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Possible Impacts of Climate Change on Daily Streamflow and Extremes at Local Scale in Ontario, Canada. Part II: Future Projection

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ABSTRACT

The paper forms the second part of an introduction to possible impacts of climate change on daily streamflow and extremes in the Province of Ontario, Canada. Daily streamflow simulation models developed in the companion paper (Part I) were used to project changes in frequency of future daily streamflow events. To achieve this goal, future climate information (including rainfall) at a local scale is needed. A regression-based downscaling method was employed to downscale eight global climate model (GCM) simulations (scenarios A2 and B1) to selected weather stations for various meteorological variables (except rainfall). Future daily rainfall quantities were projected using daily rainfall simulation models with downscaled future climate information. Following these projections, future daily streamflow volumes can be projected by applying daily streamflow simulation models.The frequency of future daily high-streamflow events in the warm season (May-November) was projected to increase by about 45% - 55% late this century from the current condition, on average of eight-GCM A2 projections and four selected river basins. The corresponding increases for future daily low-streamflow events and future daily mean streamflow volume could be about 25% - 90% and 10% - 20%, respectively. In addition, the return values of annual one-day maximum streamflow volume for various return periods were projected to increase by 20% - 40%, 20% - 50%, and 30% - 80%, respectively for the periods 2001-50, 2026-75, and 2051-2100. Inter-GCM and interscenario uncertainties of future streamflow projections were quantitatively assessed. On average, the projected percentage increases in frequency of future daily high-streamflow events are about 1.4 - 2.2 times greater than inter-GCM and interscenario uncertainties.

Keywords: Rainfall-Related Streamflow; Future Projection; Downscaling; Statistic Methods; Ontario; Canada

1. Introduction

It is widely believed that in this century climate change might result in increased flooding in many regions over the globe, based on studies conducted in the past decades (see some of the references listed in **Table 1**). A number of studies have specifically focused on projecting changes in future annual/seasonal average streamflow volumes under a changing climate. In most of the studies, global climate model (GCM) projections are commonly used as the future climatic conditions. The GCM projecttions have been used in the studies in different ways: 1) GCM-implied changes applied to the observed daily climate; 2) statistically downscaled GCM simulations; and 3) dynamically downscaled GCM data—regional climate model (RCM) simulations. In addition, hypothesized scenarios, such as increases in annual mean temperature of 1˚C, 2˚C, 4˚C and/or changes in annual precipitation of ±5%, ±10%, ±20%, relative to the baseline climate, were used in the analysis on hydrological impacts of climate change.

GCM-implied changes were applied to the observed rainfall and potential evaporation to generate inputs for conceptual or semi-distributed rainfall-runoff hydrological simulation models (e.g., [1-5]). The change values that are derived from averaging multi-year monthly GCM outputs are applied to daily or even hourly observed data [6]. In addition to changes derived from GCM projections, the hypothesized scenarios were used as the input to hydrological models to project future water balance components (e.g., [7,8]). To project future climates required by hydrological models, daily and hourly observed hydrometeorological variables, such as temperature and rainfall, were modified by adding a sin-

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gle change value for a month or whole study period. It seems that this assumption might not be practical since it does not account for the anticipated changes to the variability of future climate [9,10].

As was done to project climate change impacts on streamflow at a local scale, another option is to apply down scaled simulations of GCMs to hydrological models. In addition to dynamic downscaling approach (*i.e.*, RCMs) to project future flood frequency (e.g., [6,11]), another leading technique is statistical (empirical) downscaling [12]. The statistical downscaling methods have been widely used in hydrometeorology to project changes in frequency of future high-streamflow or rainfall-driven flood events [13-18].

Table 1. Examples of previous studies on climate change and streamflow.

Scenarios	Reference	Hydrological Model	Key Results	Study Area
GCM-implied changes applied to the observed daily climate	Bultot *et al.* [1]	Conceptual hydrological model (IRMB),	Winter streamflow could increase in all of the study basins; direction of summer flow change depends on basin types under a 2 × CO_2 condition	Belgium
	Panagoulia & Dimou [2]	Conceptual hydrological model	Flood frequency, duration, and volume could increase for all increased precipitation HYPO and GISS scenarios	Central Greece
	Sefton & Boorman [32]	Unit hydrograph-based model	Mean annual flow could increase by up to 60% in most of the region under a 2 × CO_2 condition	England and Wales, UK
	Gellens & Roulin [33]	IRMB	Flood frequency could increase, especially in winter season under a 2 × CO_2 condition	Belgium
	Arnell [34]	Catchment hydrological model	Winter (DJF)/summer (JJA) streamflow could increase/decrease	Six rivers in UK
	Eckhardt & Ulbrich [35]	Conceptual hydrological model: Soil & Water Assessment Tool	Winter (DJF)/summer (JJA) streamflow could increase/decrease by 10%/50% by 2070-2099	Rhenish Massif, Germany
	Drogue *et al.* [3]	HRM (conceptual Hydrological Recursive Model)	Daily mean discharge could increase, the magnitude of which de pends upon the rainfall change scenarios by the 2050s	Grand Duchy of Luxembourg
	Cameron [4]	TOPMODEL (semi-distributed model)	Direction of the change by the 2080s varies among the GCMs	Northeastern Scotland, UK
	Forbes *et al.* [5]	ACRU agro-hydrological modeling system	Winter /spring streamflows could increase and summer/fall stream flows could decrease in the middle and late of this century	Southern Alberta, Canada
Statistically downscaled GCM scenarios	Najjar [13]	Statistical and water balance models	Annual streamflow could increase by 24% ± 13% under a 2 × CO_2 condition	Pennsylvania, US
	Whitfield *et al.* [14]	Hydrograph-based model	Frequency of rainfall-driven floods could increase in all watersheds under the projected climate scenarios; rainfall-related low flows could maintain the same frequency and magnitude	Georgia Basin, BC, Canada
	Dettinger *et al.* [15]	PPMS (physically based Precipitation-Runoff Modeling System)	Winter and summer streamflow could increase and decease in the 21st century	Three rivers in California, US
	Jasper *et al.* [16]	WaSiM-ETH (Water Flow and Balance Simulation Model)	Winter (DJF)/summer (JJA) runoffs could increase/decrease by 14% - 31%/16% - 33% at two basins by 2081-2100	Two Alpine river basins, Switzerland
	Dibike & Coulibaly [17]	Distributed hydrological models: Swedish & Canadian models	Early spring streamflow could dramatically increase; winter flow could increase and summer flow could decrease in the 21st century	Northern Quebec, Canada
	Merritt *et al.* [18]	Semi-distributed conceptual models	Annual, spring, and winter flow volumes could decrease by the 2050s and 2080s	Okanagan Basin, Canada
RCM scenarios	Kay *et al.* [6]	Simplified probability distributed model	Flood frequency could increase by the 2080s in most of catchments	Fifteen rivers across UK
	Sushama *et al.* [11]	RCM outputs directly	Annual and seasonal (except summer) streamflow in Canadian river basins (*i.e.*, Mackenzie, Yukon, Fraser) could increase in the future (2041-2070)	Six river basins, North America
Hypothesized scenarios	Arnell & Reynard [36]	Conceptual hydrological models	Annual flow could increase over 20% for the wettest scenarios and decline over 20% for the driest scenarios by 2050	21 catchments in UK
	Panagoulia & Dimou [7]	Monthly water balance model	Summer runoff could decrease by 50% for the driest scenario; winter runoff could increase by 60% for the wettest scenario	Central Greece
	Jiang *et al.* [8]	Six monthly water balance models	The six-model results are similar in reproducing historical water balance components but different in estimating future changes	Southern China

The statistical downscaling scheme used in this current study is built upon the previous studies (*i.e.*, Cheng *et al.* [19-21]) for deriving future hydrometeorological variables that were used in development of daily streamflow simulation models (constructed in Part I, [22]), which is made up of a four-step process. First, daily rainfall simulation models were developed and validated using synoptic weather typing with cumulative logit regression and nonlinear regression procedures [20]. The simulation models consider physical process of rainfall formation since the theories combining from both conceptual and statistical modeling were applied in the model development. To more effectively develop daily rainfall simulation models, the study [20] has used a number of the atmospheric stability indices in addition to the standard meteorological variables that were commonly used in most of the previous rainfall downscaling papers. Second, regression-based downscaling transfer functions developed by Cheng *et al.* [19] are adapted to derive station-scale future hourly meteorological variables (except rainfall) that were used in development of daily rainfall simulation models. Third, using downscaled future hourly climate data, future daily rainfall quantity can be projected by applying synoptic weather typing and daily rainfall simulation models [21]. Finally, it is able to project future daily streamflow volumes by applying daily streamflow simulation models [22] with down- scaled future daily rainfall and temperature data.

This paper is organized as follows: in Section 2, data sources and their treatments are described. Section 3 summarizes the previous studies (Cheng *et al.* [19-21]) on future daily rainfall projection on which the current paper was built. Section 4 describes analysis techniques as applied to projection of future daily streamflow volumes. Section 5 includes the results and discussion on 1) changes in frequencies of future daily high- and low-streamflow events, 2) changes in future return values of one-day maximum streamflow events, and 3) uncertainty of the study and limitations of the data. The conclusions and recommendations from the study are summarized in Section 6.

2. Data Sources

To project future daily streamflow volumes using streamflow simulation models developed in a companyion paper (Part I: Historical simulation, Cheng *et al.* [22]), the historical observations and future projections of the meteorological/hydrological elements are essential. Historical observations include daily surface meteorological/hydrological data (*i.e.*, rainfall, temperature, streamflow) within the four selected river basins, which were used in daily streamflow simulation modeling described in Part I [22]. The future projections include 1) future local-scale daily rainfall quantities projected by a recent study (Cheng *et al.* [21]), using daily rainfall simulation models developed by Cheng *et al.* (2010) and 2) station-scale daily temperature down-scaled by a statistical downscaling approach developed by Cheng *et al.* [19]. To better understand the study, the relevant information on projection of future daily rainfall and extremes as well as statistical down-scaling will be summarized in Section 3.

In addition to historical observations and projections of future daily rainfall quantities, daily climate change simulations from eight GCM models and two emission scenarios from the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) were used in the study, summarized in **Table 2**. The eight GCM models were selected since their simulations of all weather elements, including surface and upper-air temperature, dew point, air pressure, total cloud cover, *u*-wind and *v*-wind are available. These climate change simulations were retrieved from the Web site of the Program for Climate Model Diagnosis and Intercomparison [23]. The PCMDI is archiving the GCM simulations for two future time periods (2046-2065 and 2081-2100). Furthermore, the historical runs of these GCM simulations for the period (1961-2000) were used to remove the GCM model bias from the projection of future daily streamflow volumes. These three time windows were used in the analysis because these data are only available from the PCMDI's Web site. Furthermore, for projections of future return-period values of annual maximum high-streamflow events, three CGCM transient model simulations for a 100-year period (2001-2100) were included (**Table 2**), which were retrieved from Environment Canada's Web site [24].

3. Summary of Future Daily Rainfall Projection

As part of this research, Cheng *et al.* [21] have projected future daily rainfall quantities using daily rainfall simulation models (Cheng *et al.* [20]) with downscaled standard meteorological variables derived from statistical downscaling transfer functions (Cheng *et al.* [19]). Since the results and methods from these studies were used and adopted in this current paper to project changes in frequency of future daily streamflow events, it is necessary to outline these studies focusing on major methods and results.

As described in a recent study (Cheng *et al.* [21]), to project future daily rainfall amounts, the station-scale future climate data of the meteorological variables are necessary for the use of within-weather-type daily rainfall simulation models developed by Cheng *et al.* [20]. To derive future hourly station-scale climate information from GCM-scale simulations, Cheng *et al.* [19] have developed a regression-based statistical downscaling

Table 2. GCM simulations and scenarios used in the study.

GCM	IPCC scenario	Periods
CGCM3.1/T63 CNRM-CM3 CSIRO-Mk3.0 ECHAM5/MPI ECHO-G GFDL-CM2.0 GISS-ER MIRoc3.2 (medres)	IPCC AR4 SRES A2/B1	1961-2000 2046-2065 2081-2100
For return period analysis: CGCM1 CGCM2	IPCC Third Assessment Report (TAR) SRES A2/B2	2001-2100

Note: IPCC AR4—Intergovernmental Panel on Climate Change, Fourth Assessment Report; SRES—Special Report on Emissions Scenarios; CGCM3.1/T63—Canadian global climate model (the 3rd generation, T63 version); CNRM-CM3—French global climate model (the 3rd generation) developed atocenter National Weather Research; CSIRO-Mk3.0—Australian global climate model (the 3rd generation) developed by the Commonwealth Scientific and Industrial Research Organization; ECHAM5—Germany global climate model (the 5th generation) developed by the Max Plank Institute for Meteorology in Hamburg; ECHO-G—Germany and Korean global climate model consisting of the atmospheric model ECHAM4 and the ocean model HOPE (Hamburg ocean Primitive Equation); GFDL-CM2—US global climate model (the 2nd generation) developed by Geophysical Fluid Dynamics Laboratory; GISS-ER—US global climate model developed by Goddard Institute for Space Studies, NASA. MIRoc3.2 (medres)—Japanese global climate model (the 3rd generation, med-res. version), Model for Interdisciplinary Research on Climate.

method to spatially downscale daily GCM simulations to the selected weather stations in south-central Canada and then to temporally downscale daily scenarios to hourly timesteps. The downscaling transfer functions were constructed using different regression methods for different meteorological variables since a regression method is suitable only for a certain kind of data with a specific distribution. The downscaled meteorological variables include surface and upper-air temperature, dew point temperature, west-east and south-north winds, air pressure, and total cloud cover. These weather parameters are essential to project future daily rainfall quantities using rainfall simulation models constructed via combination of an automated synoptic weather typing and cumulative logit/nonlinear regression analyses. Performance of the downscaling transfer functions was evaluated by 1) analyzing model R^2s of downscaling transfer functions; 2) validating downscaling transfer functions using a leave-one-year-out cross-validation scheme; and 3) comparing data distributions, extreme characteristics, and seasonal/diurnal changes of downscaled GCM historical runs versus observations over a comparative time period of 1961-2000. The results showed that regression-based downscaling methods performed very well in deriving station-scale hourly and daily climate information for all weather variables. For example, the hourly downscaling transfer functions for surface air temperatures, dewpoint, and sea level air pressure possess the highest model R^2 (>0.95) of the weather elements. The functions for south-north wind speed (*y* wind) are the weakest model (model R^2s ranging from 0.69 to 0.92 with half of them greater than 0.89). Details of the hourly and daily downscaling methodologies and evaluations of the results are not presented in this current paper owing to the limitations of space (refer to Cheng *et al.* [19] for details).

Following downscaling of the meteorological variables, future daily rainfall amounts are able to be projected using within-weather-type daily rainfall simulation models developed by Cheng *et al.* [20,21]. As described in the study [20], 10 synoptic weather types in the study area were identified over the 45-yr period as primary rainfall-related weather types. Within-weather-type daily rainfall simulation models were developed in a two-step process: 1) cumulative logit regression to predict the occurrence of daily rainfall events; and 2) using probability of the logit regression, a nonlinear regression procedure to simulate daily rainfall quantities. To more effectively distinguish heavy rainfall events, the daily rainfall simulation models were constructed using not only the standard meteorological variables but also a number of the atmospheric stability indices (e.g., lifted index [25], K-index [26], total totals index [27]). The performance of within-weather-type daily rainfall simulation models was evaluated, and as described by Cheng *et al.* [20], the results showed that the models were successful at verifying occurrence of daily rainfall events and daily rainfall quantities. Cheng *et al.* [20] have found that, across the four selected river basins, the percentage of excellent and good daily rainfall-quantity simulations ranged from 62% to 84%, based on absolute difference between observed and simulated daily rainfall amounts. In addition, it is noteworthy that the rainfall simulation models are able to capture most of daily heavy rainfall events (*i.e.*, ≥32.5 mm) with the percentage of excellent and good simulations: 62%, 68%, 70%, and 81% for Grand, Thames, Humber, and Rideau River Basins, respectively.

Following development of daily rainfall simulation models, future daily rainfall and its extremes were projected by applying within-weather-type rainfall simulation models altogether with downscaled future GCM climate data. Cheng *et al.* [21] have used three GCMs and two emission scenarios (A2 and B2) from the IPCC Third Assessment Report (TAR) to project future daily rainfall and its extremes. Since climate simulations from eight GCMs and two IPCC AR4 emission scenarios A2 and B1 were used in this current study, it is necessary to update projections of future daily rainfall quantities using these downscaled updated GCM simulations. The number of future seasonal rain days and future seasonal rainfall totals projected by rainfall simulation models versus historical observations are graphically illustrated in **Figure 1**. The rainfall projections were evaluated by comparing differences in the number of seasonal rain days and seasonal rainfall totals derived from down-scaled historical runs and observations during a comparative time period 1961-2000. As shown in **Figure 1**, the values derived from both downscaled historical runs and observations are very similar. This implies that daily rainfall downscaling method used in the study is suitable for projecting changes in the number of future seasonal rain days and future seasonal rainfall totals, which is similar to the conclusion made by Cheng *et al.* [21].

From **Figure 1**, it can be seen that the modeled results found that the frequency of future daily rainfall events could increase late this century due to the changing climate projected by GCM scenarios. For example, on average across the selected GCMs, the frequency of future rainfall events with daily rainfall ≥15 mm is projected to increase by about 2 - 7 days in the future across the selected river basins (from the current four-river-basin average of 10.5 days for the period April-November 1961-2002). The corresponding increases for rainfall events with daily rainfall ≥25 mm are projected to be about 1 - 3 days from the current four-river-basin average of 3.2 days for the period April-November 1961-2002. Owing to limitations of the space, refer to Cheng *et al.* [20,21] for details on daily-rainfall simulation modeling and future daily-rainfall projections.

4. Analysis Techniques

Following the projection of future daily rainfall amounts and downscaling of future daily temperature, future daily rainfall-induced streamflow volumes can be projected using daily streamflow simulation models-developed in Part I (Cheng *et al.* [22]). Using future downscaled/projected daily rainfall quantities and temperature data, the predictors used in the development of daily streamflow simulation models were derived for the future time periods according to the same criteria as were the models developed using historical observations (constructed in Part I [22]). Following the projection of future daily streamflow volumes, the changes in frequency of high-/low-streamflow events and magnitude of daily mean streamflow volumes from the current condition (1961-2000) are able to be evaluated. High-streamflow events were defined as a day with streamflow volume greater than or equal to the 95th percentile derived from the observations; low-streamflow events were defined as a day with streamflow volume less than the 5th percentile.

Although the daily streamflow simulation models demonstrated significant skill in the prediction of historical daily streamflow volumes as well as occurrence of high-/low-streamflow events [22], it is necessary to ascertain whether the methods are suitable for the future projection. To achieve this, the data distribution of daily streamflow volumes was evaluated for both the down-

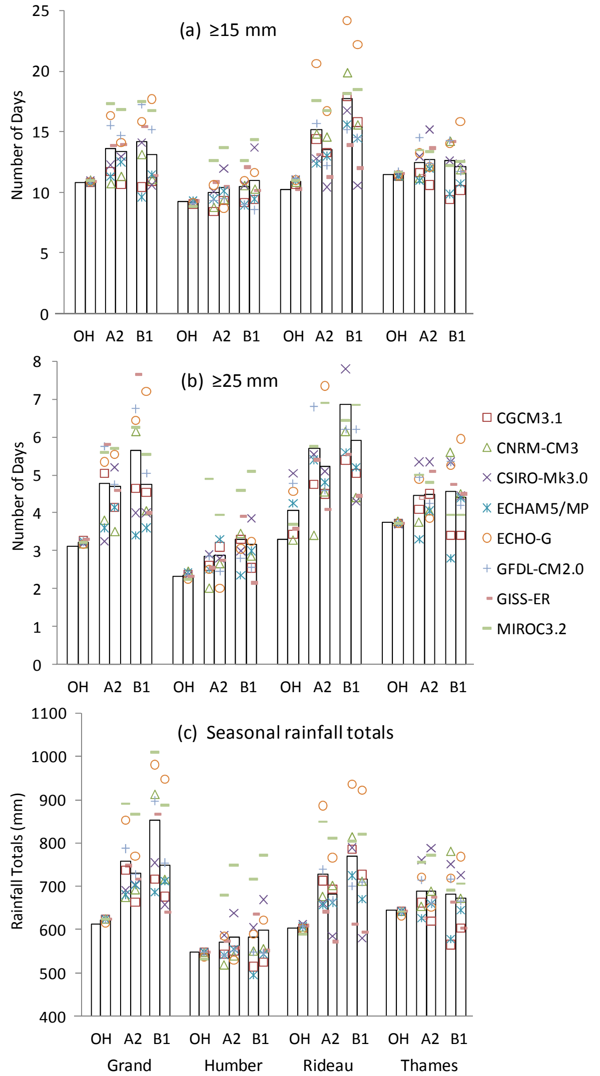

Figure 1. The number of future seasonal rain days [(a): ≥15 and (b): ≥25 mm) and (c): future seasonal rainfall totals versus the observed values during the period April-November 1961-2002 (O-observations and H-downscaled historical runs, following four bars represent eight-GCM-A2-averaged values and eight-GCM-B1-averaged values, for two time periods 2046-2065 and 2081-2100).

scaled GCM historical runs and observations over a comparative time period (1961-2000). **Figure 2** shows quantile-quantile (Q-Q) plots of the sorted daily streamflow volumes from both downscaled GCM historical runs and observations in the selected river basins. The Q-Q plot is a graphical technique for determining if two datasets come from populations with a common distribution, showing that the points should fall approximately along with the 45-degree reference line. Otherwise, the greater the departure from this reference line, the greater the evidence for the conclusion that the two datasets come from populations with different distributions. From **Figure 2**, it is clear that data distributions of both datasets are similar; so that it can conclude that the methods used in the study are suitable for projecting or downscaling future daily streamflow information on a local scale.

Any small differences between downscaled GCM historical runs and observations, as shown in **Figure 2**, were used to further adjust GCM model biases for projections of changes in frequency of future daily streamflow events. To quantitatively assess how much these differences affect projections of changes in frequency of future daily streamflow events, we have calculated mean relative absolute differences (*RAD*) between observations (O_i) and downscaled GCM historical runs (D_i) by the following expression:

$$RAD = \frac{1}{N}\sum_{i=1}^{n}\frac{\left|O_i - D_i\right|}{O_i} \tag{3}$$

where N is the number of total pairs of the data sample. The *RAD* was calculated for the days when daily streamflow volumes greater than each of various thresholds (e.g., 5, 10, 20, 30, 40, 100 $m^3 \cdot s^{-1}$), for each of downscaled GCM historical runs and each of four selected river basins. Then the mean *RAD* for each of the thresholds was determined by pooling eight downscaled GCM historical runs for each of four river basins. The results show that for thresholds with daily streamflow of 100, 10, 40, and 40 $m^3 \cdot s^{-1}$ or less in Grand, Humber, Rideau, and Upper Thames river basins, respectively, the differences between downscaled GCM historical runs and observations affect the future projections by about 1% - 2%. The corresponding effects for daily streamflow volumes greater than the thresholds are about 2% - 5% for Humber, Rideau, and Upper Thames river basins. However, for the Grand River Basin, the departure from the 45-degree reference line for a portion of the high streamflows is somewhat greater than for the other river basins. This is likely a result of having limited data; specifically, hourly meteorological observations within the river basin are not available. As a result, for the Grand River Basin, hourly meteorological variables observed at the London International Airport (located in the Thames River) were used in the analyses, including synoptic weather typing, downscaling of meteorological variables, and daily rainfall historical simulations and future projections (Cheng *et al.* [20,21]). In addition, another reason is that a very small data sample for the high-streamflow events, for instance, four observations above 150 $m^3 \cdot s^{-1}$, contributes a great departure from the 45-degree reference line.

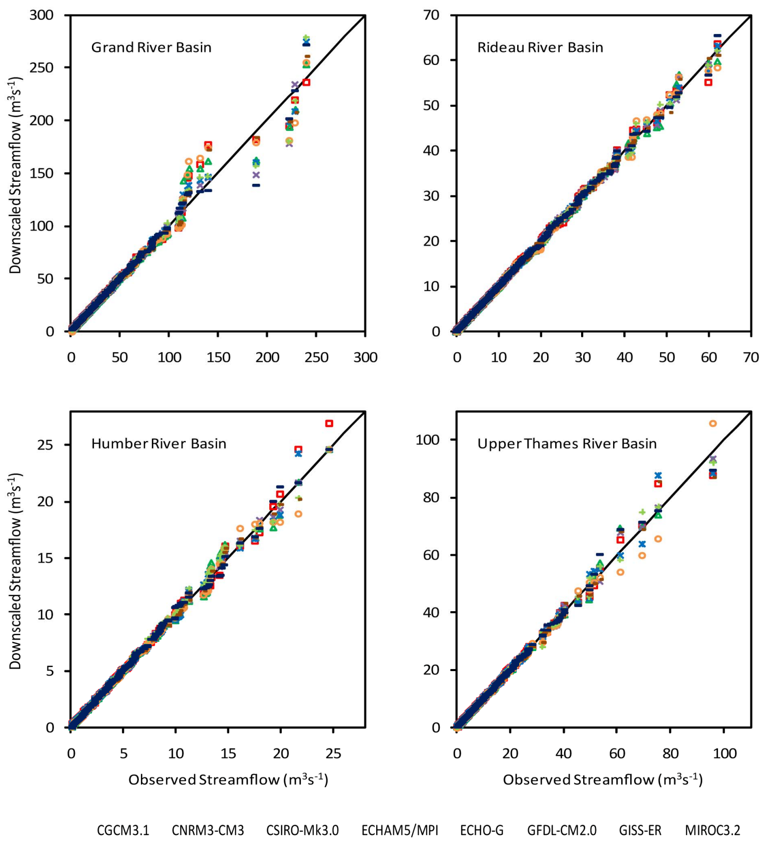

Figure 2. Quantile-quantile plots of daily streamflow volume derived from downscaled GCM historical runs versus observations over a comparative time period (May-November 1961-2000) in the selected river basins (A 45-degree reference line suggests that both datasets come from populations with the same distribution).

5. Results and Discussions

5.1. Changes in Frequency of Future Daily High- and Low-Streamflow Events

Following the projection of future daily rainfall quantities, the daily streamflow volumes are able to be projected by applying streamflow simulation models developed in Part I (Cheng *et al.* [22]). Since the antecedent precipitation index (API) calculated using rainfall data from the previous 24 days was used as a predictor in daily streamflow simulation modeling (refer to [22]), the time period for the projection of future daily streamflow volumes is from May, rather than April, to November. The number of projected future daily high-/low-streamflow events and future daily mean streamflow volumes versus observations are graphically illustrated in **Figure 3**. The daily high- and low-streamflow events were defined as those days with a streamflow volume greater than or equal to the 95th percentile and less than the 5th percentile, respectively derived from the observations. The frequencies of future high- and low-streamflow events were determined based upon historical observed values of the 95th and 5th percentiles listed in **Table 3**. As shown in **Figure 3**, the modeled results from this study found that the frequency of future daily high-/low-streamflow events and daily mean streamflow volumes could increase late this century due to the changing climate projected by GCM scenarios. In addition, the streamflow projections were evaluated by comparing differences in the number of seasonal high-/low-streamflow events and daily mean streamflow volumes derived from downscaled historical runs and observations during time period 1961-2000. It is noteworthy that as shown in **Figure 3**, the values from both datasets are very similar, which implies that the streamflow downscaling methods used in the study are suitable to project changes in the number of future daily high-/low-streamflow events and daily streamflow volumes.

To more clearly present changes in the frequency of future daily high-/low-streamflow events and daily mean streamflow volumes, four-river-basin-average relative increases from the current conditions of May-November 1961-2002 are shown in **Table 4**. The percentage increase in frequency of the daily high-/low-streamflow events by 2081-2100 is projected to be greater than that by the time period 2046-2065. Across the four selected river basins, for example, on average of eight-GCM A2projections, the frequency of future high-streamflow events is projected to increase by 46% and 55%, respectively by the periods 2046-2065 and 2081-2100 (from the current 11 days for the period May-November). The corresponding increases for future low-streamflow events are projected to be 26% and 89%. Daily mean streamflow volume is projected to increase by about 13% - 22%

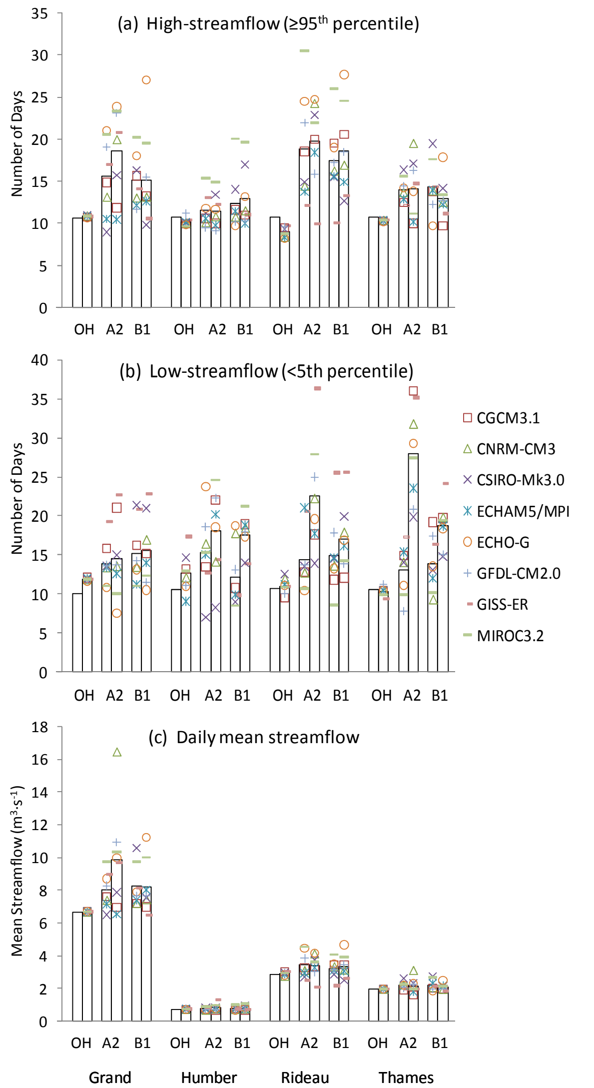

Figure 3. The number of future (a) daily high-streamflow events (≥95th percentile of the historical observation) and (b) low-streamflow events (<5th percentile of the historical observation) as well as (c) future mean daily streamflow volumes versus the historical observed values (O-observations and H-downscaled historical runs, following four bars represent eight-GCM-A2-averaged values and eight-GCM-B1-averaged values, for two time periods 2046-2065 and 2081-2100).

Table 3. Historical observed streamflow volumes ($m^3 \cdot s^{-1}$) of the 95th and 5th percentiles (May-November 1958-2002 for Grand and Upper Thames Rivers, May-November 1967-2002 for Humber River, and May-November 1970-2002 for Rideau River).

	Grand	Humber	Rideau	Upper Thames
95th percentile	18.90	2.91	11.60	6.73
5th percentile	1.93	0.16	0.05	0.25
Daily mean streamflow	6.61	0.73	2.94	1.93

late this century. In addition, the projected four-river-basin-averaged percentage increases derived from eight-GCM ensemble A2 scenario are greater than those from B1 scenario for the period 2081-2100; while the increases are very similar between two scenarios for the period 2046-2065. These projected increases are associated with GCM simulations: temperature increases between scenarios A2 and B1 are very similar for the period 2046-2065; however, for the period 2081-2100, the increases simulated from scenario A2 are greater than those from B1.

As shown in **Figure 3**, the projections of future daily high-/low-streamflow events and daily mean streamflow volumes vary across the selected GCMs. To evaluate performance of GCMs' projections, the individual GCM's projections were compared with eight-GCM-average changes to determine which GCMs' projections with the closest to or the most faraway from averaged future projection. A case with the closest to averaged future projection was defined as a relative change in future projection is within 10% around the average, while a case with the most faraway from averaged future projection was defined as a relative change is more than 50% higher or lower than the average. From **Table 5**, it can be seen that the top three best-performed GCMs having the highest numbers of the cases with the closest to and the lowest numbers of the cases with the most faraway from eight-GCM-average relative changes are GFDL-CM2—US global climate model (the 2nd generation), CNRM-CM3—French global climate model (the 3rd generation), and ECHAM5—Germany global climate model (the 5th generation). While the worst performed GCMs are MI-Roc3.2 (medres)—Japanese global climate model (the 3rd generation, med-res. version) and GISS-ER—US global climate model.

The projected increases in the frequency of future high-streamflow events might be due to the potential increase in the frequency of future heavy rainfall events projected by downscaled future GCM scenarios [21]. Possible reasons for an increase in the frequency of future low-streamflow events might be an increase in the frequency and severity of future drought condition and the magnitude of future evapotranspiration in summertime. Although future seasonal rainfall totals in the study

Table 4. Four-river-basin-averaged percentage increases in the frequency of future seasonal high-streamflow/low-streamflow days and future daily mean streamflow volumes from the current conditions of May-November 1961-2002, presented by eight-GCM A2 and B1 ensemble.

Streamflow events	Current conditions	Eight-GCM A2		Eight-GCM B1	
		2046-2065	2081-2100	2046-2065	2081-2100
High-streamfow (≥95th percentile)	10.7 days	46	55	44	45
Low-streamflow (<5th percentile)	10.4 days	26	89	25	55
Daily mean streamflow	0.74 - 6.68 $m^3 \cdot s^{-1}$	13	22	13	13

Table 5. Evaluation on GCM's projections of future daily streamflow derived from Figure 3: the number of cases with the closest to the eight-GCM ensemble future projection (defined as a relative change is within 10% around the average); the number of cases with the most faraway from the eight-GCM ensemble future projection (defined as a relative change is at least 50% higher or lower than the average).

	Closest to averaged future projections					Most faraway from averaged future projections				
GCM	Grand	Humber	Rideau	Thames	Total	Grand	Humber	Rideau	Thames	Total
CGCM3	5	6	6	3	20	3	1	0	3	7
CNRM3	3	7	6	8	24	1	1	0	2	4
CSIRO3	4	6	2	4	16	5	3	2	4	14
ECHAM5	2	7	5	7	21	2	0	1	0	3
ECHO	3	8	2	6	19	4	2	4	2	12
GFDL-CM2	6	7	5	5	23	0	0	0	2	2
GISS-ER	3	5	0	5	13	4	1	10	1	16
MIRoc3	1	1	1	6	9	0	8	6	2	16
Total	27	47	27	44	145	19	16	23	16	74

area are projected to increase under a changing climate, the number of days without rainfall or with a little rainfall is also projected to be greater than is currently the case. For example, the number of future annual average no-rain days in Upper Thames River Basin is projected to increase by about 5% from the average condition of 137 days during the period 1961-2002. Furthermore, the future warmer temperatures projected by the GCM models could also enhance the low-streamflow situation due to increased evapotranspiration capacities.

5.2. Changes in Future Return Values of One-day Maximum Streamflow Events

The statistical return period analysis was employed to project the return values of one-day maximum streamflow events for a number of return periods. A return period also known as a recurrence interval is an estimate of the likelihood of events like one-day maximum streamflow volume of a certain intensity. It is a statistial measurement denoting the average recurrence interval over an extended period of time. Return values are thresholds that will be exceeded on average once every return period. The design of stormwater infrastructure is constrained by the largest precipitation/streamflow event anticipated during a fixed design period (e.g., 20, 50 or 100 years). Due to climate change, the return values of one-day maximum streamflow events could increase in the future.

To project future return values of one-day maximum streamflow events, an annual series of historical one-day maximum streamflow events were fitted to the Gumbel (Extreme Value Type I) distribution for each of the selected river basins. The streamflow data observed for the entire period used in the study were applied to determine the return values for the historical period. The projected future daily streamflow data, using three downscaled CGCM simulations for three 50-year periods (2001-2050, 2026-2075, and 2051-2100), were used to project future return values. The results showed that the projected return values of the one-day maximum streamflow events for all evaluated return periods (e.g., 20, 25, 30, 50, 100 years) could increase late this century (**Figure 4**). For example, in the Grand River Basin, the 20-year return period values of one-day maximum streamflow events are 173 $m^3 \cdot s^{-1}$ for the past 45 years and potentially 240, 256, and 311 $m^3 \cdot s^{-1}$ for the periods 2001-2050, 2026-2075, and 2051-2100, respectively.

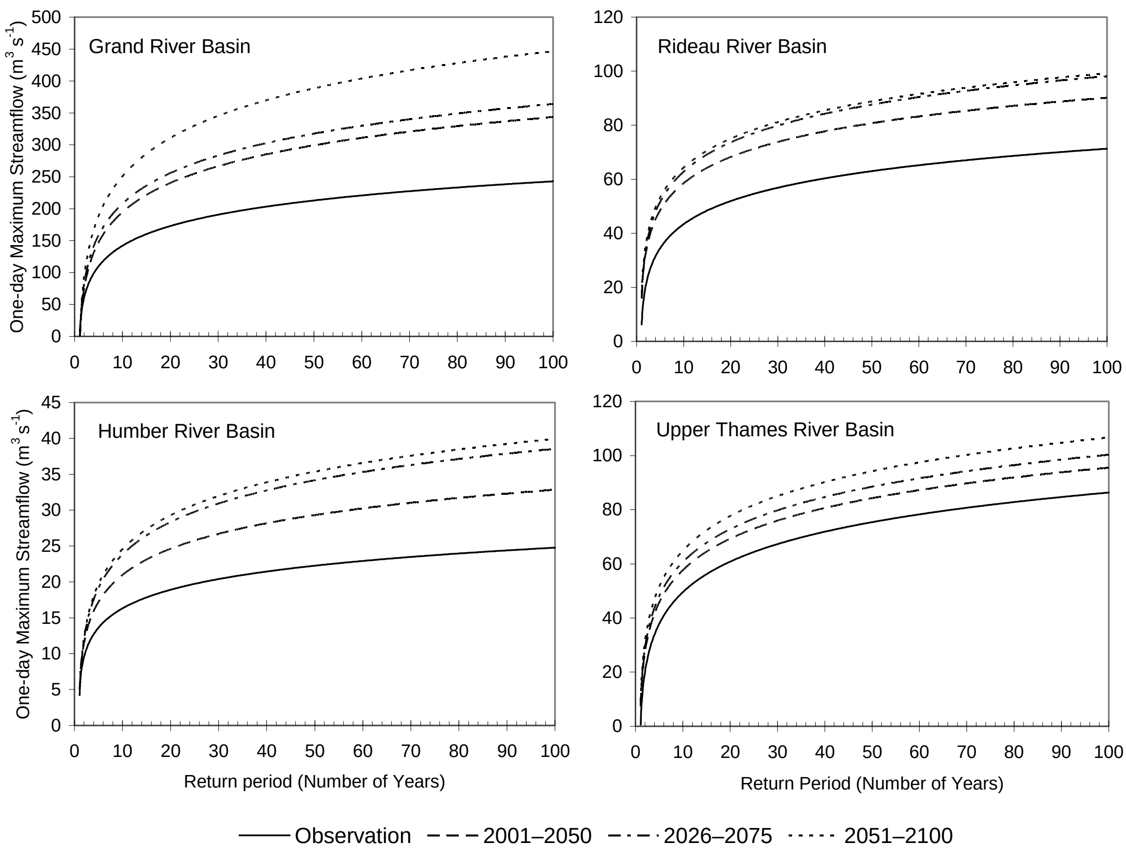

Figure 4. Return values of annual one-day maximum streamflow volumes as shown by observation (Grand and Upper Thames: 1961-2002; Humber: 1967-2002; Rideau: 1970-2002) and downscaled three-CGCM ensemble (2001-2050, 2026-2075, and 2051-2100).

In addition to the increase in return values shown in **Figure 4**, the relative increases in future return values of one-day maximum streamflow volume from the current condition were analyzed. The relative increases are more similar across the return periods and the river basins than the absolute increases of the return values, as shown in **Table 6**. Across the selected river basins, on average of the three downscaled CGCM simulations, the return values of the one-day maximum streamflow volume for various return periods (*i.e.*, 2, 5, 10, 15, 20, 25, 30, 50, 100 years) are projected to increase by approximately 15% - 40%, 25% - 50%, and 30% - 80% in the future three 50-year periods 2001-2050, 2026-2075, and 2051-2100, respectively. More specifically, for example, in the Grand River Basin, the 20-year return-period values of one-day maximum streamflow volume for future three 50-year periods are projected to increase by 39%, 48%, and 80%, respectively from the observed value of 173 $m^3 \cdot s^{-1}$ for the past 45 years. Among the three downscaled CGCM simulations, the projected percentage increases in the return values are similar, usually with slightly greater values derived from downscaled CGCM-A2 than those from downscaled CGCM-B2. For example, across four selected river basins, the difference in the percentage increases between downscaled CGCM2-A2 and CGCM2- B2 is usually less than 10% for future three 50-year periods, with a few exemptions. In addition, from **Table 6**, it can be seen that the 95% confidence interval for future projected return-period values is similar to the observed ones, which implies that the future projected return-period values are plausibly reliable.

Table 6. Percentage increases in future annual one-day maximum streamflow volumes for various return periods (downscaled three-CGCM ensemble) from current observed values (95% confidence interval in parentheses).

Return Period (Year)	Thames River Basin				Grand River Basin			
	Obs.	2001-2050	2026-2075	2051-2100	Obs.	2001-2050	2026-2075	2051-2100
	(m^3/s)	(%)	(%)	(%)	(m^3/s)	(%)	(%)	(%)
2	20 (±7.5)	36 (±6.5)	44 (±5.6)	56 (±5.2)	61 (±5.9)	23 (±9.8)	35 (±11)	53 (±11)
5	38 (±5.0)	21 (±4.3)	27 (±3.7)	36 (±3.4)	110 (±4.1)	34 (±6.7)	44 (±7.6)	72 (±7.5)
10	50 (±5.2)	16 (±4.4)	22 (±3.8)	31 (±3.5)	142 (±4.3)	37 (±7.0)	46 (±7.9)	77 (±7.8)
15	56 (±5.4)	15 (±4.5)	21 (±3.9)	29 (±3.6)	160 (±4.4)	38 (±7.3)	47 (±8.2)	79 (±8.1)
20	61 (±5.4)	14 (±4.6)	20 (±4.0)	28 (±3.7)	173 (±4.5)	39 (±7.5)	48 (±8.4)	80 (±8.3)
25	64 (±5.6)	13 (±4.7)	19 (±4.0)	27 (±3.8)	183 (±4.6)	39 (±7.6)	48 (±8.5)	81 (±8.5)
30	67 (±5.7)	13 (±4.8)	19 (±4.1)	26 (±3.8)	191 (±4.7)	40 (±7.7)	49 (±8.7)	81 (±8.6)
50	75 (±5.9)	12 (±4.9)	17 (±4.2)	25 (±4.0)	213 (±4.7)	41 (±8.0)	49 (±9.0)	83 (±8.9)
100	86 (±6.0)	11 (±5.1)	16 (±4.4)	24 (±4.1)	243 (±4.9)	41 (±8.3)	50 (±9.3)	84 (±9.3)
Mean		17 (±4.9)	23 (±4.2)	31 (±3.9)		37 (±7.8)	46 (±8.7)	76 (±8.7)

Return Period (Year)	Humber River Basin				Rideau River Basin			
	Obs.	2001-2050	2026-2075	2051-2100	Obs.	2001-2050	2026-2075	2051-2100
	(m^3/s)	(%)	(%)	(%)	(m^3/s)	(%)	(%)	(%)
2	10 (±3.0)	20 (±6.5)	26 (±8.3)	28 (±7.8)	21 (±4.3)	58 (±5.1)	64 (±6.7)	73 (±6.1)
5	14 (±2.1)	26 (±5.6)	40 (±7.2)	44 (±6.7)	34 (±3.2)	41 (±3.8)	50 (±5.0)	54 (±4.6)
10	16 (±3.1)	29 (±6.3)	46 (±8.1)	51 (±7.6)	43 (±3.7)	35 (±4.1)	45 (±5.4)	48 (±5.0)
15	18 (±2.8)	30 (±6.7)	48 (±8.7)	53 (±8.1)	48 (±3.8)	33 (±4.3)	43 (±5.6)	46 (±5.2)
20	19 (±3.2)	30 (±7.0)	50 (±9.1)	55 (±8.5)	52 (±3.8)	31 (±4.4)	42 (±5.8)	44 (±5.4)
25	20 (±3.0)	31 (±7.2)	51 (±9.3)	56 (±8.7)	55 (±4.0)	30 (±4.5)	41 (±5.9)	43 (±5.5)
30	20 (±3.5)	31 (±7.4)	52 (±9.6)	57 (±8.9)	57 (±4.0)	30 (±4.6)	40 (±6.0)	43 (±5.6)
50	22 (±3.6)	32 (±7.8)	53 (±10)	59 (±9.5)	63 (±4.3)	28 (±4.8)	39 (±6.3)	41 (±5.8)
100	25 (±3.6)	33 (±8.4)	56 (±11)	61 (±10)	71 (±4.5)	26 (±5.0)	38 (±6.6)	39 (±6.1)
Mean		29 (±7.0)	47 (±9.0)	52 (±8.4)		35 (±4.5)	45 (±5.9)	48 (±5.5)

Note: To effectively compare the 95% confidence intervals between observed and future projected return values, as the same as the future projections, the 95% confidence intervals derived from observations are presented as percentages below or above the return values.

5.3. Uncertainty and Limitations

The uncertainty of climate change impacts on future heavy rainfall events described in a recent study (Cheng *et al.* [21]) also applies to this paper since the projection of future daily rainfall quantities was used in the current study to project future daily streamflow volumes. As described in the study [21], considerable effort was made to transfer GCM-scale simulations to station-scale climate information using statistical downscaling transfer functions. Through the downscaling process, most of the GCM model bias was removed, using the 50-year historical relationships between regional-scale predictors and station-scale weather elements [28]. As a result, the quality of the GCM climate change projections was much improved after using the statistical downscaling (Cheng *et al.* [19]). However, conclusions made in the current study about the impacts of climate change on future high-/low-streamflow events still rely on GCM scenarios/projections and, consequently, there is corresponding uncertainty about the study findings.

To quantitatively assess inter-GCM and interscenario uncertainties of future daily streamflow projections, we have analyzed the four-river-basin-average absolute difference between pairs of eight selected GCM models under the SRES B1 scenario as well as absolute difference between two selected scenarios (A2 versus B1). The absolute difference used in analysis is to avoid negative values cancelling out positive values. As shown in **Table 7**, overall, the inter-GCM uncertainties of percentage increases in the frequency of future daily high-streamflow events are greater than the interscenario uncertainties. For daily mean streamflow projections, both uncertainties are similar. From **Tables 5** and **7**, it can be seen that the uncertainties of future daily high-streamflow events are smaller than the future projections. The overall mean projected percent- age increases in frequency of future daily high-stream- flow events are about 1.4 - 2.2 times greater than overall mean inter-GCM and interscenario uncertainties. For projections of future daily low-streamflow events and daily mean streamflow volumes, the inter-GCM and interscenario uncertainties are generally similar to or greater than the projected future percentage increases.

Although the models developed from this study can simulate most high-streamflow events for the selected river basins, it was found that the models have difficulty in capturing some of the cases, especially for urban river basins, such as the Black Creek tributary of the Humber River (refer to Part I, Cheng *et al.* [22]). This model limitation is also reflected by the simulation difficulty of the localized convective heavy rainfall events. As described by Cheng *et al.* [20], the rainfall simulation models can simulate most heavy rainfall events, but it was found that the models have difficulty in capturing some of localized convective heavy rainfall events. It is likely that projection of changes in frequency of future rainfall-related high-streamflow events offered by this study will represent the lower bound values for the study area. As a result, southern Ontario could in the future possibly receive more rainfall-related high-streamflow events than is currently projected by the study.

In addition to uncertainty of GCM projections and limitation of daily streamflow simulation models, the observed streamflow data used in the study have their limitation. Daily mean streamflow volumes which are averaged over a 24-hour period (*i.e.*, 00:00-23:00 LST, local standard time) are currently used in the analysis. Daily streamflow data are limited in their usefulness for studying more detailed information on the simulation of the high-streamflow events, especially for rapidly rainfall-streamflow responding urban watersheds (e.g., the Black Creek tributary of the Humber River). If the short-duration (less than one day) streamflow data were available, the streamflow simulation model for Humber River Basin could possibly be improved by using streamflow information at a shorter time step.

Furthermore, the limitation of meteorological data, described in the study [21] for developing rainfall simulation models, also affect daily streamflow historical simulation and future projection. The major limitation of

Table 7. Four-river-basin-average inter-GCM and interscenario uncertainties of projected percentage increases in the frequency of future seasonal high-streamflow/low-streamflow days and future daily mean streamflow volumes from the current conditions of May-November 1961-2002.

Streamflow events	Current conditions	Uncertainty (absolute difference)			
		Mean 8-GCM B1[a]		Mean 8-GCM A2 - B1[b]	
		2046-2065	2081-2100	2046-2065	2081-2100
High-streamfow (≥95th percentile)	10.7 days	32	40	20	31
Low-streamflow (<5th percentile)	10.4 days	40	40	28	53
Daily mean streamflow	0.74 - 6.68 m^3s^{-1}	19	21	11	21

[a]Mean 8-GCM B1 is average of absolute differences between pairs of eight GCM B1 models; [b]Mean 8-GCM A2 - B1 is average of absolute differences between scenarios A2 and B1 of eight GCM models.

meteorological data includes that hourly meteorological observations are not available in the Grand River Basin, which are essential to develop synoptic weather typing and rainfall simulation models. Consequently, hourly meteorological data gathered at the London International Airport (located in Thames watershed) were used to classify synoptic weather types and to derive rainfall predictors (e.g., atmospheric stability indices) for the Grand River. Therefore, the rainfall simulation results, derived for the Grand River Basin, were not as accurate as they might be were hourly meteorological data for the Grand River Basin available. In turn, these results could affect projection of frequency of future heavy rainfall events and ultimately influence on projections of frequency of future high-streamflow events derived from this study.

6. Conclusions and Recommendation

The overall purpose of this study is to project possible changes in the frequency of high-/low-streamflow events late this century for four selected river basins (*i.e.*, Grand, Humber, Rideau, and Upper Thames) in Ontario, Canada. To achieve this goal, the streamflow simulation models developed in Part I (Cheng *et al.* [22]) were applied collectively with downscaled future GCM simulations. As described in the studies (Cheng *et al.* [19,22]), a formal verification process of model results has been built into the whole exercise, comprising daily streamflow simulation modeling and the development of downscaling transfer functions. The study results demonstrate that the streamflow simulation models are able to reproduce daily streamflow volumes in the observed period for the selected river basins, through model calibration and verification. Furthermore, in this current study, the streamflow simulation models were evaluated using downscaled GCM historical runs to ascertain whether the models are suitable for projecting future daily streamflow volumes. The results of the verification in terms of data distribution and frequency of the high-/low-streamflow events, based on historical observations of the outcome variables simulated by the models, showed good agreement. As a result, a general conclusion from this study is that a combination of the streamflow modeling and statistical downscaling can be useful to project changes in frequency of future daily high-/low-streamflow events.

The modeled results from this study found that due to a changing climate, the frequency of future high- and low-streamflow events for the period 2046-2065 is projected by averaging eight-GCM A2 projections to increase by about 45% and 25%, respectively from the current condition, which are similar to the increases by averaging eight-GCM B1 projections. The corresponding increases for the period 2081-2100 are much different between two scenarios: high-streamflow events will increase by 45% and 55% derived from eight-GCM scenarios B1 and A2, respectively; for low-streamflow events, the corresponding increases are 55% and 89%. These findings are consistent with the results reported in the IPCC Fourth Assessment Report [29], in terms of the increase tendency in high- and low-streamflow events. The implication of these increases should be taken into consideration when revising engineering infrastructure design standards (including infrastructure maintenance and new construction) and developing adaptation strategies and policies. As the IPCC [29] pointed out, "More extensive adaptation than is currently occurring is required to reduce vulnerability to future climate change." This study aims to provide decision makers with scientific information needed to improve the adaptive capacity of the infrastructure at risk of being impacted by heavy rainfall-related flooding in Ontario due to climate change. The results of the study are intended to contribute to the *Ontario Emergency Management and Civil Protection Act* under *Bill* 148, which attempts to reduce risks of disasters by requiring that all municipalities, regional governments, and provincial ministries develop emergency and disaster risk management plans [30,31].

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