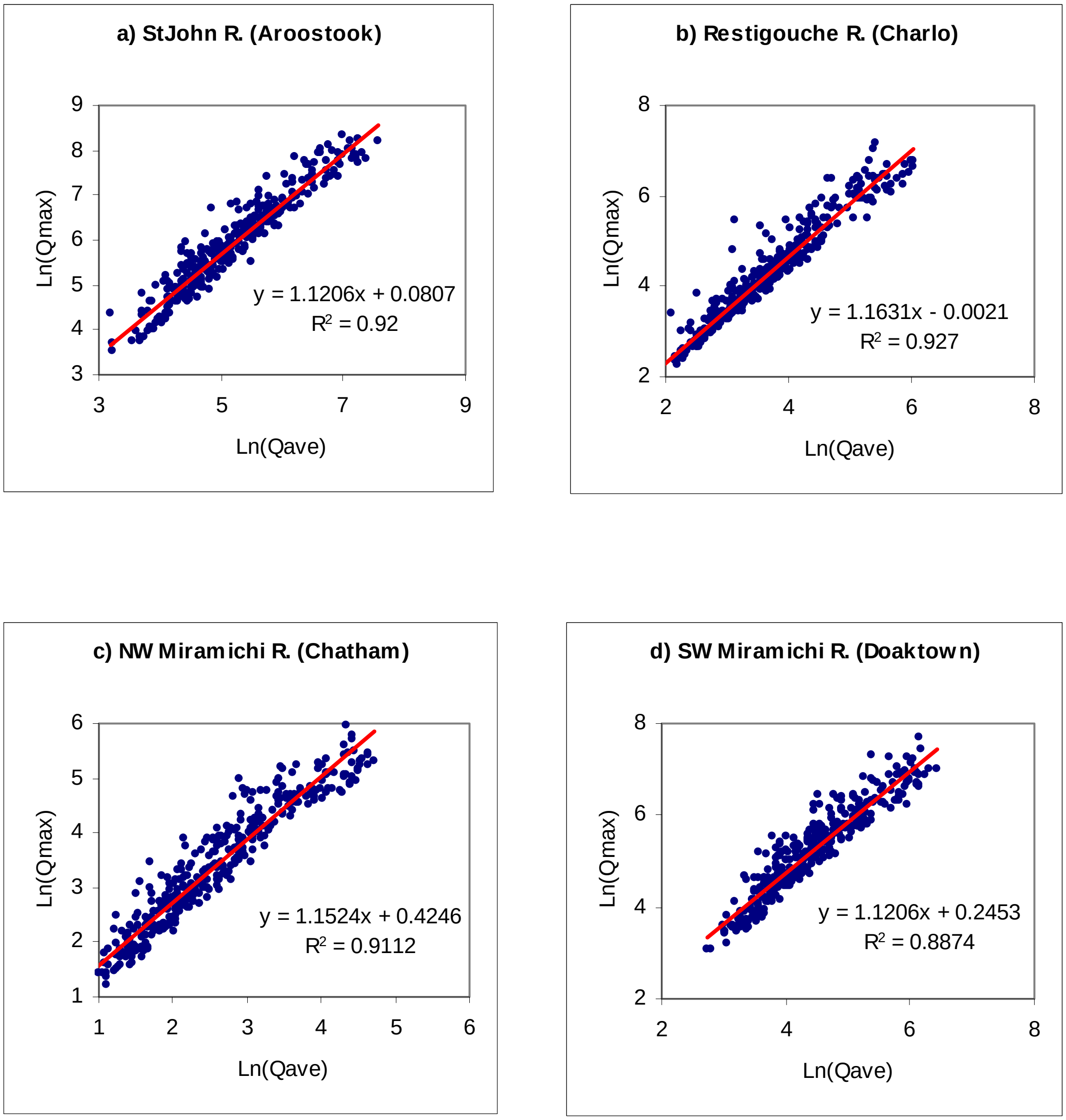


Figure 6 – Ln(Mean flow, m^3/s) vs. Ln(High flow, m^3/s) for a) Saint John R. b) Restigouche R. c) NW Miramichi R. d) SW Miramichi R. e) Nashwaak R. f) Canaan R. g) Kennebecasis R.

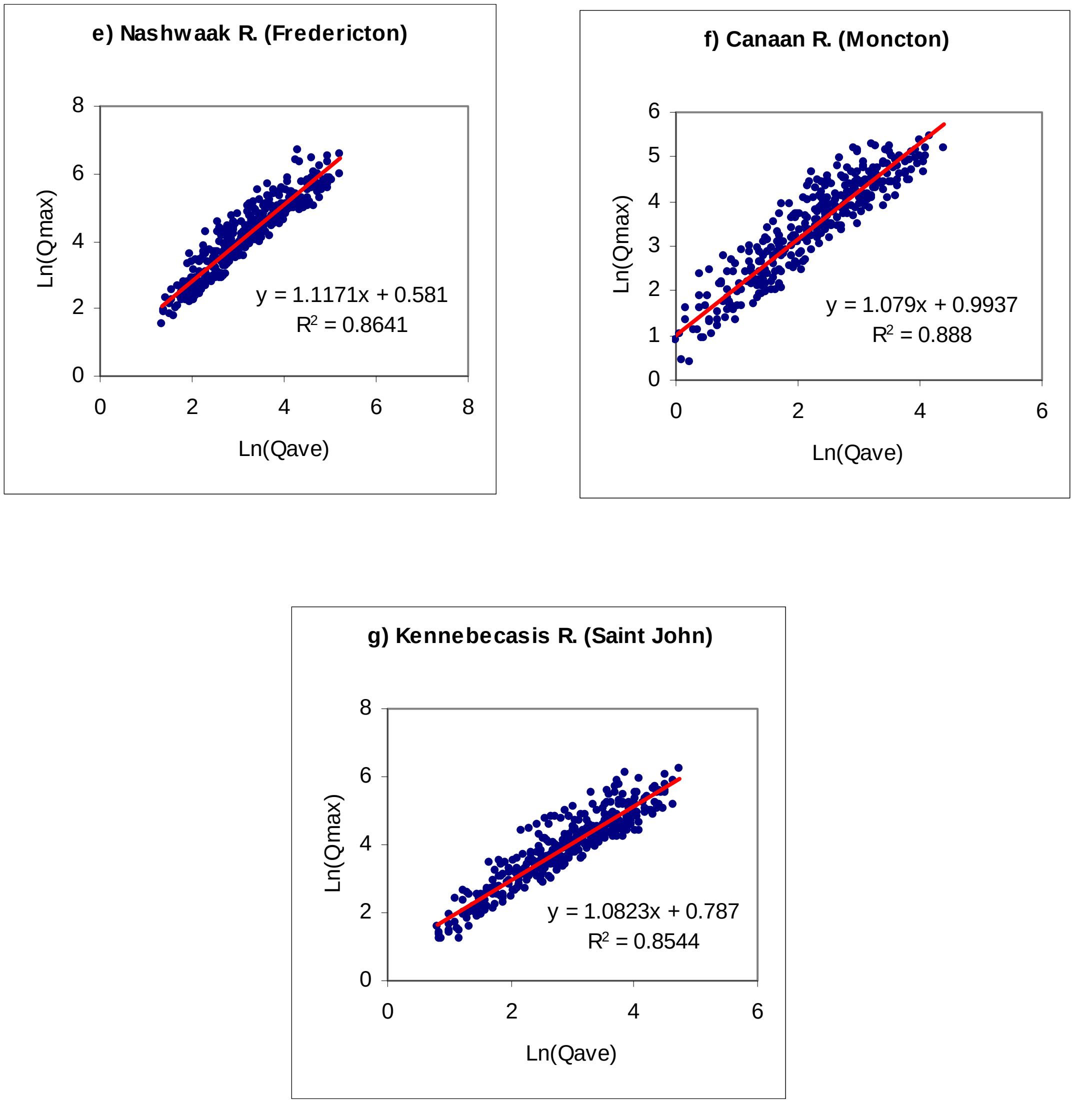


Figure 6 – Ln(Mean flow, m^3/s) vs Ln(High flow, m^3/s) for a) Saint John R. b) Restigouche R. c) NW Miramichi R. d) SW Miramichi R. e) Nashwaak R. f) Canaan R. g) Kennebecasis R.

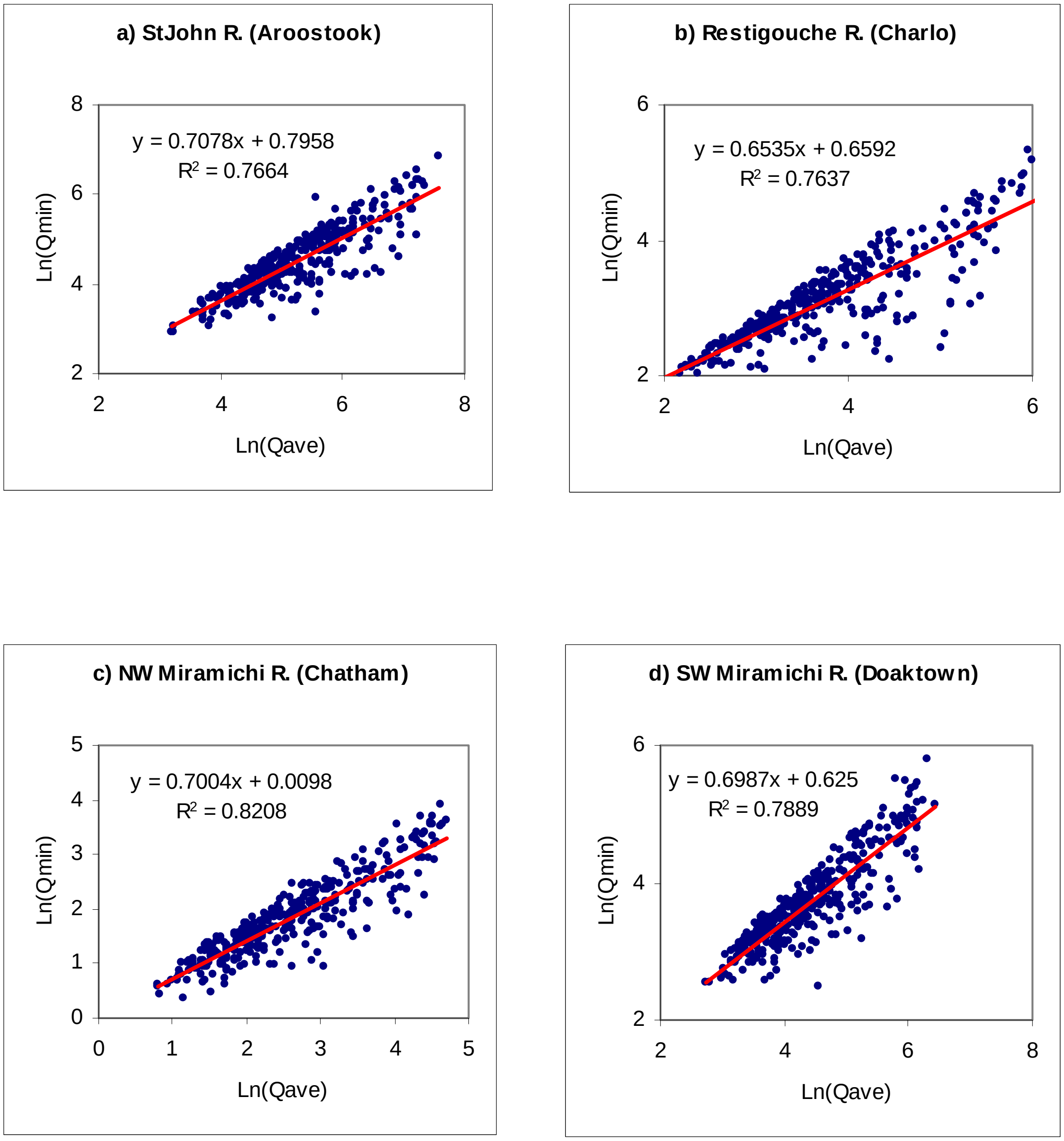


Figure 7 - Ln(Mean flow, m^3/s) vs Ln(Low flow, m^3/s) for a) Saint John R. b) Restigouche R. c) NW Miramichi R. d) SW Miramichi R. e) Nashwaak R. f) Canaan R. g) Kennebecasis R.

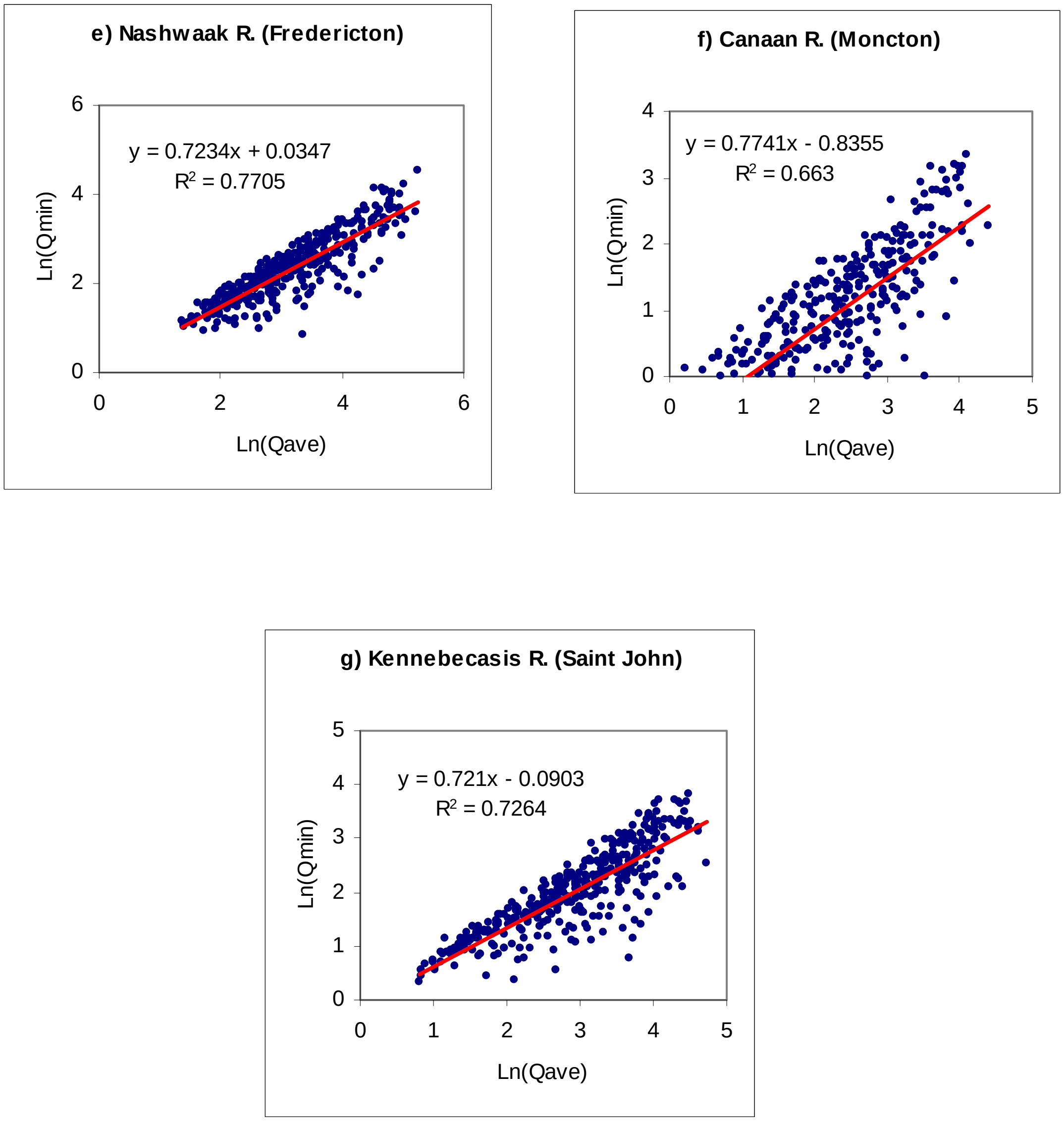


Figure 7 - Ln(Mean flow, m^3/s) vs Ln(Low flow, m^3/s) for a) Saint John R. b) Restigouche R. c) NW Miramichi R. d) SW Miramichi R. e) Nashwaak R. f) Canaan R. g) Kennebecasis R.

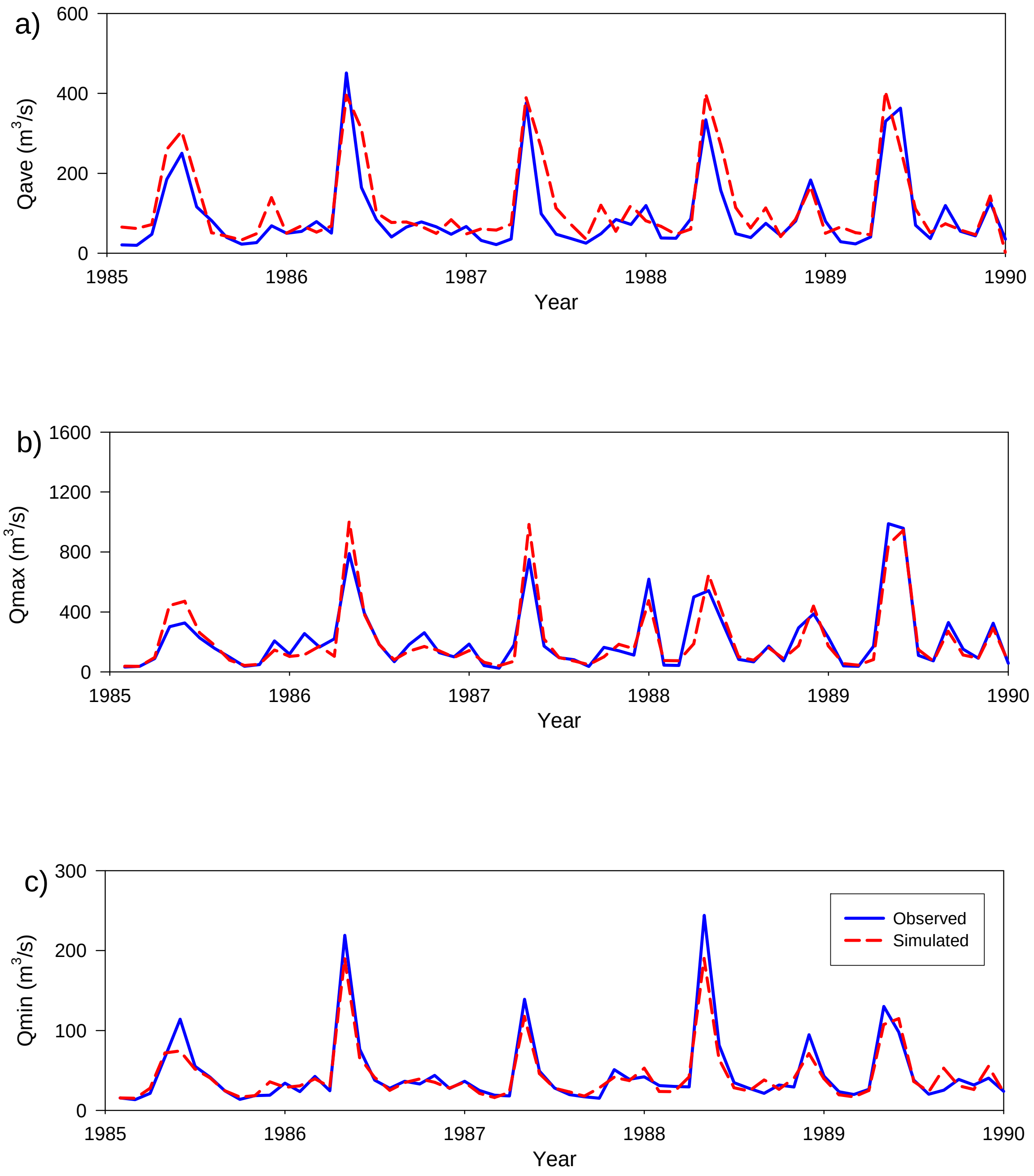


Figure 8 – Observed and simulated monthly discharges for SW Miramichi River a) mean discharge b) maximum discharge c) minimum discharge

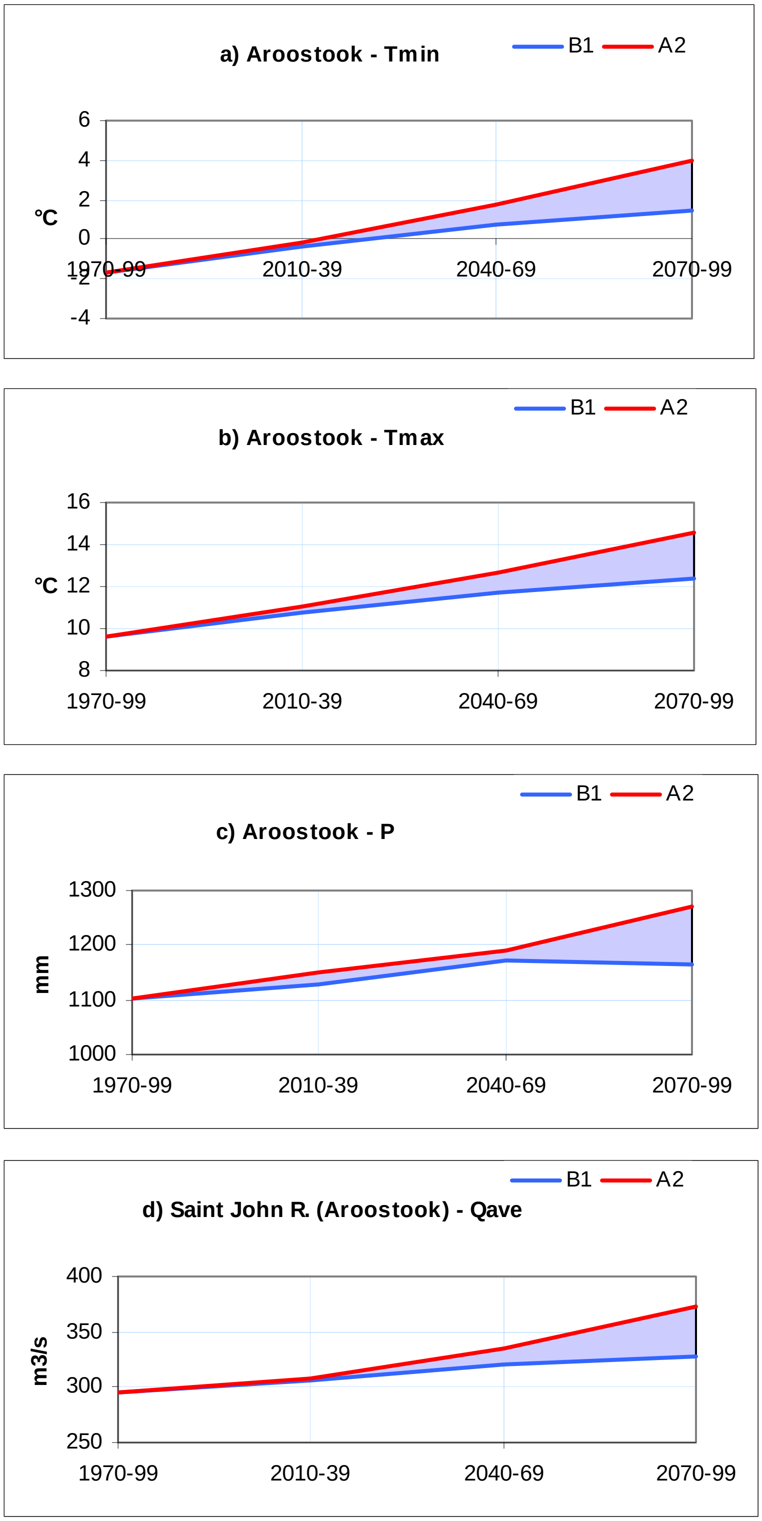


Figure 9 – Observed (1970-99) and simulated (scenarios B1 & A2) (2010-39, 2040-69, 2070-99) annual means at Aroostook a) minimum temperature b) maximum temperature c) total precipitation d) average discharge (Saint John R.)

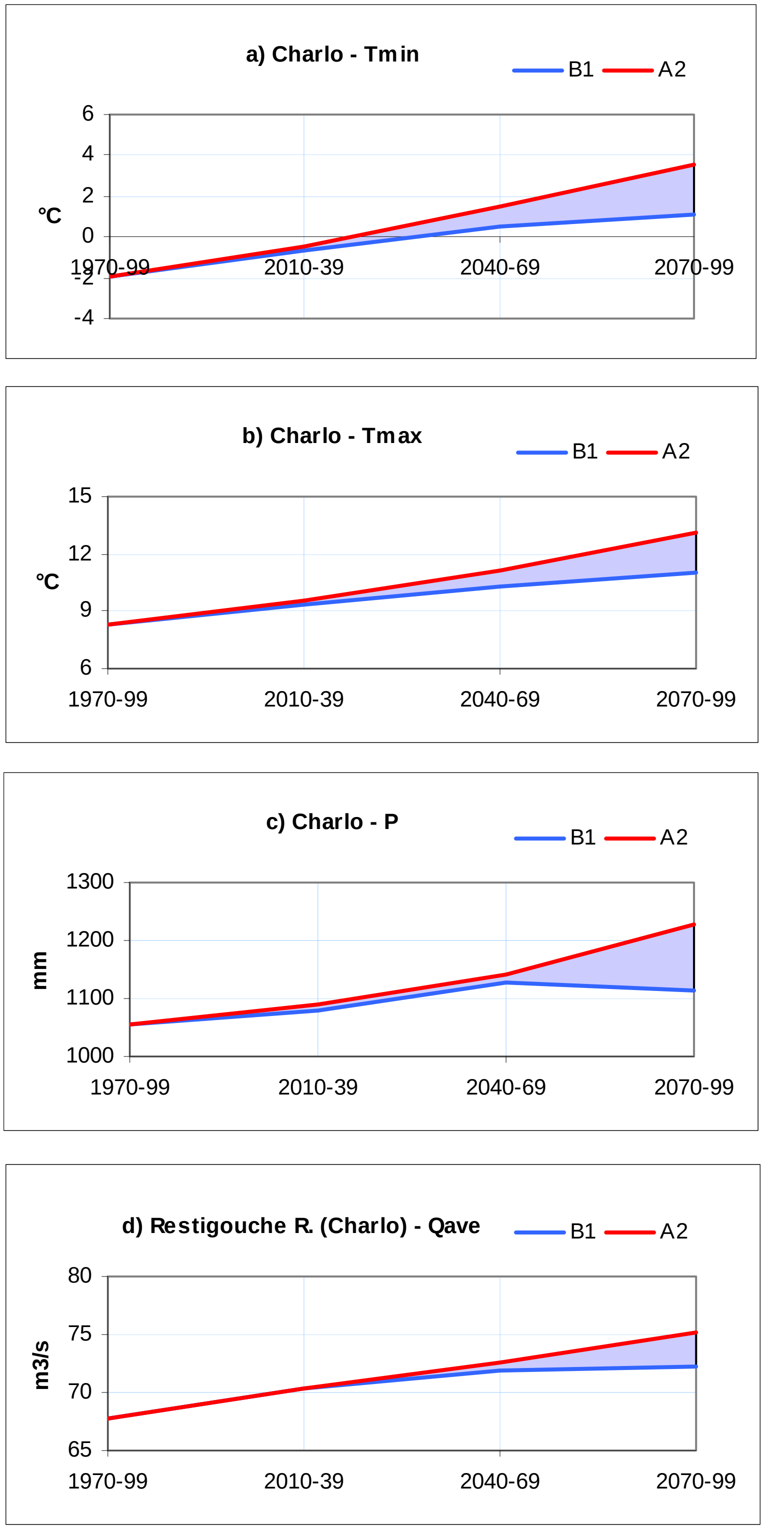


Figure 10 –Observed (1970-99) and simulated (scenarios B1 & A2) (2010-39, 2040-69, 2070-99) annual means at Charlo a) minimum temperature b) maximum temperature c) total precipitation d) average discharge (Restigouche R)

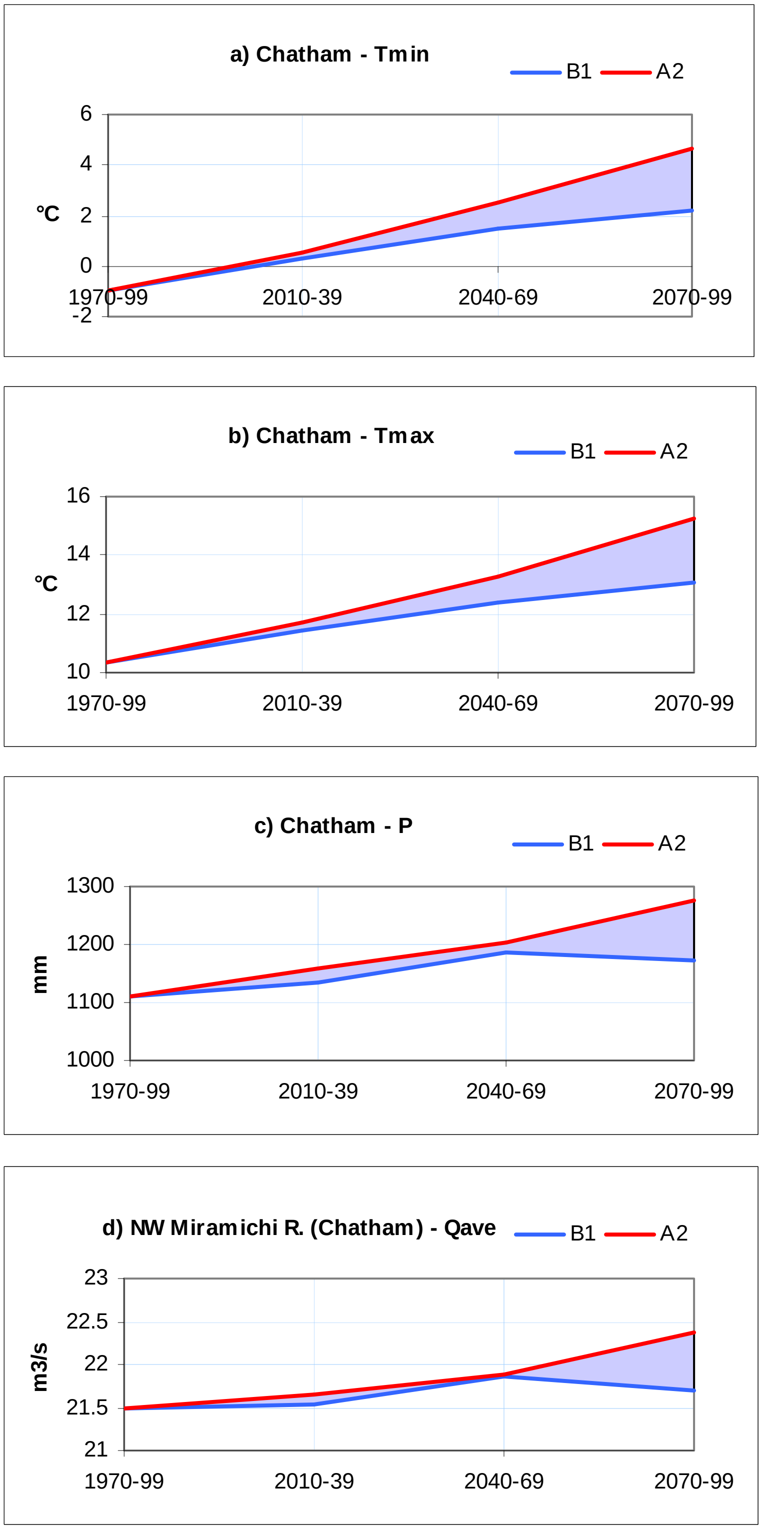


Figure 11 – Observed (1970-99) and simulated (scenarios B1 & A2) (2010-39, 2040-69, 2070-99) annual means at Chatham a) minimum temperature b) maximum temperature c) total precipitation d) average discharge (NW Miramichi R.)

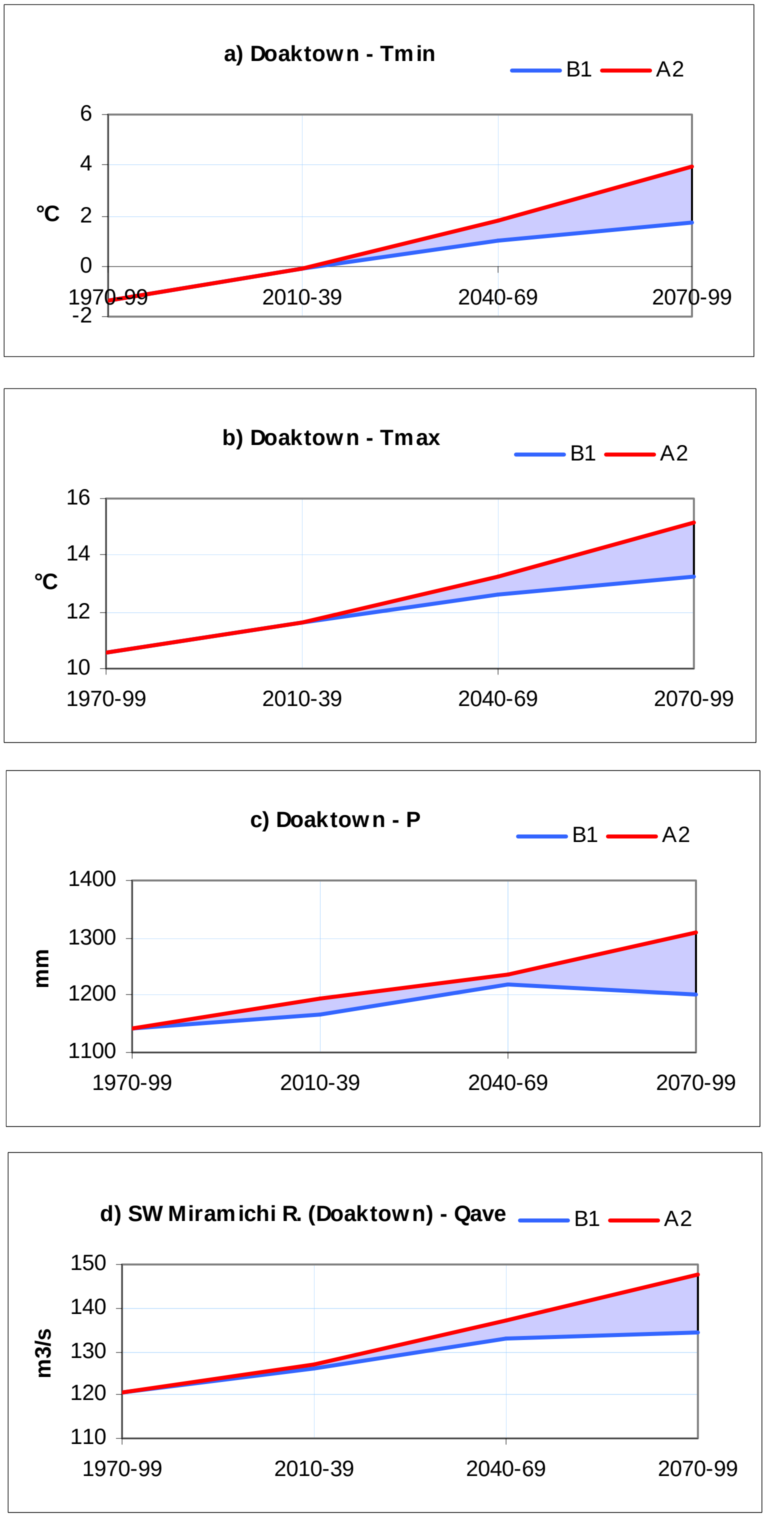


Figure 12 – Observed (1970-99) and simulated (scenarios B1 & A2) (2010-39, 2040-69, 2070-99) annual means at Doaktown a) minimum temperature b) maximum temperature c) total precipitation d) average discharge (SW Miramichi R.)

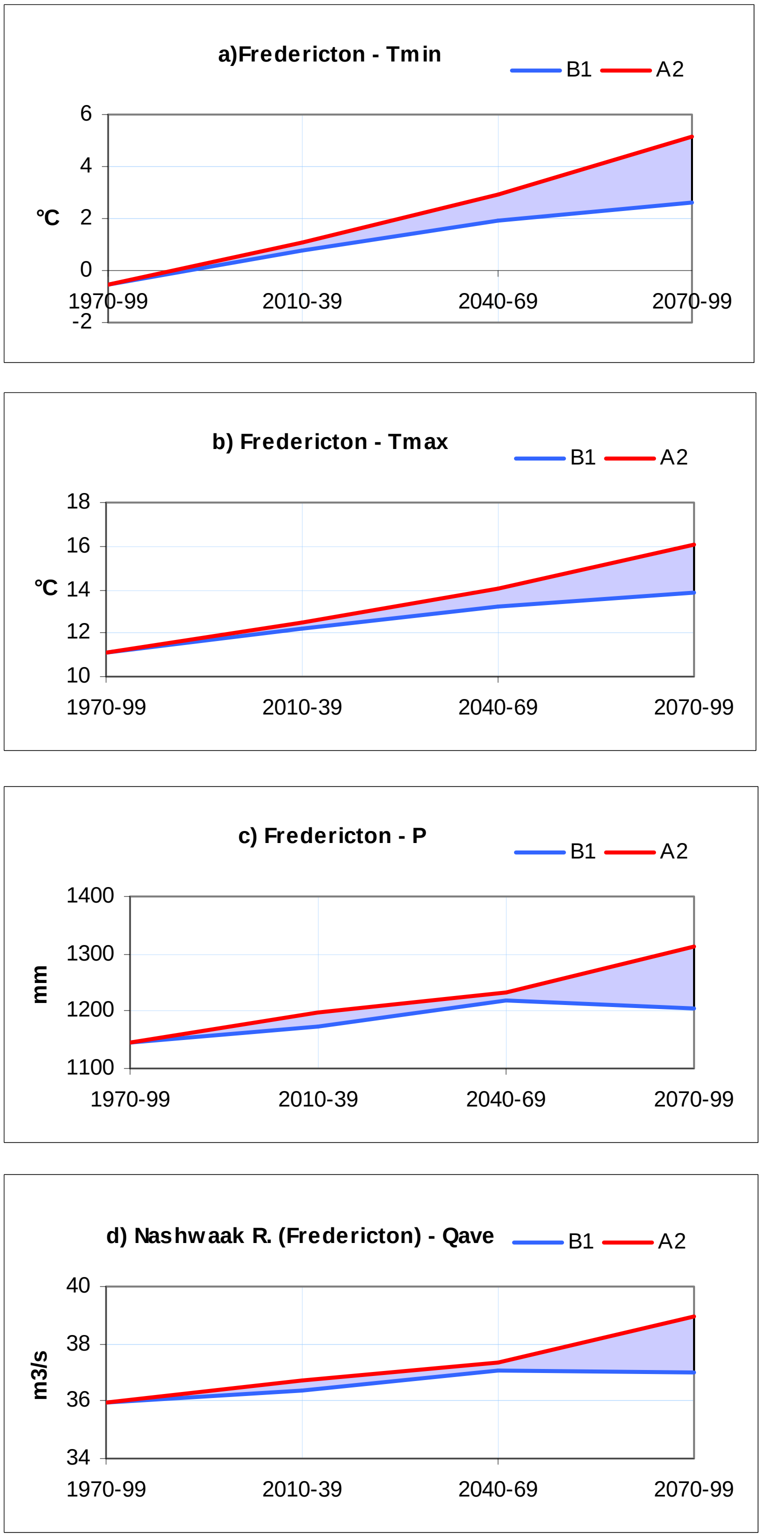


Figure 13 – Observed (1970-99) and simulated (scenarios B1 & A2) (2010-39, 2040-69, 2070-99) annual means at Fredericton a) minimum temperature b) maximum temperature c) total precipitation d) average discharge (Nashwaak R.)

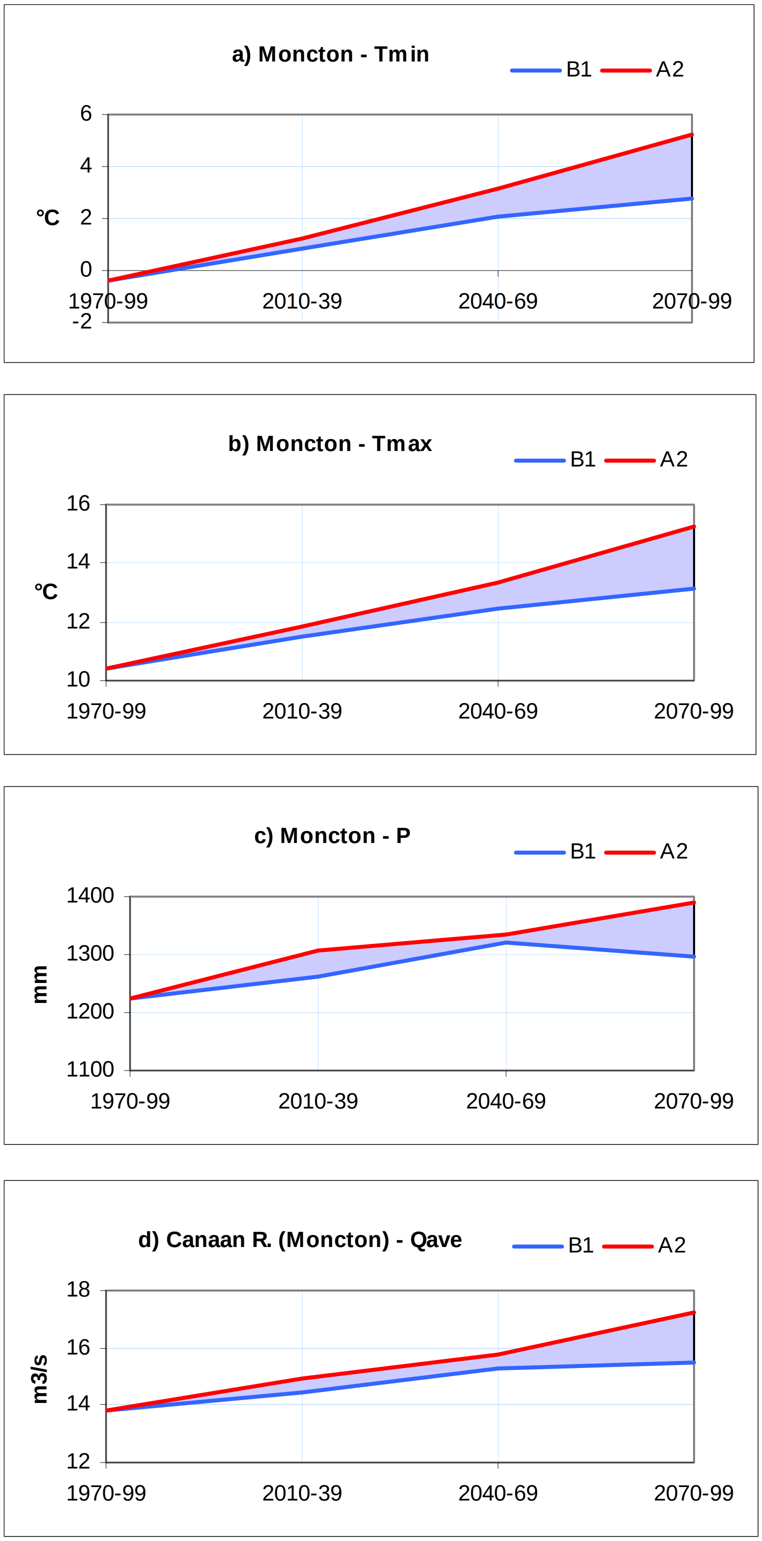


Figure 14 – Observed (1970-99) and simulated (scenarios B1 & A2) (2010-39, 2040-69, 2070-99) annual means at Moncton a) minimum temperature b) maximum temperature c) total precipitation d) average discharge (Canaan R.)

Figure 15 – Observed (1970-99) and simulated (scenarios B1 & A2) (2010-39, 2040-69, 2070-99) annual means at Saint John a) minimum temperature b) maximum temperature c) total precipitation d) average discharge (Kennebecasis R.)

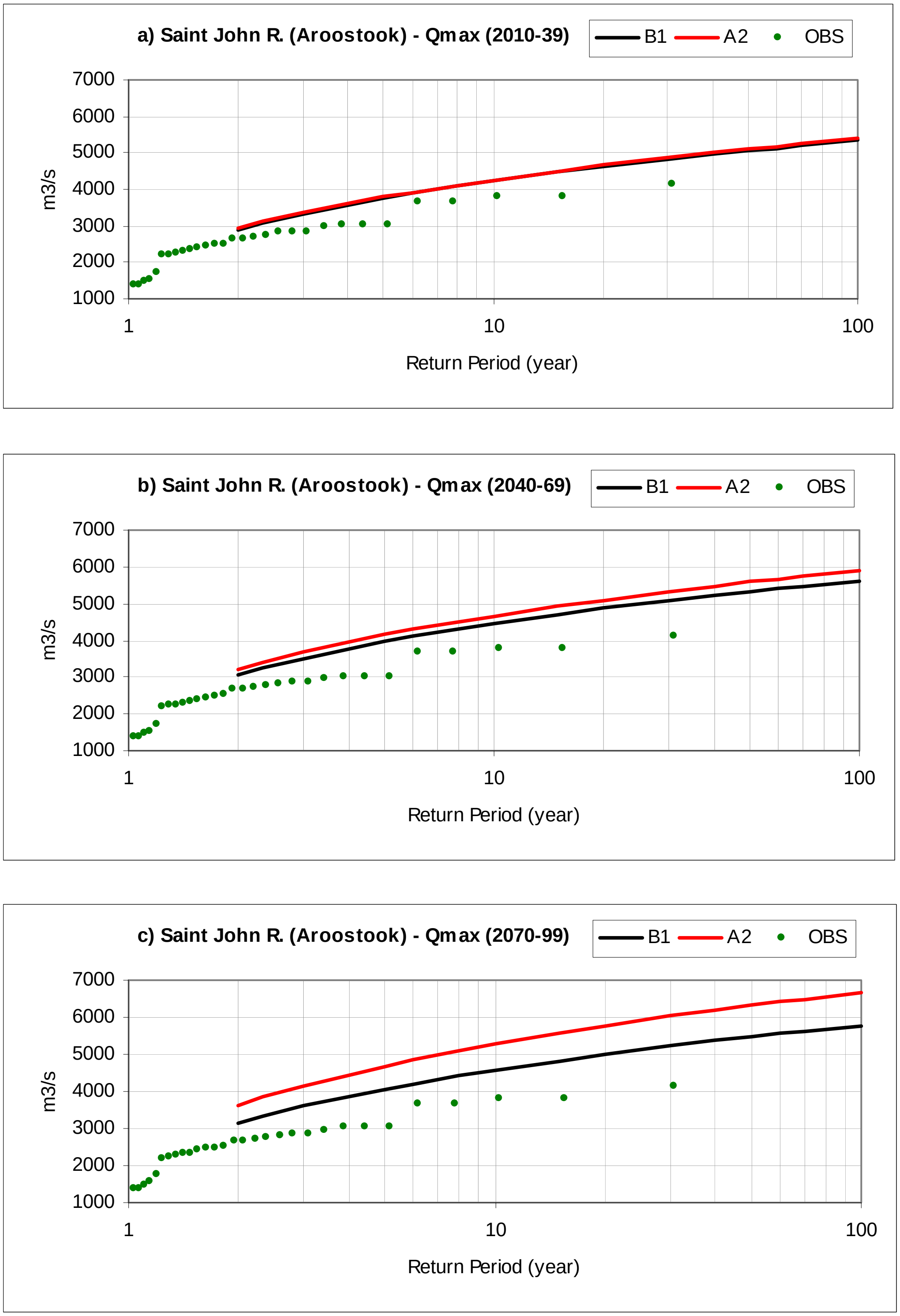


Figure 16 – Observed and simulated (using scenarios B1 & A2) annual flood frequency curves for Saint John River (Aroostook) a) 2010-39 b) 2040-69 c) 2070-99

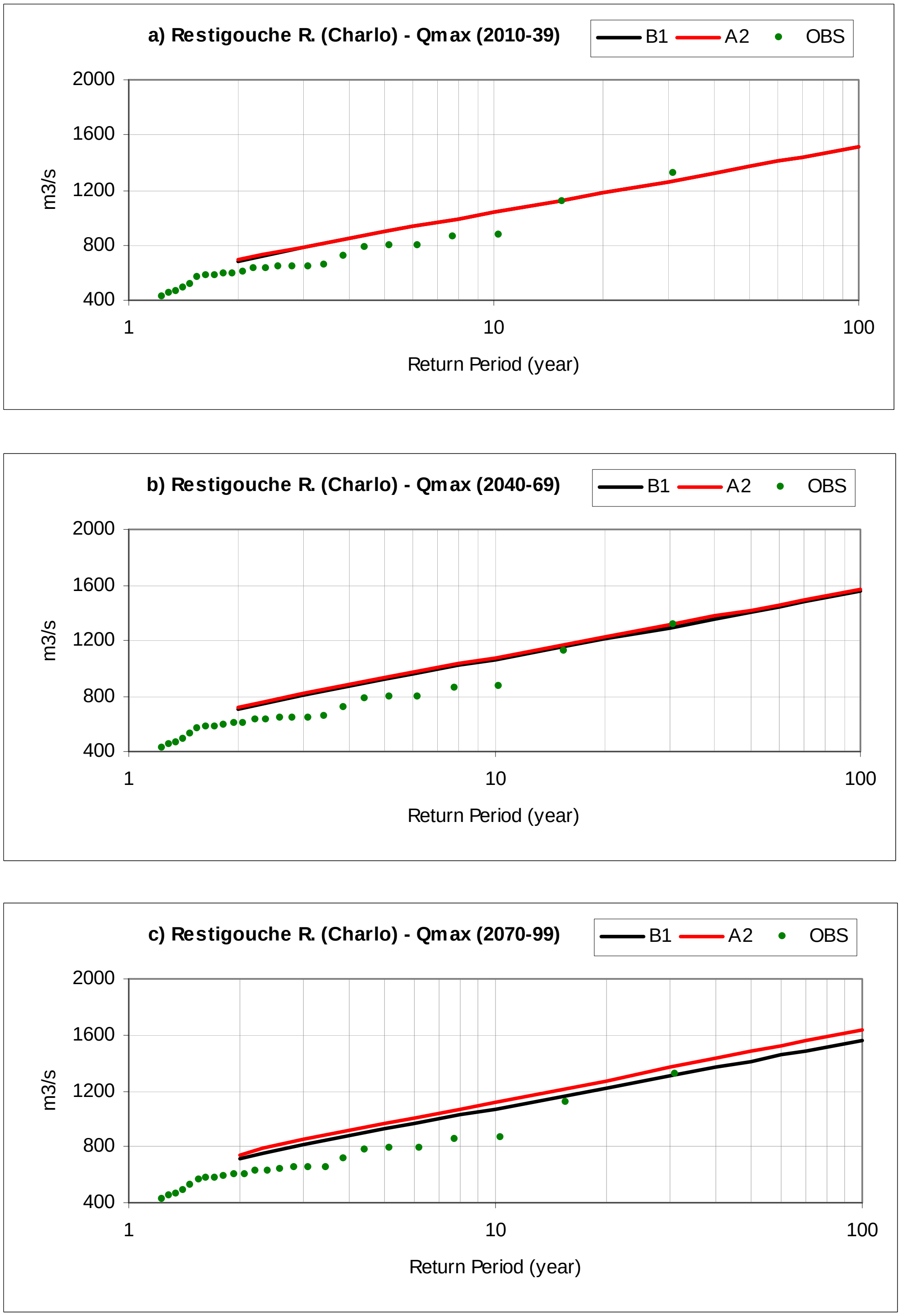


Figure 17 – Observed and simulated (using scenarios B1 & A2) annual flood frequency curves for Restigouche River (Charlo) a) 2010-39 b) 2040-69 c) 2070-99

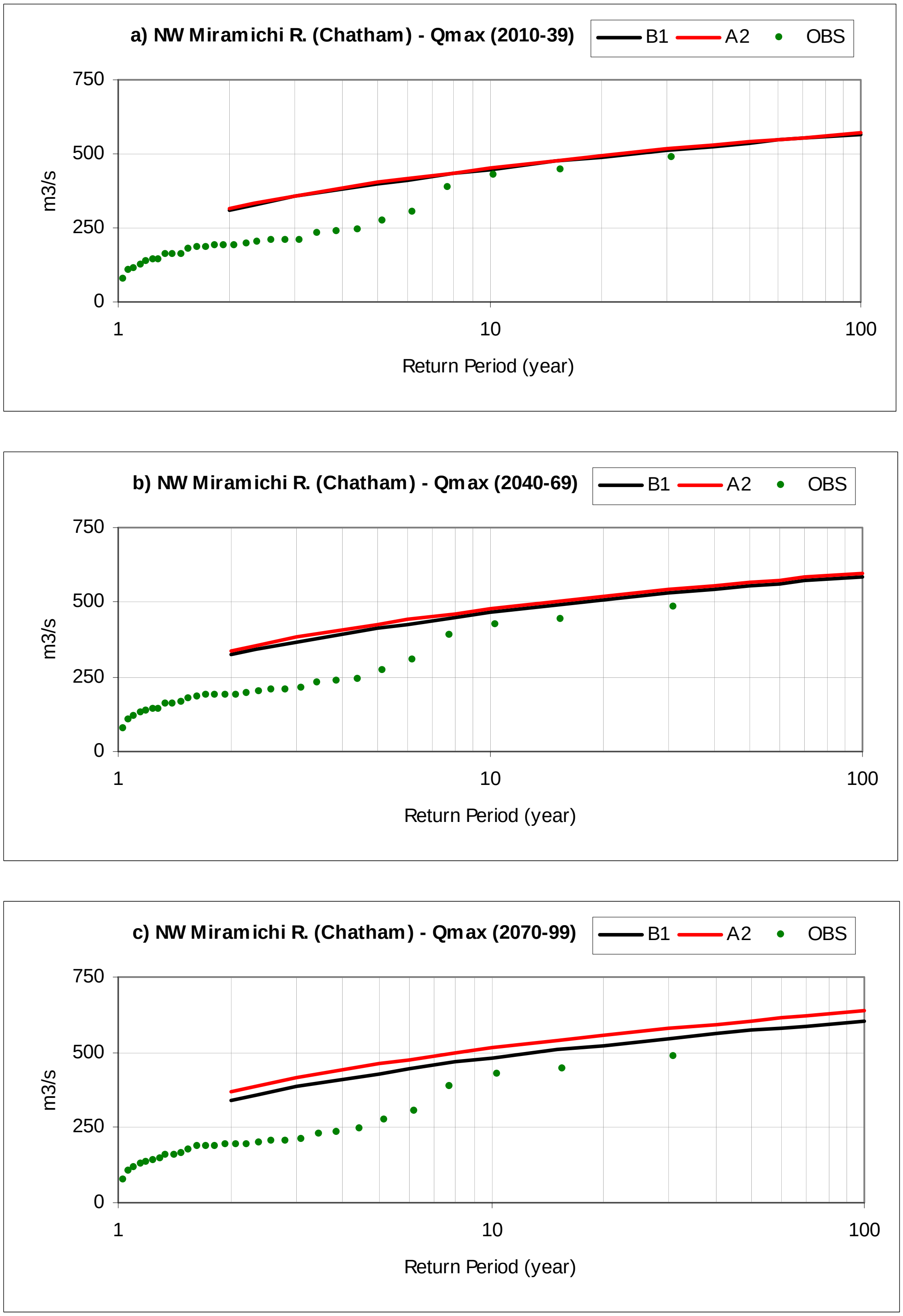


Figure 18 – Observed and simulated (using scenarios B1 & A2) annual flood frequency curves for NW Miramichi River (Chatham) a) 2010-39 b) 2040-69 c) 2070-99

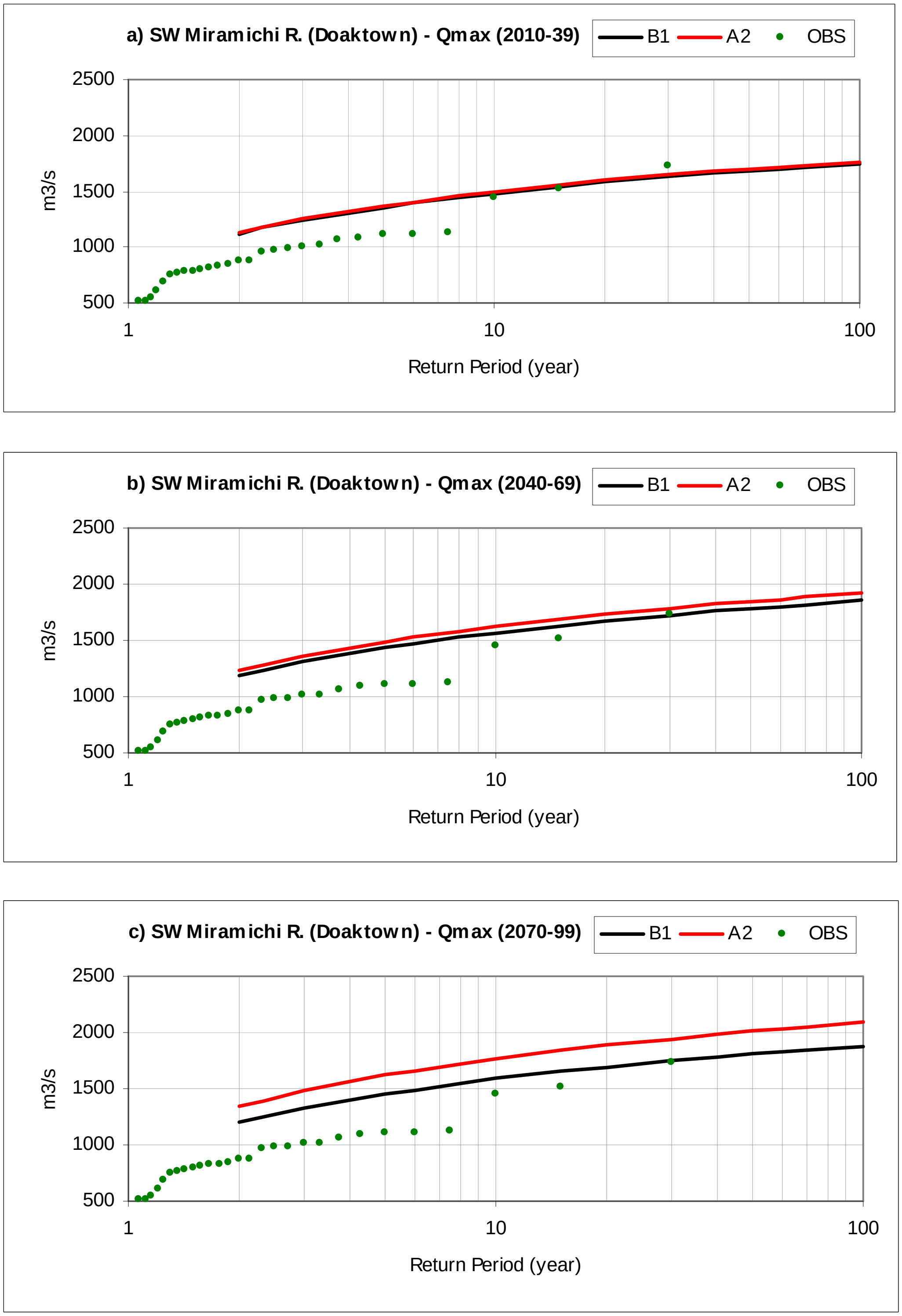


Figure 19 – Observed and simulated (using scenarios B1 & A2) annual flood frequency curves for SW Miramichi River (Doaktown) a) 2010-39 b) 2040-69 c) 2070-99

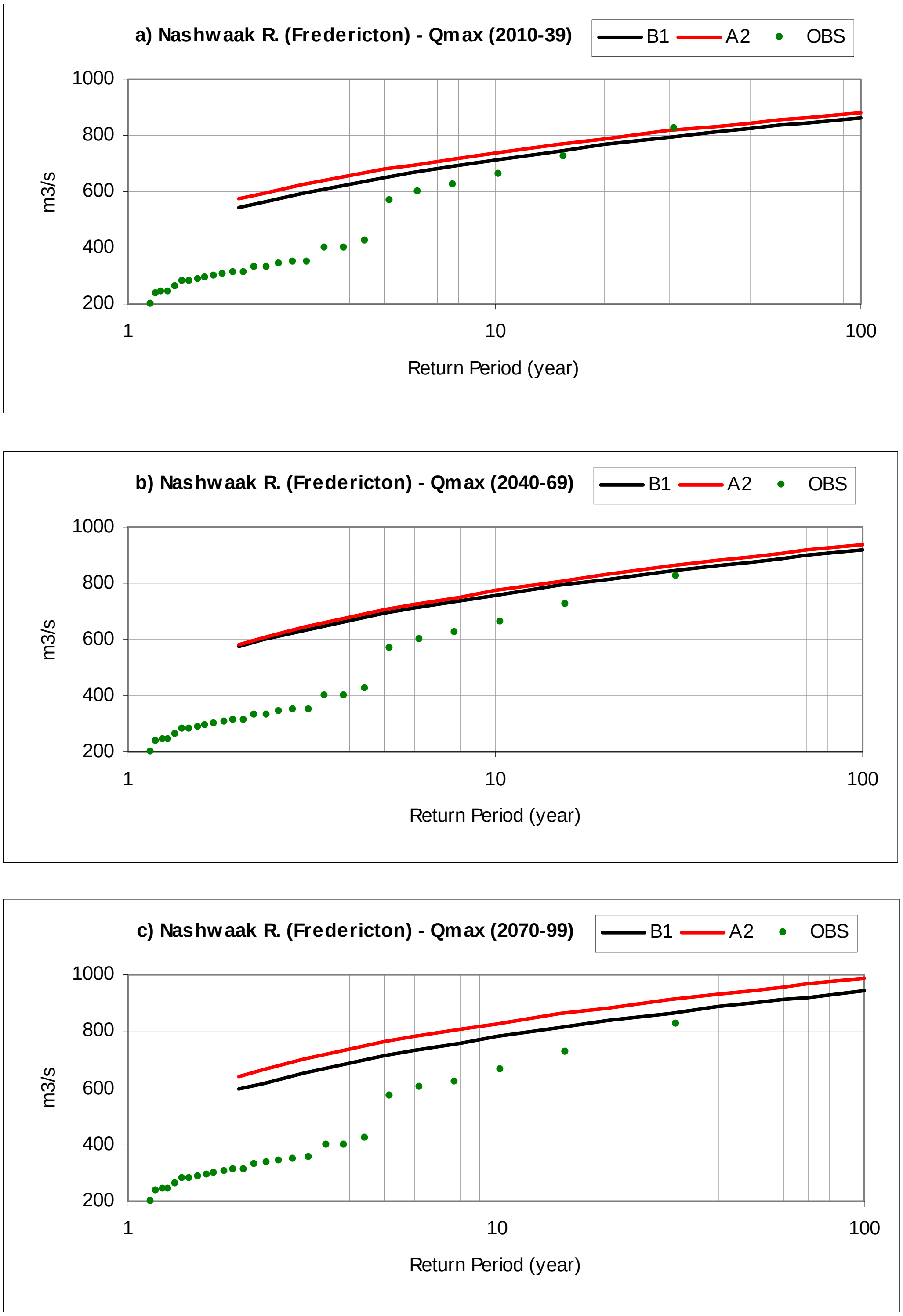


Figure 20 – Observed and simulated (using scenarios B1 & A2) annual flood frequency curves for Nashwaak River (Fredericton) a) 2010-39 b) 2040-69 c) 2070-99

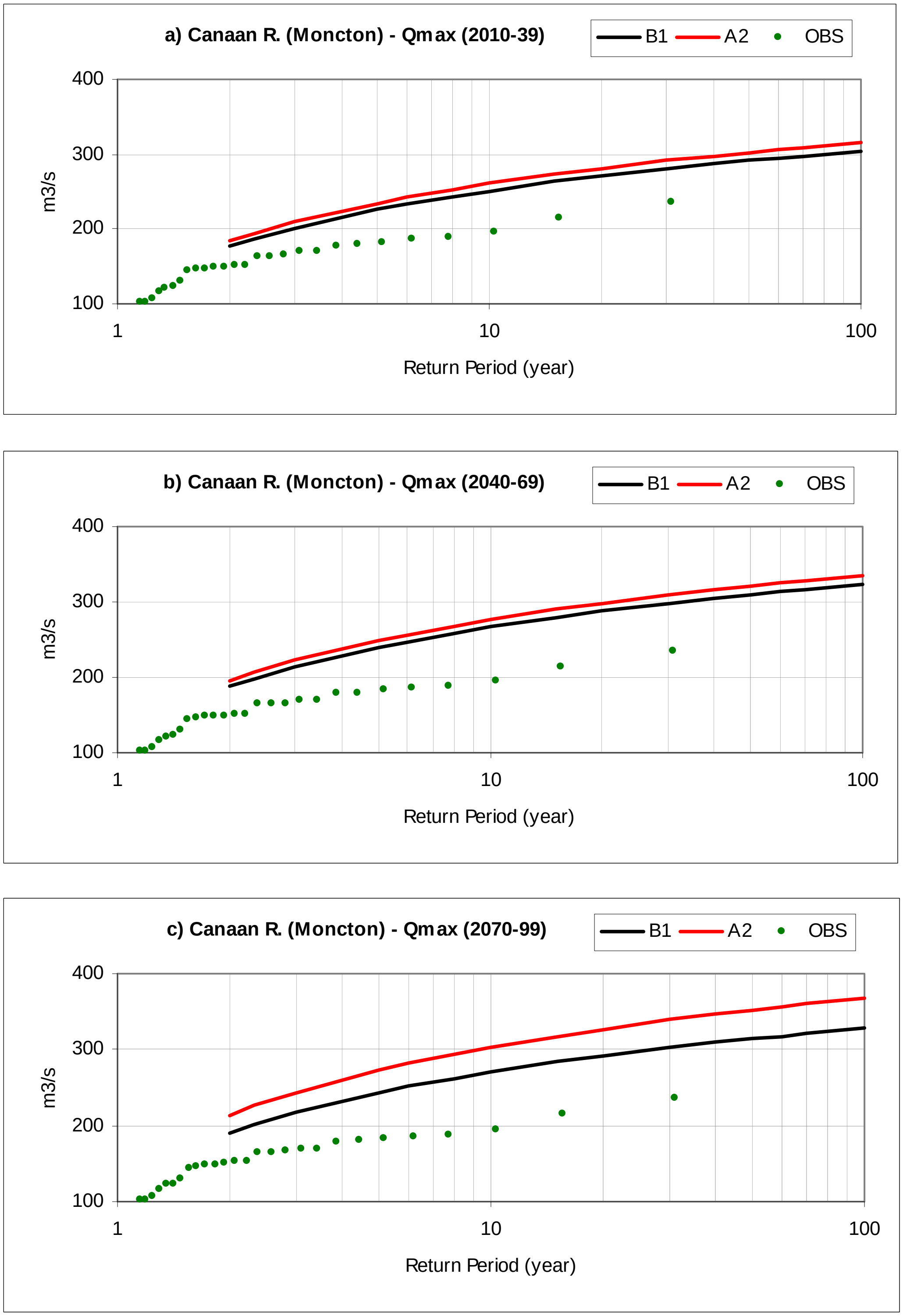
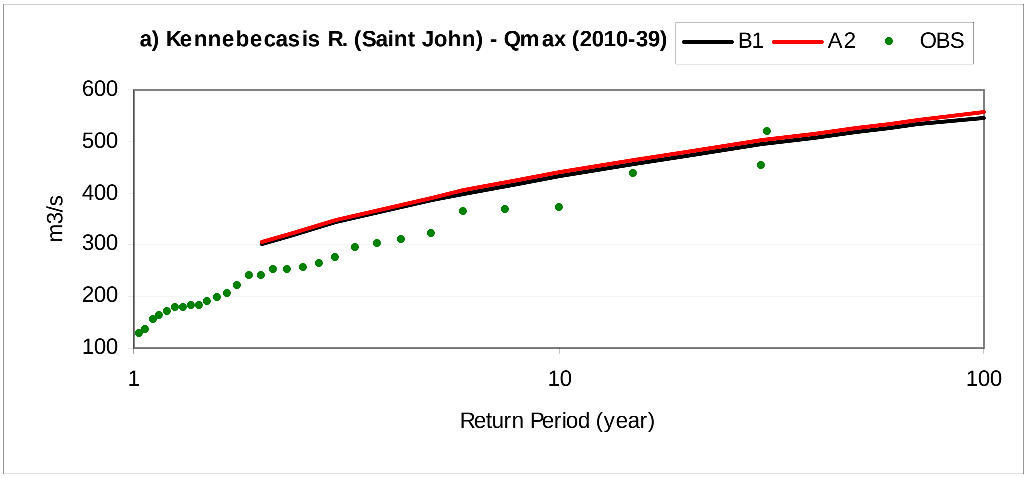
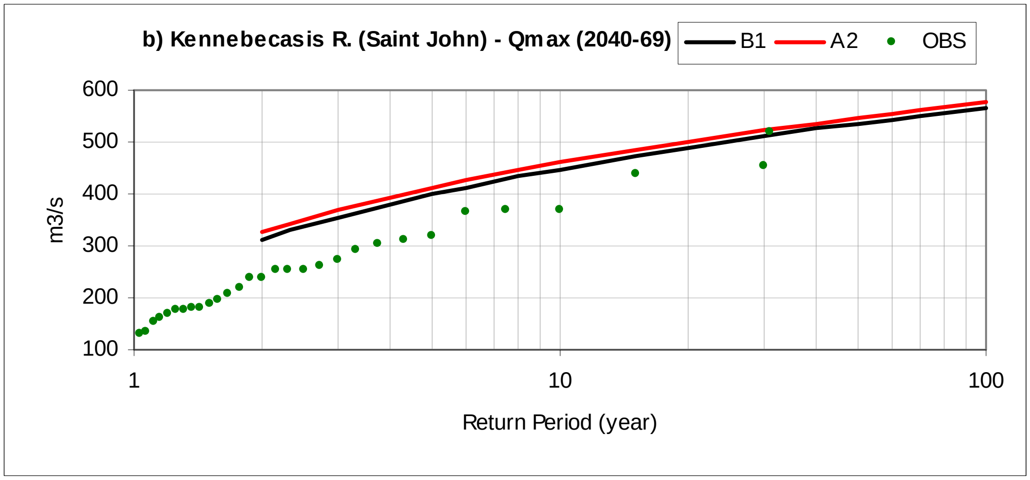


Figure 21 – Observed and simulated (using scenarios B1 & A2) annual flood frequency curves for Canaan River (Moncton) a) 2010-39 b) 2040-69 c) 2070-99





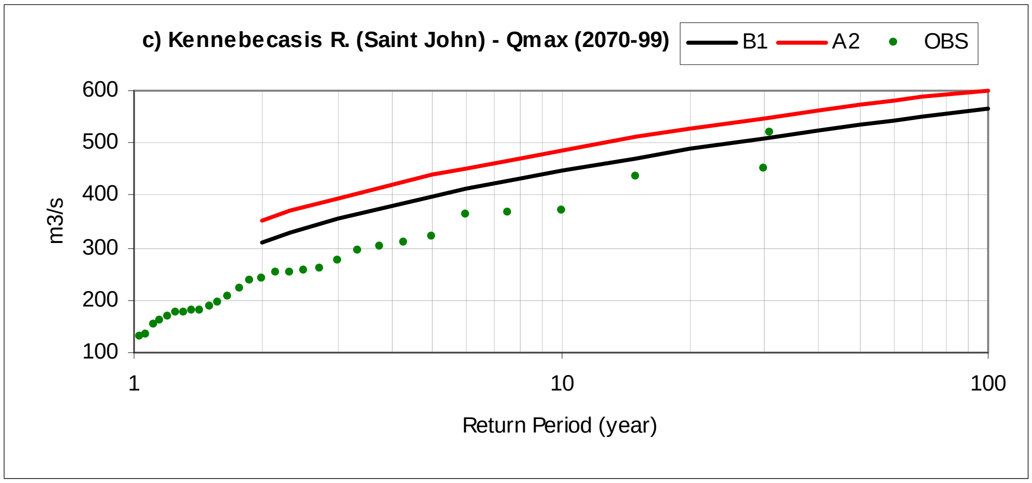


Figure 22 – Observed and simulated (using scenarios B1 & A2) annual flood frequency curves for Kennebecasis River (Saint John) a) 2010-39 b) 2040-69 c) 2070-99

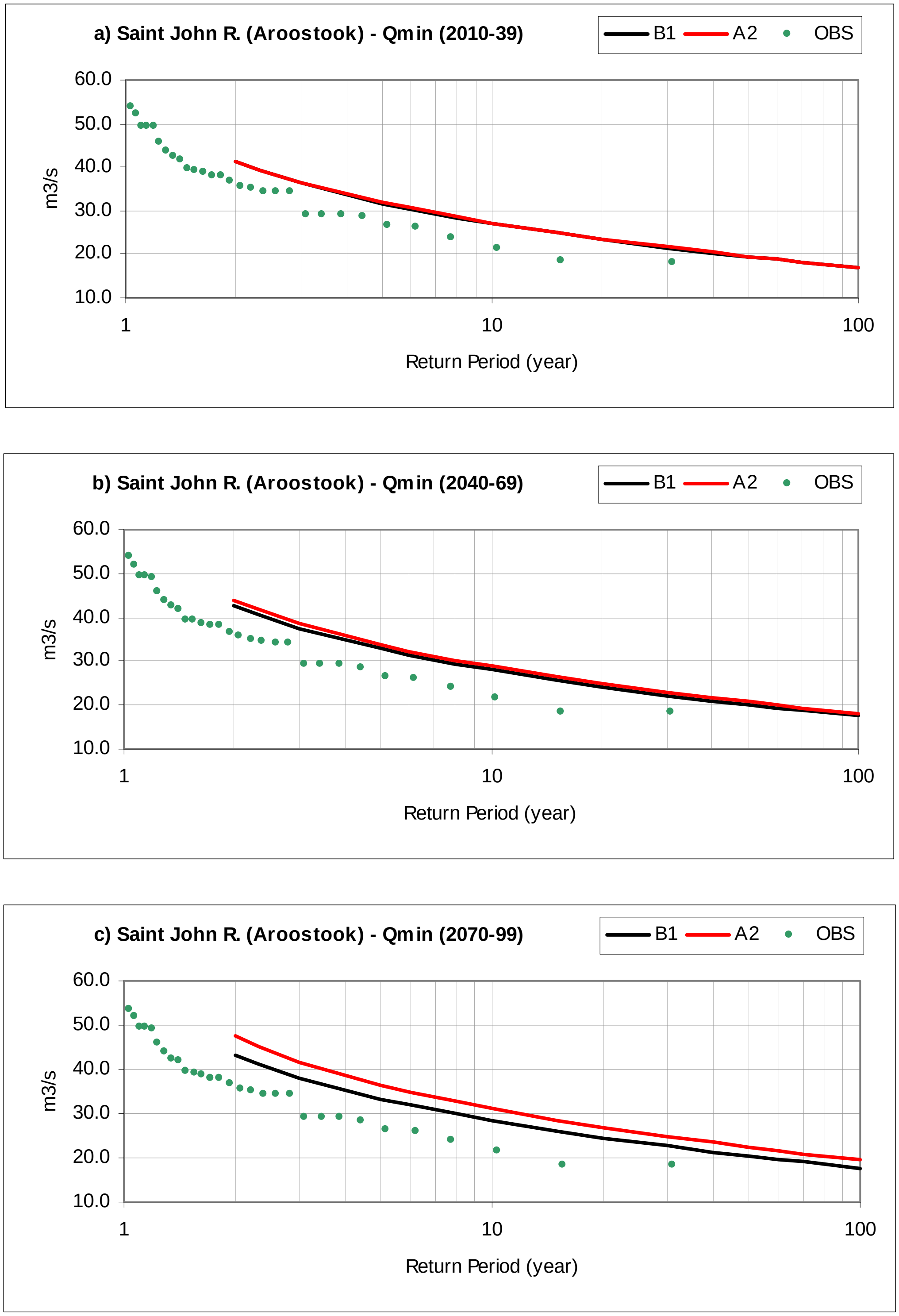


Figure 23 – Observed and simulated (using scenarios B1 & A2) annual drought frequency curves for Saint John River (Aroostook) a) 2010-39 b) 2040-69 c) 2070-99

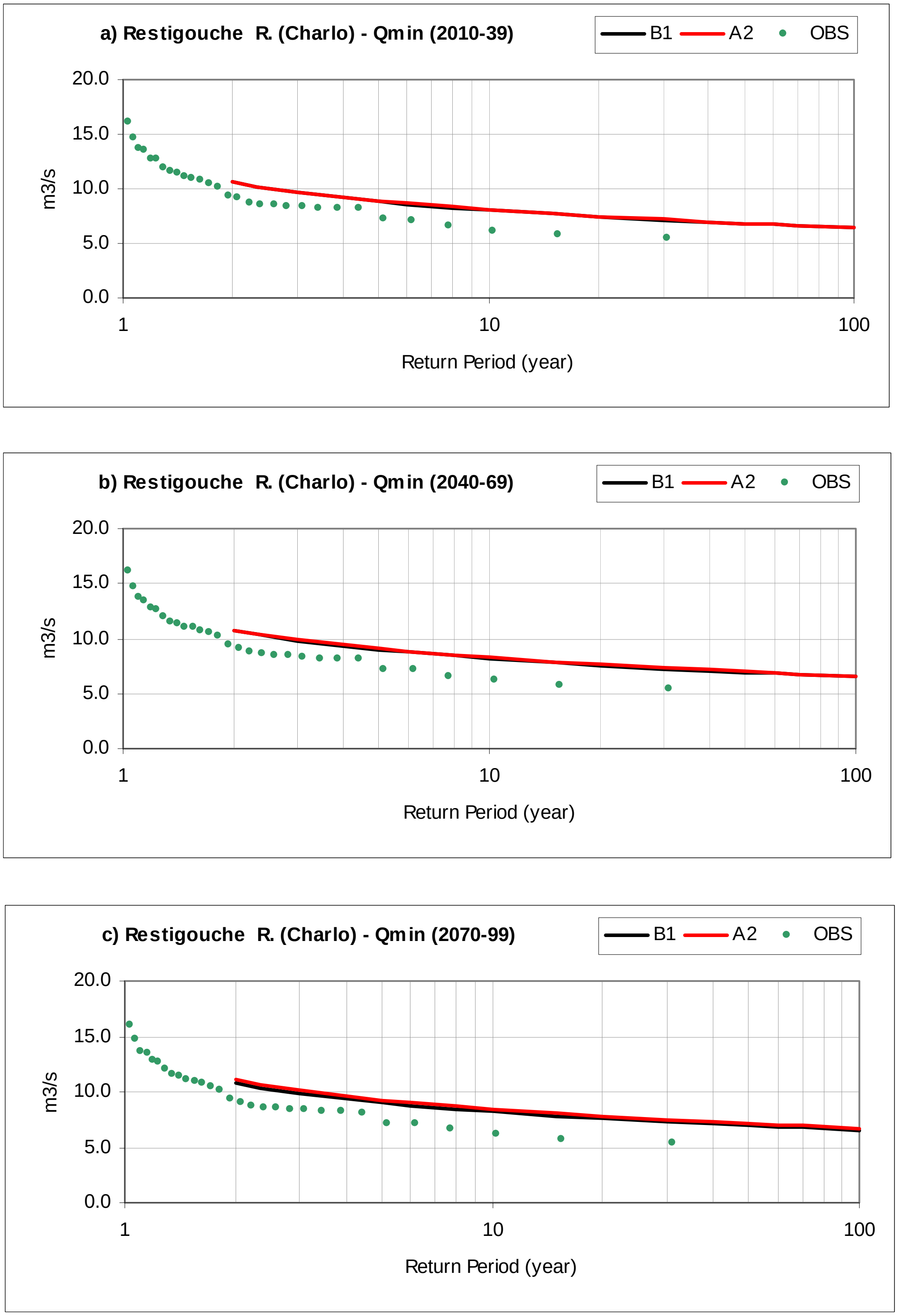


Figure 24 – Observed and simulated (using scenarios B1 & A2) annual drought frequency curves for Restigouche River (Charlo) a) 2010-39 b) 2040-69 c) 2070-99

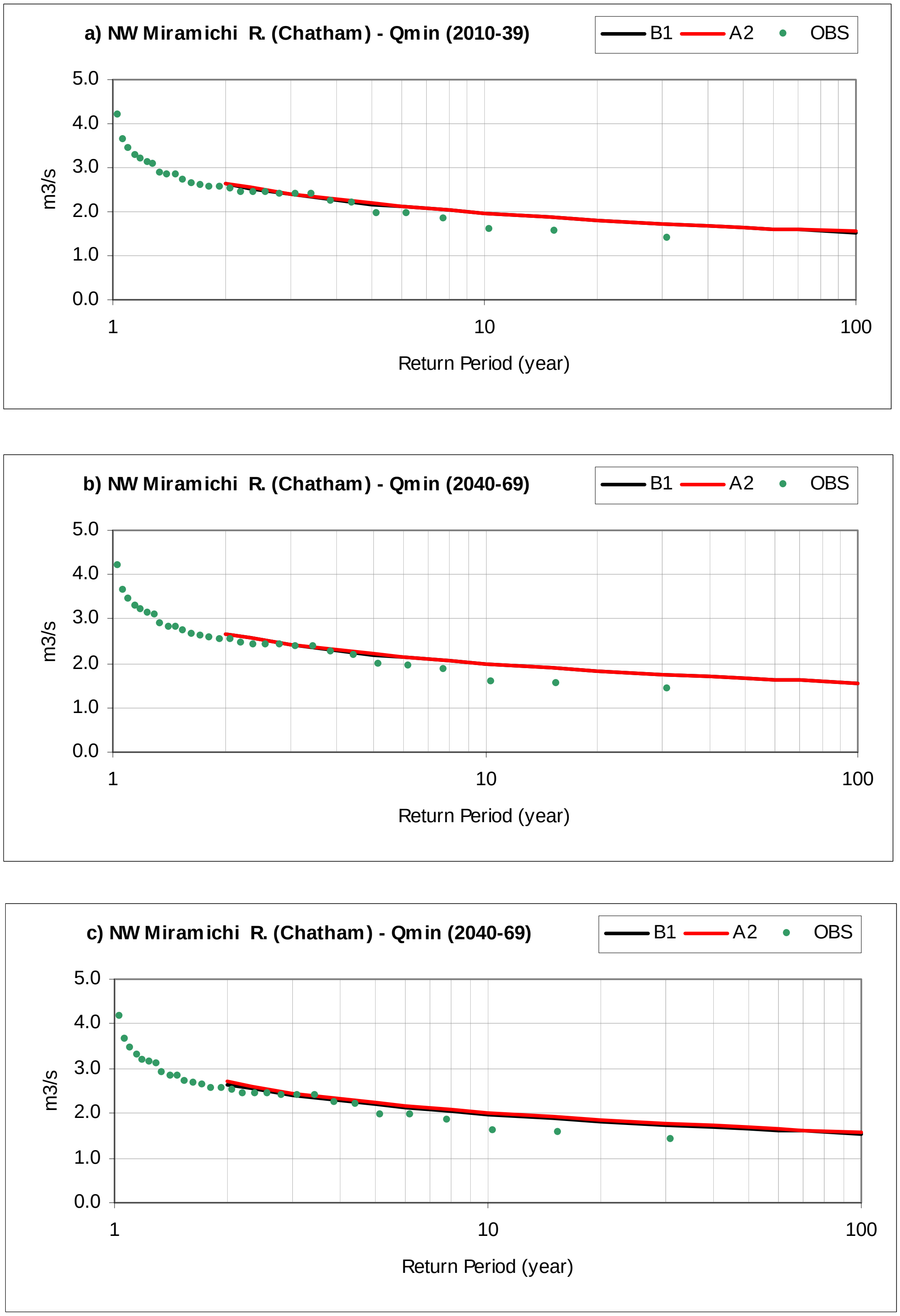


Figure 25 – Observed and simulated (using scenarios B1 & A2) annual drought frequency curves for NW Miramichi River (Chatham) a) 2010-39 b) 2040-69 c) 2070-99

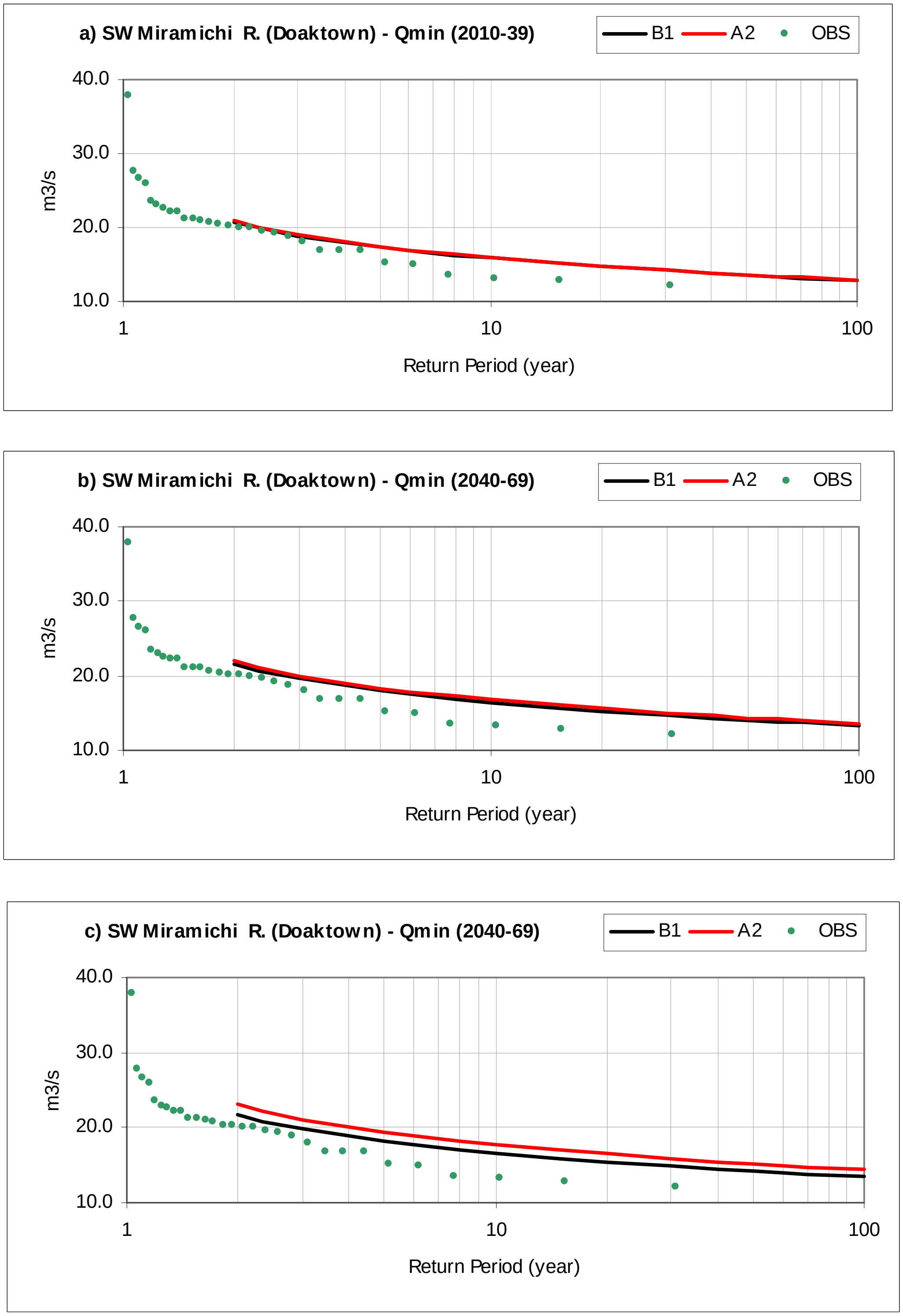
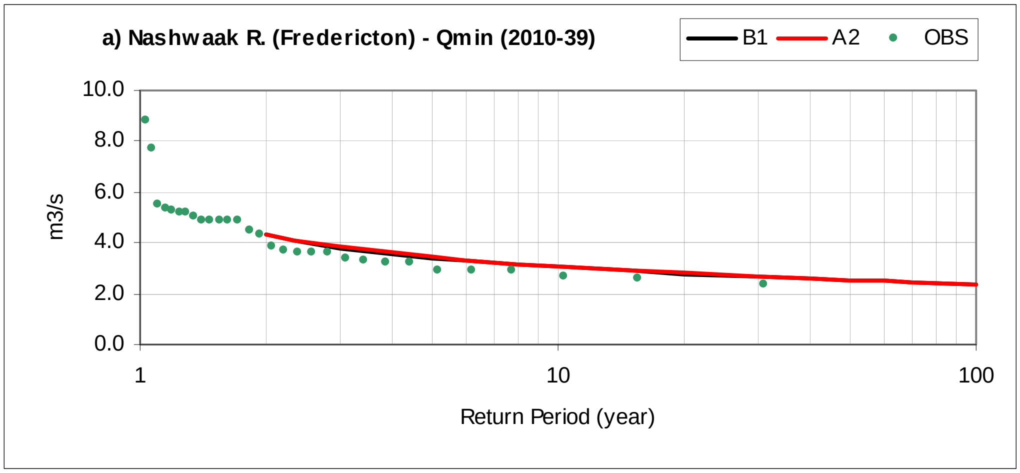
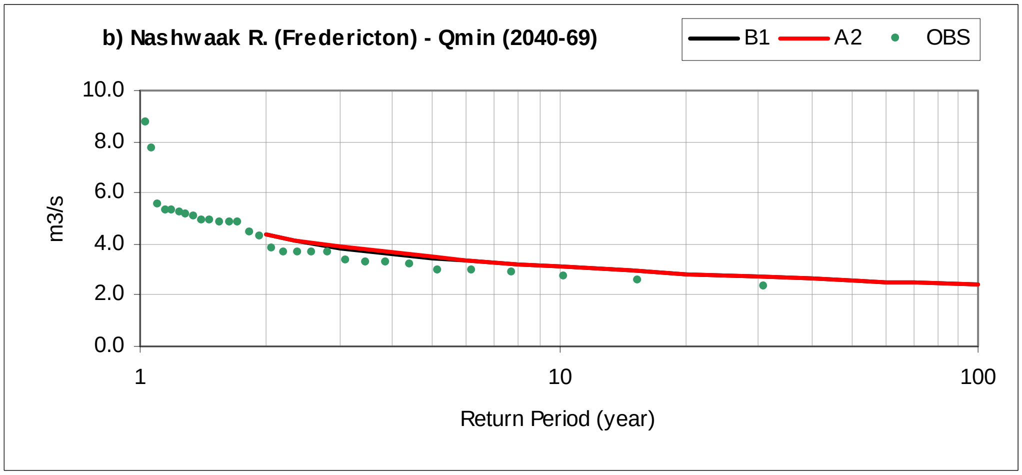


Figure 26 – Observed and simulated (using scenarios B1 & A2) annual drought frequency curves for SW Miramichi River (Doaktown) a) 2010-39 b) 2040-69 c) 2070-99





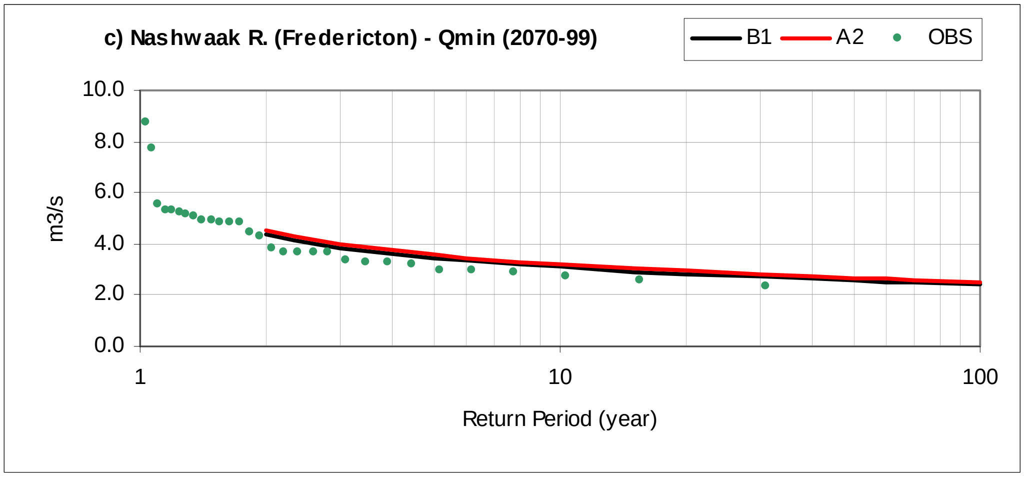


Figure 27 – Observed and simulated (using scenarios B1 & A2) annual drought frequency curves for Nashwaak River (Fredericton) a) 2010-39 b) 2040-69 c) 2070-99

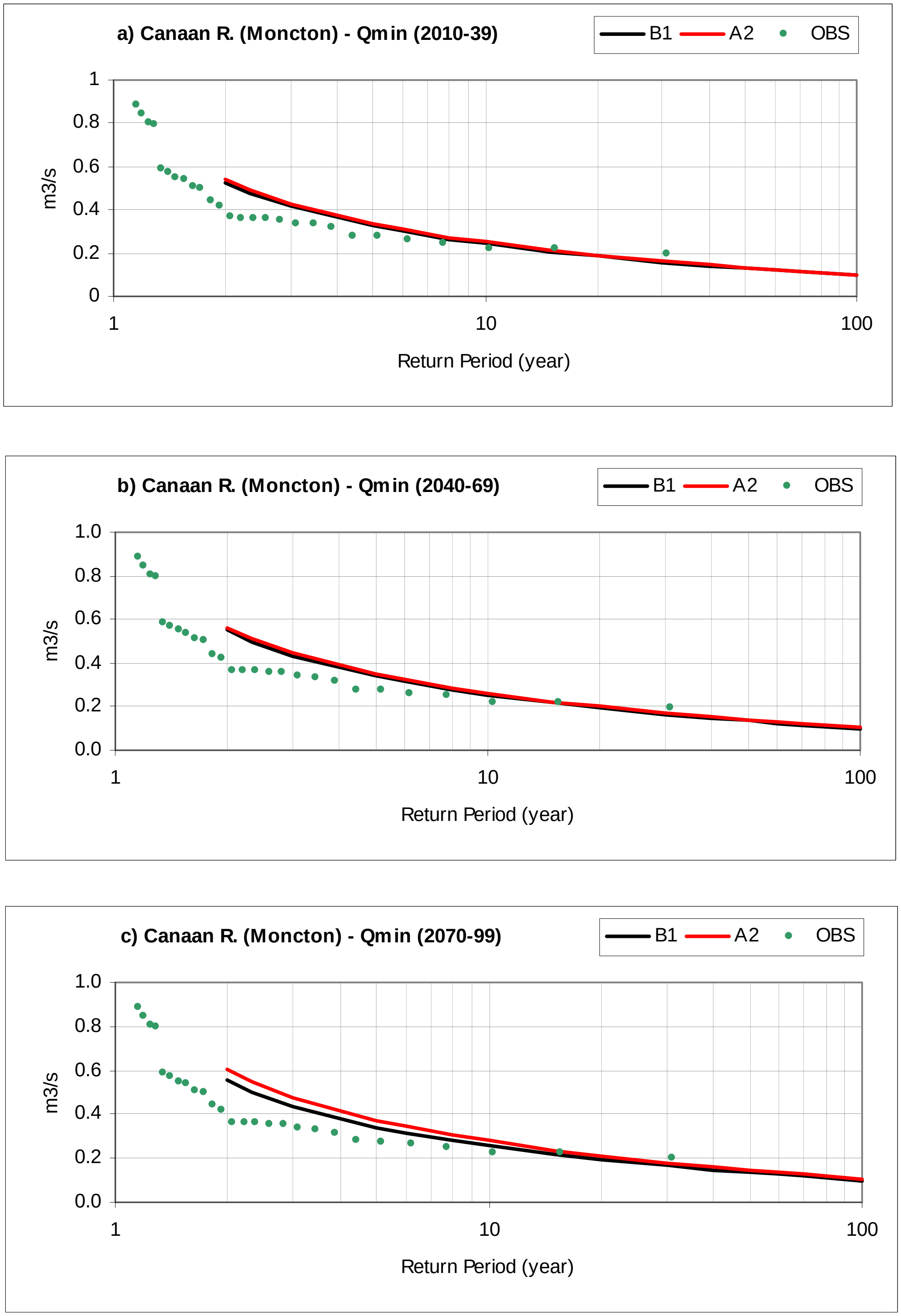


Figure 28 – Observed and simulated (using scenarios B1 & A2) annual drought frequency curves for Canaan River (Moncton) a) 2010-39 b) 2040-69 c) 2070-99

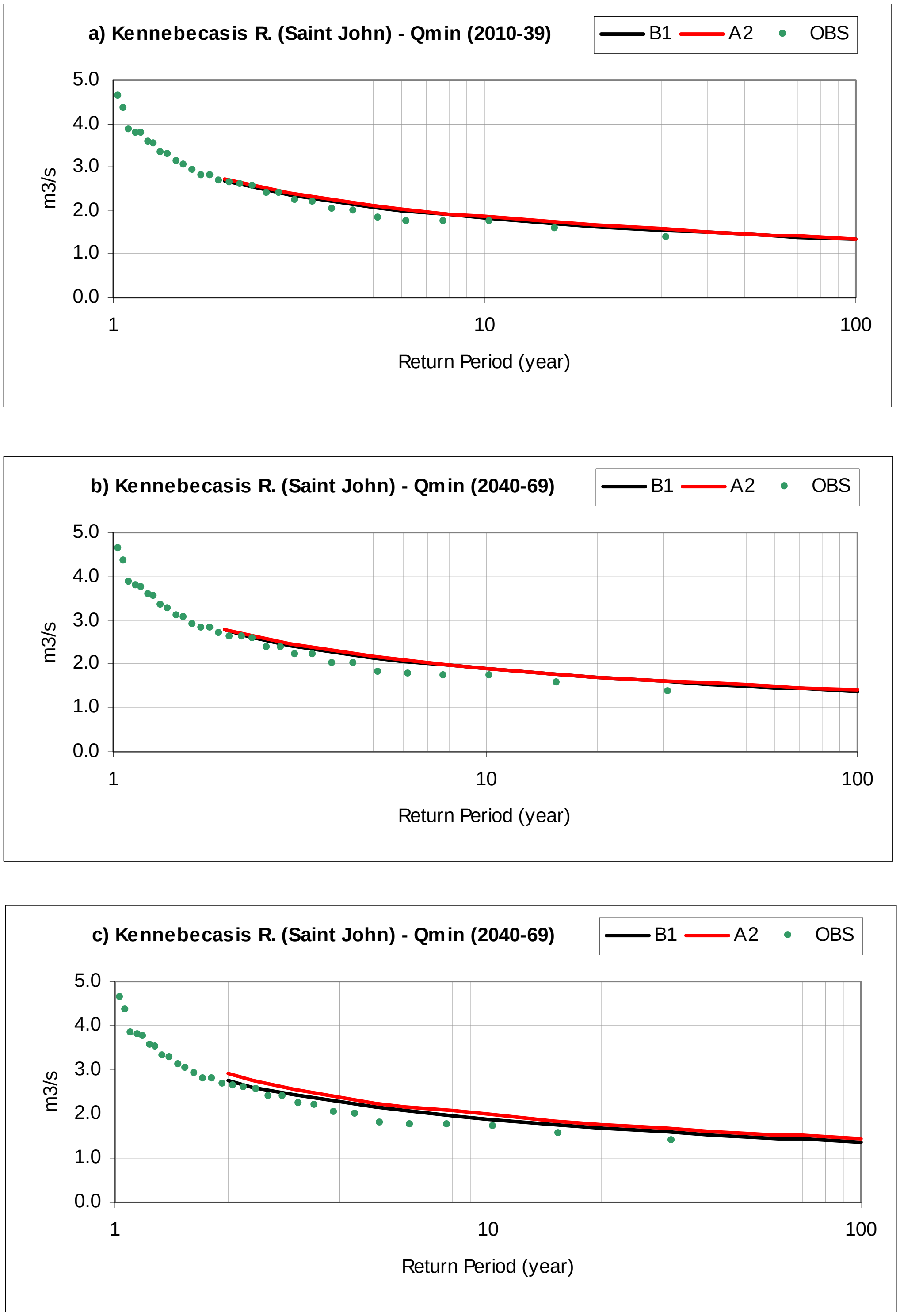


Figure 29 – Observed and simulated (using scenarios B1 & A2) annual drought frequency curves for Kennebecasis River (Saint John) a) 2010-39 b) 2040-69 c) 2070-99

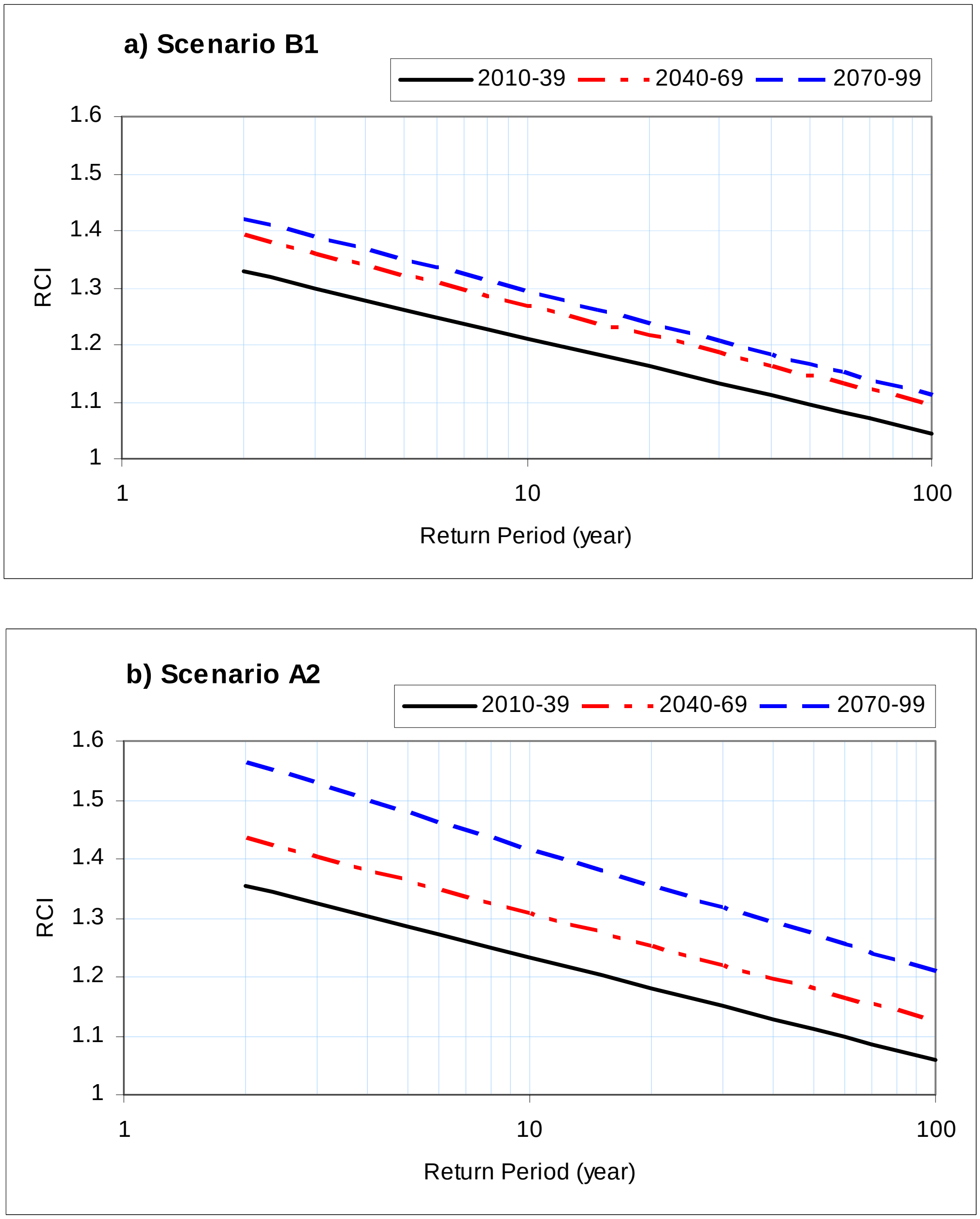
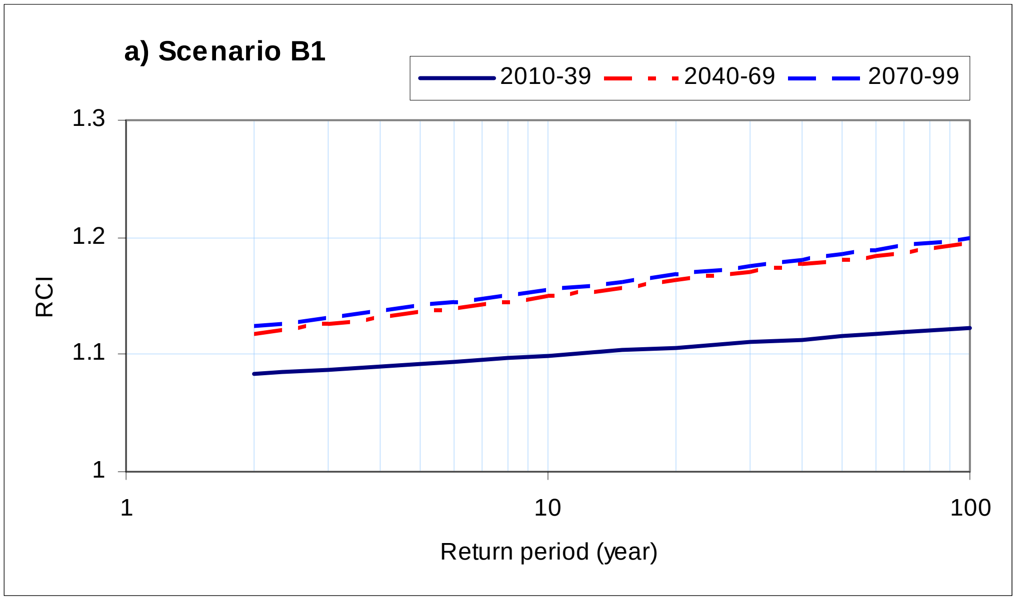


Figure 30 – New Brunswick regional climate index curves for flood at time slices 2010-39, 2040-69 and 2070-99 under a) scenario B1 b) scenario A2



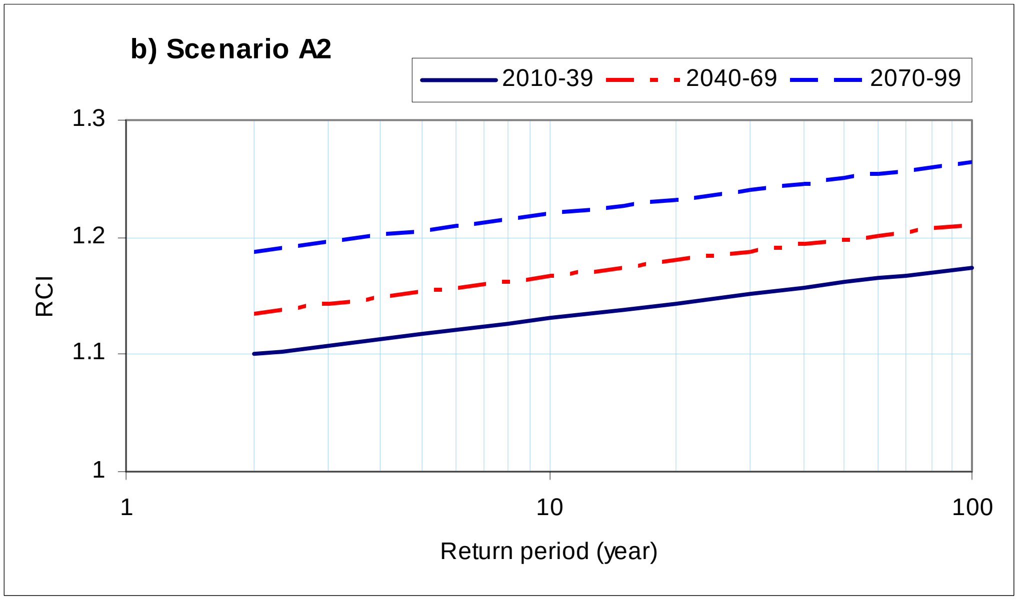


Figure 31 – New Brunswick regional climate index curves for drought at time slices 2010-39, 2040-69 and 2070-99 under a) scenario B1 b) scenario A2