FLOODS AND DROUGHTS MODELING UNDER CLIMATE CHANGE SCENARIOS USING NEURAL NETWORKS

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Abstract: The purpose of this study is to investigate the impact of climate change on floods and droughts in New- Brunswick, Canada, using downscaled climate models and neural networks. Future climate data were extracted from the Canadian Coupled General Circulation Models (CGCM2) and the Hadley Circulation Model (HadCM3) with a multilayered feed-forward neural network models to predict the local variability in river discharge and extreme events. With projected high and low flow frequency calculations, it will be possible to compare current design criteria with future scenarios that consider climate change. The simulations were computed using the generalized extreme value (GEV) distribution function, and the parameters of the distribution were estimated using L-moments method.

Key words: Climate Change, Droughts, Floods, GEV, Neural Networks.

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 an intense, broad-based international research effort in the natural and social sciences. However, understanding the nature and potential consequences of climate change at regional scales remains a challenge. Moreover, it has been recognized that changes in the frequency and magnitude of extreme weather events are likely to 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 heavy floods, severe droughts and extreme heat around the world. These have caused serious risks to ecosystems and have had severe economic consequences on sectors such as agriculture and water resources. Anticipating specific climatic impacts, is thus, as much a challenge of assessing risks and uncertainties associated with plausible scenario of climate extremes and variability as it is in predicting changes in the average climate. As such, it is important 1) to improve our ability to manage extreme climatic risks, 2) to assess the consequences of such extreme events in the coming decades, and 3) to develop new tools and design criteria to more accurately assess the impact of such extremes on water resources. Improved knowledge and assessment tools would assist policy-makers in formulating more robust policies to mitigate the impacts of climate change and to develop adaptation strategies.

2. BACKGROUND AND DATA GATHERING

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 stream flow (Hengeveld 1990; Natural Resources Canada 2002) and significant impacts on aquatic resources (Minns et al. 1995). The demand for water withdrawal from rivers (e.g. irrigation, drinking water, etc.) and maintaining adequate instream flow for the protection of aquatic resources are tenuously balanced, and represent an ongoing challenge in water resources management. Many rivers in eastern Canada have recently experienced record low flow conditions, coupled with record high water temperatures (Caissie 1999a,b; Caissie 2000), and an increase in water withdrawal. 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. 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.

Major rivers and many smaller streams flow from the interior highlands of New Brunswick. Rainfall, snowmelt, and groundwater all contribute to the volume of flow, producing variations from season to season and year to year. Most high flows and floods are caused by spring snowmelt. Heavy rainfall can also cause high flows and floods, especially on small streams. Low flows generally occur in late summer, when precipitation is low and evaporation is high, and in late winter, when precipitation is stored until spring in the form of ice and snow.

Daily maximum and minimum air temperature and total precipitation data from 7 meteorological stations in New Brunswick were obtained from Environment Canada (Figure 1 and Table1). Air temperature data from the National Climate Data Archive was "homogenized" 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. Daily discharge (m^3/s) data from 7 hydrometric stations in New Brunswick (Figure 1 and Table 2) were obtained from Environment Canada's National Water Data Archive (HYDAT). Discharge series included data from 1919 to 2005, with continuous series extending 43 to 79 years at some stations.

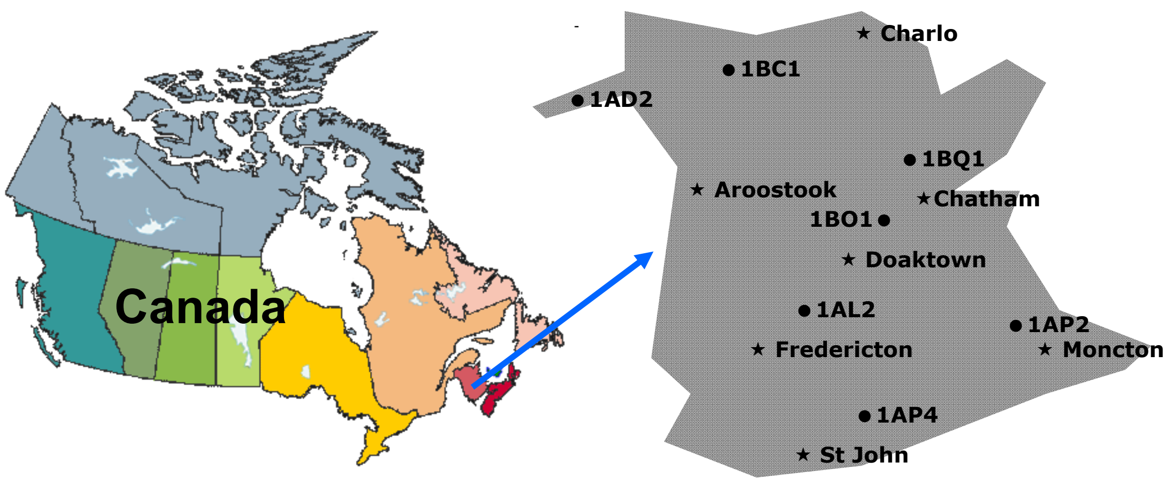

Figure 1. Location of meteorological and hydrometric stations in New Brunswick, Canada

(● Hydrometric station ★ Metrological station)

Table 1. Location and length of air temperature and precipitation time series at meteorological stations in New Brunswick.

Meteorological Station	Latitude, Longitude	Air Temperature Series	Precipitation Series
Aroostook	46º 48’ N; 67º 43’ W	1913-1999 (87 yrs.)	1929-2005 (77 yrs.)
Charlo Airport	47º 59’ N; 66º 20’ W	1945-1999 (55 yrs.)	1966-2005 (40 yrs.)
Chatham Airport	47º 01’ N; 65º 27’ W	1895-1999 (105 yrs.)	1943-2005 (63 yrs.)
Doaktown[1]	46º 33’ N; 66º 09’ W	1952-1999 (48 yrs.)	1934-2005 (72 yrs.)
Fredericton Airport	45º 52’ N; 66º 32’ W	1895-1999 (105 yrs.)	1951-2005 (55 yrs.)
Moncton Airport	46º 06’ N; 64º 47’ W	1895-1999 (105 yrs.)	1939-2005 (67 yrs.)
Saint John Airport	45º 19’ N; 65º 53’ W	1895-1999 (105 yrs.)	1946-2005 (60 yrs.)

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

Hydrometric Station	Latitude, Longitude	Drainage Area (km^2)	Period of Record
Saint John R. at Fort Kent	47° 15’ N, 68° 36’ W	14,700	1927-05 (79 yrs.)
Nashwaak R. at Durham Bridge	46° 08’ N, 66° 37’ W	1,450	1962-05 (43 yrs.)
Canaan R. at East Canaan	46° 04’ N, 65° 22’ W	668	1926-40, 1963-05 (58 yrs.)
Kennebecasis R. at Apohaqui	45° 42’ N, 65° 36’ W	1,100	1962-05 (43 yrs.)
Restigouche R. below Kedgwick R.	47° 40’ N, 67° 29’ W	3,160	1963-05 (42 yrs.)
SW Miramichi R. at Blackville	46° 44’ N, 65° 50’ W	5,050	1919-32, 1962-05 (57 yrs.)
NW Miramichi R. at Trout Bk.	47° 06’ N, 65° 50’ W	948	1962-05 (43 yrs.)

3. METHODOLOGY

3.1 Climate data downscaling

According to the CGCM grid, western and central regions of New Brunswick fall within grid box 30X12Y, while the eastern coast falls within grid box 31X12Y. Observed NCEP (National Centers of Environmental Prediction) grid-scale predictors were interpolated to the 30X12Y and 31X12Y CGCM grid and made available by the Canadian Institute for Climate Studies (CICS) project. Local scale predictand (maximum and minimum air temperature, precipitation, and discharge) data from 1961-2100 were obtained from Environment Canada. A statistical model was used to downscale climate data. Statistical downscaling model were calibrated using daily series of maximum temperature (T_{MAX}), minimum temperature (T_{MIN}), wet-day amounts of precipitation (P). Statistical “downscaling” involves the development of significant relationships between local and large-scale climate based on coupled atmosphere ocean general circulation model (AOGCM) output. 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).

Statistical downscaling models were developed from daily series of maximum (T_{MAX}, equation (1)) and minimum temperature (T_{MIN}, equation (2)):

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

$$T_{MIN_i} = \delta_0 + \delta_T T_i + \delta_{T_{i-1}} T_{i-1} + \sum_{j=3} \left(\delta_X X_i\right)_j \tag{2}$$

where T_i = mean air temperature at 2-m;
X_i = other meteorological variables selected on a per site basis
α, δ = regression constant and coefficients

and wet-day amounts of precipitation (P, equation (3)):

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

where q_{500} = specific humidity at 500 hPa;
U_s = surface zonal velocity;
X = other meteorological variables selected on a per site basis
μ = regression constant and coefficients

Downscaling models were calibrated using observed predictor variables and the observed predictand and validated with data withheld from the calibration process. Site-specific meteorological parameters were provided by Environment Canada across New Brunswick, using statistical downscaling model (SDSM) (Lines et al., 2005). Observed data for daily maximum and minimum air temperatures, and total daily precipitation were used as meteorological variables to construct suites of downscaled climate variable projections. The output from two models was obtained, namely the second generation Coupled General Circulation Model (CGCM2) and the third Hadley Centre Coupled Atmosphere-Ocean General Circulation model (HadCM3) in conjunction with the greenhouse gas + aerosol emission experiment. Results from these models will be used to provide a range of values or future discharge using Neural Network numerical models.

3.2 Neural Network Model

Future river discharge data were generated using Artificial Neural Networks (ANN). The type of ANNs used in the present study are multilayered feed-forward networks. It consists of an input layer, a hidden layer and an output layer. The learning is supervised and the training is accomplished using the Levenberg-Marquardt algorithm. The three types of architectures used are depicted in Table 3.

Table 3 – Neural network architectures

Type	Network
A	{M, T_{MIN}, T_{MAX}, Ptot} → {Qa}
B1	{M, T_{MIN}, T_{MAX}, Ptot, Qa} → {Q_{MAX}}
B2	{M, T_{MIN}, T_{MAX}, Ptot, Qa} → {Q_{MIN}}
M (1,2,..,12), T_{MIN},T_{MAX} (°C), Ptot (mm), Qa, Q_{MAX}, Q_{MIN} (m^3/s)	

It was observed that the extreme discharge events were better predicted if the average discharge was used as an input in the model. Therefore, the simulated average discharge, Qa, from the network A was used in networks B1 and B2 for subsequent predictions of high flows (Q_{MAX}) and low flows (Q_{MIN}).

As an example, future river discharge for the Fredericton site (New Brunswick) will be used in the characterization of low flow and flood events. The characteristics of these extreme events will be used to calculate the discharge of different recurrence intervals. For this location, the performance of the networks showed a R^2 of 0.80 (A) and 0.92 (for B1 and B2) for the different network architectures presented in Table 3. Also, Figure 2 show how well the ANN model simulated monthly Q_{MAX} and Q_{MIN} between 1985 and 1990 compared to observed discharge values.

A visual inspection confirms that the simulated discharges coincided fairly well with the observed discharges.

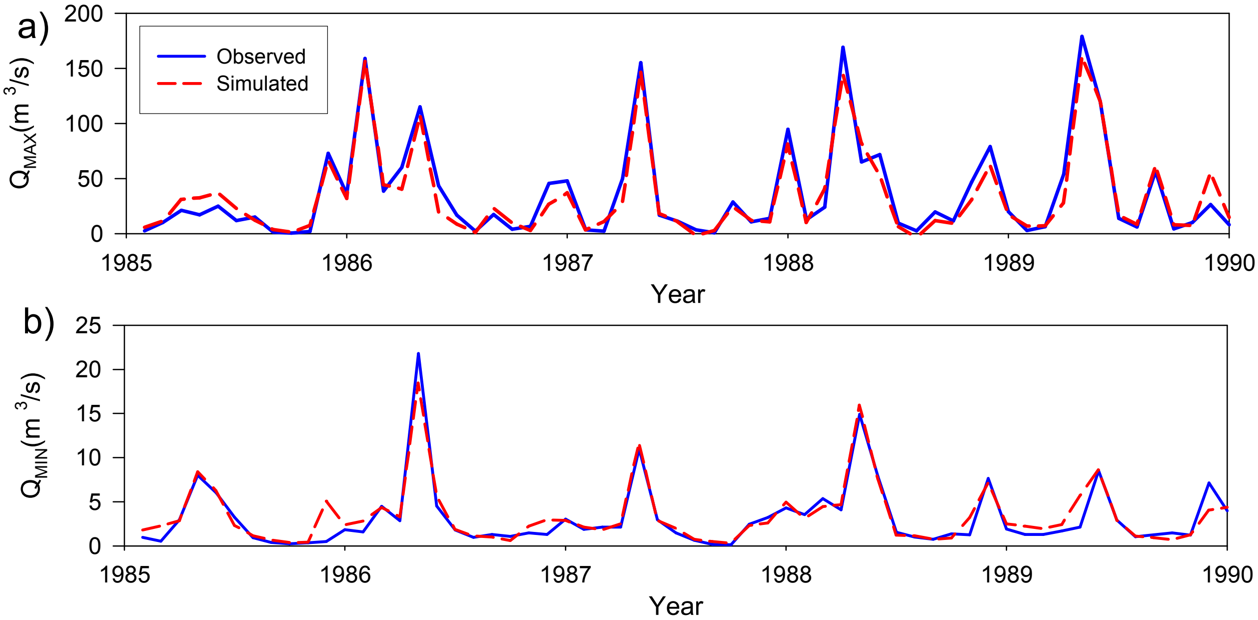

Figure2. Observed and simulated a) maximum monthly discharge b) minimum monthly discharge (using historical data)

3.3 Characterization of extreme events (high and low flows)

Stream flow data constitute the basis of information used by hydrologists to make predictions of floods and low flow events and their corresponding frequencies. The probabilistic approach is useful in the analysis due to the random nature of such events and the flexibility of this approach in characterizing extreme events. Such analysis of hydrologic data, also called a frequency analysis, 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.

3.4 Frequency of extreme events under climate change

Once that extreme event characteristics were determined (floods and low flows), a study of changes in intensity over time were carried out. For instance, the associated frequency of extreme events is very important in infrastructure design and these frequencies will most likely change under a future climate. The frequency (or return period) of high and low flow events will be calculated for the 2010-2100 period. With projected high or low flow frequency calculations, it will be possible to compare current design criteria with future scenarios that consider climate change. For instance, a 50-year high flow event today could potentially become a much more dominant high flow event in the future and thus represent a high flow event with a much lower recurrence interval. A similar situation with more severe summer droughts could also change current event frequencies. Such changes in high and/or low flow frequencies will be evaluated under climate change. The frequency of future events will ultimately impact on infrastructure design and development, flood and drought management, hydraulic and municipal water supply management as well as current statistics used by the insurance industry.

4. CASE STUDY

Future river discharge for the Fredericton site (New Brunswick) will be used in the characterization of low flow and flood events. The characteristics of these extreme events will be determined for different recurrence intervals. The annual maximum air temperature at the Fredericton site shows a significant increase for the period 2000-2100 compared to current climate conditions (1960-2000), by approximately 4 ºC. As for precipitation, the mean annual precipitation is projected to increase from approximately 1230 mm to 1670 mm within the next hundred years.

The frequency of high and low flow events was calculated based on present day data and on future climate variation. With projected high or low flow frequency calculations, it was possible to compare current design criteria with future scenarios under climate change. Therefore, the return period analysis is shown in Figure 3 for the maximum and minimum discharge. The discharge event of different recurrence intervals were computed using the generalized extreme value (GEV) distribution (F(x)). The *T* year return period for high flow is estimated by:

$$T = \frac{1}{1 - F(x)} \tag{4}$$

and the low flow by:

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

The parameters were estimated by the method of L-moments and they are given in Table 4.

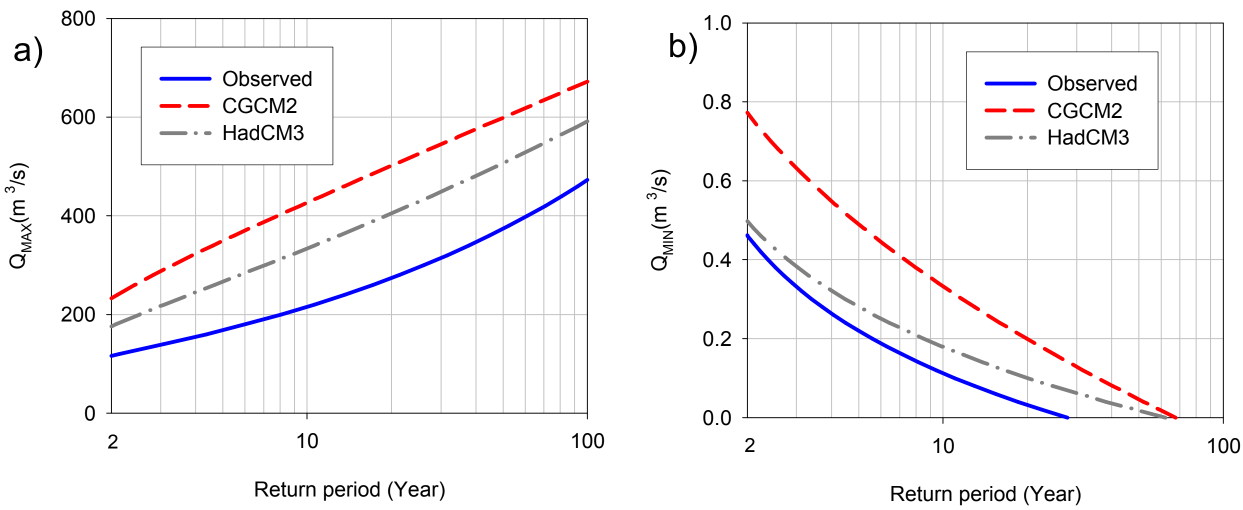

Figure 3. Return periods of observed and simulated a) maximum discharge b) minimum discharge

Table 4 Parameters of GEV used in return values

	Q_{MAX}			Q_{MIN}		
	Observed	CGCM2	HadCM3	Observed	CGCM2	HadCM3
k	0.34135	0.00632	0.12714	-0.0691	-0.46113	-0.16208
σ	33.092	102.12	70.705	0.28641	0.32474	0.25498
μ	103.51	195.27	149.49	0.35818	0.66265	0.40667

k, shape parameter σ, scale parameter μ, location parameter

For example, results showed that a 50-year high flow event could potentially become a more dominant high flow event in the future (and thus representing a flow with a much lower recurrence interval in the future). Figure 3a shown such results where a 50-year event could potentially be closer to a 20 or 10-year event in the future depending on the climate model used. The low flow analysis also shows less severe low flow, especially with the CGCM2 model under climate change (Fig. 3b). In contrast, the HadCM3 showed results that were closer to current climate low flows. The analysis show that the intensity and frequency of discharges will most likely increase in severity according both climate models (the CGCM2 showing the strongest flood increase); however, results of low flows that future climate may bring more water during periods of low flow particularly when using the CGCM2 model.

5. CONCLUSIONS

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, climate change will undoubtedly alter the quantity and quality of water resources. Success of such industries as agriculture, forestry, and fisheries are intrinsically linked to climate, making New Brunswick particularly vulnerable to the impacts of climate change. Undoubtedly, these industries (among others) will be significantly affected by a warmer, wetter climate (in some seasons and locations) with increased water during some time of year and diminished during other times. Adaptation will be essential to maintaining their viability.

A warmer climate in New Brunswick would result in significant changes in water availability at different times within the year. 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.

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 can increase infrastructure damage, cause soil erosion, crop damage and others. However, increased precipitation patterns may enhance water resources (groundwater and stream flow) especially in spring and summer time.

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