Reservoir management under predictable climate variability and change
Ahmad Asnaashari, Bahram Gharabaghi, Ed McBean and Ali Akbar Mahboubi

ABSTRACT
The potential effects of climate change on future water budget components and streamflow in the Mississippi River (Ontario) are assessed. Analyses of historic hydrometric data indicate an increasing trend in winter streamflows due to the rising winter air temperatures across the region over the latter half of the 20th century. These temperatures have resulted in reduced snow accumulation and earlier spring snowmelt. Projected future climate data are developed using the second generation Coupled Global Climate Model and downscaled using the change factor method for the Mississippi River watershed (Ontario). The projected future climate data are then used as input to a calibrated hydrologic model for simulation of future water balance and streamflows in this river basin. These simulations predict a gradual annual rate of change of: 0.1% increase in total precipitation; 0.2% increase in rainfall; 0.7% decrease in snowfall; 0.2% increase in potential evapotranspiration; 0.1% decrease in soil moisture; 1.4% increase in water deficit; 0.5% increase in streamflow during winter months; and 0.3% decrease in summer streamflows. Cyclic pattern analysis of the historic streamflow records suggests the existence of pronounced 3-year and 12-year cycles, providing short-term streamflow forecasting opportunities for optimum reservoir management operations during the wet-year/dry-year cycles.

Key words | climate change, hydrological modeling, Mississippi River, reservoir management, water balance

ACRONYMS AND ABBREVIATIONS

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>AHCCD</td>
<td>Adjusted Historic Canadian Climate Database</td>
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<tr>
<td>CF</td>
<td>change factor</td>
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<tr>
<td>CGCM2</td>
<td>Meteorological Research Institute Coupled Atmosphere–Ocean General Circulation Model, version 2</td>
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<td>CNRM-CM5</td>
<td>Centre National de Recherches Météorologiques Coupled Global Climate Model, version 5</td>
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<tr>
<td>DEM</td>
<td>digital elevation model</td>
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<td>DHI</td>
<td>Danish Hydraulic Institute</td>
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<tr>
<td>ENSO</td>
<td>El-Nino Southern Oscillation</td>
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<td>IPCC</td>
<td>Intergovernmental Panel on Climate Change</td>
<td></td>
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<tr>
<td>IPSL-CM5B-LR</td>
<td>Institute Pierre Simon Laplace, Paris, France, version 5B (low resolution)</td>
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<td>MAF</td>
<td>mean annual flow</td>
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<tr>
<td>MIROC5</td>
<td>Model for Interdisciplinary Research on Climate, version 5</td>
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<td>MNR</td>
<td>Ministry of Natural Resources</td>
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<tr>
<td>MPI-ESM-MR</td>
<td>Max Planck Institute Earth System Model, medium resolution</td>
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historically observed (Cunderlik & Simonovic 2007) cycle will produce extremes unlike those that have been observed daily streamflow for the period of 1900–1998. Trend evaluations were performed for minimum and maximum daily temperatures and total precipitation, indicating annual total precipitation increased by 5–35% across Canada during the second half of the 20th century.

In terms of streamflow, earlier spring runoff in Canada has been reported by both Whitfield & Cannon (2000) and Zhang et al. (2000). Summer (May–August) flows of the Athabasca River have declined 20% since 1958 (Schindler & Donahue 2006). This is broadly consistent with the work done by Merritt et al. (2006) and Harma et al. (2012) in the Okanagan Basin in British Columbia. In both studies, a projected reduction in flow volumes in July and August was found. Null et al. (2010) also found the mean annual flow will be reduced with climate warming in California’s Sierra Nevada. In Europe, Martínez-Fernández et al. (2013) in Spain and Dorchies et al. (2014) in France have observed decreases in the discharge in the summer time for all the rivers studied for climate change.

Lehman & Kunjikutty (2008) evaluated changes in the timing of streamflow in the Mississippi River watershed (Ontario) using long-term streamflow records from the Water Survey of Canada’s HYDAT data archives (www.ec.gc.ca/rhc-wsc/). Of the two WSC stream gauges used in the watershed, the Appleton (WSC 02KF006) gauge showed a more continuous record, including the 87 year period from 1919 to 2005. Lehman & Kunjikutty plotted the average observed daily streamflow for the periods 1919–1979 and 1980–2005, with findings showing significant variations in

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**NOTATIONS**

- $C_{\text{snow}}$: degree-day coefficient
- $CK_{\text{BF}}$: time constant for base flow
- $CK_{1,2}$: time constants for routing overland flow
- $CK_{\text{IF}}$: time constant for interflow
- $CQ_{\text{OF}}$: overland flow runoff coefficient
- $L_{\text{max}}$: maximum water content in root zone storage
- $T_0$: base temperature snow/rain
- $T_{\text{IF}}$: root zone threshold value for interflow
- $T_G$: ground water parameters
- $T_{\text{OF}}$: root zone threshold value for overland flow
- $U_{\text{max}}$: maximum water content in surface storage

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**INTRODUCTION**

The Intergovernmental Panel on Climate Change (IPCC 2014) report states that the effects of climate change are already occurring on all continents and across the oceans. Further, it is broadly agreed in the international scientific community that global climate change will increase air temperatures and, as a result, the enhanced hydrologic cycle will produce extremes unlike those that have been historically observed (Cunderlik & Simonovic 2007).

Several studies have been conducted to investigate climate change in Canada. Vincent & Mekis (2006) found that climate warming from 1900 to 2003 has led to a decrease in total precipitation occurring as snowfall in the western provinces and prairies. Houghton et al. (1996) reported that warmer temperatures will most likely intensify the hydrologic cycle, leading to increases in the precipitation intensity and frequency, which will have adverse impacts on flooding, water quality and soil erosion. In another study, Mekis & Vincent (2005) examined precipitation-related climate change indicators during the 20th century using the Adjusted Historic Canadian Climate Database (AHCCD) developed at the Climate Research Branch in Toronto. Their analysis indicates that the amount of annual total snowfall and the number of frost days have decreased during the last half century. Golmohammadi et al. (2013) also observed warmer winters and hotter summers in the Grand River basin in Southern Ontario.

Zhang et al. (2000) evaluated data from 210 weather stations across Canada to identify trends in temperature. Daily precipitation data were analyzed from 489 stations, for the period of 1900–1998. Trend evaluations were performed for minimum and maximum daily temperatures and total precipitation, indicating annual total precipitation increased by 5–35% across Canada during the second half of the 20th century.

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magnitude and timing of streamflows. As their results indicate, the timing of peak flows was as much as 10 days earlier during the latter period. This shift in the time-to-peak flow is similar to the findings from the Fraser River (Morrison et al. 2002). In addition to the observed time shift, the 1974–2002 winter months had higher average flows than winter flows for the 1919–1973 period. Increased winter and spring flows were also reported for the Basswood, English, and Winnipeg Rivers, indicating seasonal changes which occurred in many rivers in western Canada (Stewart et al. 2005; St George et al. 2007).

There is also a wide discussion on the El Niño Southern Oscillation (ENSO) and La Niña effects and how they could impact precipitation and runoff in the region. For instance, Piechota & Dracup (1996) used the Southern Oscillation Index to identify patterns in atmospheric circulation and streamflow variability in the United States. Garen (1998) evaluated the use of the Southern Oscillation Index as a primary variable in streamflow forecasting using statistical methods. Tootle & Piechota (2004) found a strong ENSO signal exists at the winter and spring streamflow of the Suwannee River. Several studies in Canada also investigated the impact of large-scale atmospheric processes such as ENSO on streamflow trends and variability (Woo & Thorne 2003; Burn et al. 2004). In southern Quebec basins, Saint-Laurent et al. (2009) also showed the same discharge variability in the Saint-François and Eaton Rivers. For example, they found that the years 1974, 1976, 1983, and 1990 have the highest discharge at stations 02OE007, 02OE027 and 02OF002.

The literature provides a variety of watershed-scale modeling studies reporting on climate change impacts on the hydrology of watersheds in North America (e.g. DeJong et al. 2010; Vasiljevic et al. 2012; Singh et al. 2012; Ahmed et al. 2013; Liu et al. 2015). As a matter of reservoir operation under future climate conditions, the literature is limited. Dorchies et al. (2014) have recently assessed multi-objective reservoir management on the Seine River basin, France, under climate change scenarios. The objective of this project was to propose adaptation strategies in response to climate change for the four large dams within the Seine River basin. Eum & Simonovic (2010) and Ferreira & Teegavarapu (2012) adapted climate change in multi-purpose reservoirs management. Ferreira & Teegavarapu (2012) developed adaptive operations for a multi-purpose hydropower system under near future climate conditions. Eum & Simonovic (2010) used a framework of an integrated reservoir management system, including a weather generator (WG) model examining future meteorological variables and a hydrological model, for the Nakdong River basin in Korea.

This research is one of the few comprehensive modeling attempts to study potential effects of future climate on water balance and streamflows in an effort to help reservoir managers adapt to future climate conditions. Moreover, this study is one of the first that aims to capture the predictable short-term cyclic variability in streamflows as part of reservoir management strategy. As future climate varies naturally or by human-induced change at the global level, it is a safe bet for reservoir managers to take into account both predictable and random changes.

MATERIALS AND METHODS

Catchment description and data

The Mississippi River watershed in eastern Ontario is composed of a complex network of rivers, streams, rapids, and more than 250 lakes. The river runs from an upstream elevation of 325 m above sea level for 212 km to a downstream elevation of 73 m above sea level, for a total drop of 252 m with an average slope of about 0.1%. This large river, along with the lakes and dams, are managed by the Mississippi Valley Conservation Authority (MVCA).

This modeling study was conducted for the western sub-watershed of Marble lake, which is located in the headwaters of the Mississippi River (Ontario) at approximately 46.36° N and 75.00° W (Figure 1). This portion of the river system includes three major reservoirs used for stream flow regulation. Mazinaw lake is the first significant lake on the Mississippi river system. Bon Echo creek and Semi-circle creek are the two significant streams which enter lower Mazinaw lake. Semi-circle creek contains the first major water control structure on the system, at the outlet of Shabomeka lake. From Mazinaw lake, the river flows through the smaller Little Marble, Marble and Georgia lakes into Kashwakamak lake (Mississippi Valley Conservation Authority 2006).
The Mississippi River has a drainage area of 3,740 km² from its headwaters to its outlet into the Ottawa River. The region's topography is highly variable, and generally slopes from the west toward the east with a total relief of approximately 420 m. Historically, the watershed receives approximately 870 mm of precipitation annually and loses about 530 mm due to evaporation and transpiration (Mississippi Valley Conservation Authority 2006). Based on long term Environment Canada climate station Ottawa CDA (6105976) records, the average minimum, maximum, and mean monthly temperatures in the region are in the ranges of −1.5 to −20 °C, 9.5 to 12 °C, and 4 to 7 °C, respectively.

Thirty years of available climate records from the river made it a suitable watershed for analysis of how climate change is affecting water resources (using guidelines from the World Meteorological Organization (WMO) standard suggesting a 30-year period of climate data for analysis). Climate data from the Drummond Center station (No. 6102J13) within the watershed and adjacent climate stations with long-term records were selected for examination of trends in the climate variables. The Ottawa CDA station (6105976), located on the north-west corner of the basin, has climate records since 1891. Table 1 presents historic long-term trend analysis of mean precipitation and minimum temperature at the Ottawa CDA Station (1891–2002) showing that precipitation has remained unchanged while the minimum temperature has been increasing.

In addition, streamflow data, geographic information system layers (including soils, land use, topography, and stream network), and operating information for dams and reservoirs were applied throughout the modeling process.

Long-term surface water flow data for the river were obtained from the Water Survey of Canada’s HYDAT data archives and website (www.ec.gc.ca/rhc-wsc/) to establish the hydrologic model. The streamflow data available in the
watershed comes from four stations: namely, Mississippi River below Marble Lake (02KF016); Clyde River Gordons Rapids (02KF013); Clyde River Lanark (02KF010); and Mississippi River Appleton (02KF006). These stations have a long-term record of continuous data (average 49 years); gauge 02KF006 has the longest with 94 years data as of 2012. Surface water flows in the river peak in April due to snowmelt contributions. The lowest flows are observed in July, August and September due to high evapotranspiration (Mississippi Valley Conservation Authority 2006).

**Modeling approach**

To provide the MVCA with insight on the impact of global warming on the Mississippi River, an integrated modeling approach was established. The structure of the integrated modeling is described in Figure 2. This flowchart maps the relationship between the modeling tools and the steps used to achieve the current research objective.

The approach begins first with a collection of historic climatic and hydrometric data in the gauging stations across the watershed area. The ClimGen model was used to generate weather data parameters based on actual measured data at the climate stations to produce future time series. The change factor (CF) method was utilized to downscale the global climate change model to generate

### Table 1

<table>
<thead>
<tr>
<th>Precipitation</th>
<th>Minimum temperature</th>
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<tbody>
<tr>
<td>Rate of change (mm/yr)</td>
<td>Rate of change (C/yr)</td>
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<tr>
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<td>Kendall statistics</td>
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<td>Z-value</td>
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<td>Significant (%)</td>
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</tr>
<tr>
<td>December</td>
<td>−0.05</td>
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</tbody>
</table>

**Figure 2** Flowchart for the steps of model development.
future climate data in the study watershed. The CF method is superior to statistical downscaling (SD) methods as it more accurately simulates the key seasonal changes that are important for major hydrologic processes such as spring flood events governed by snowmelt. However, as the CF approach is the only approach used in this study, the results may need to be considered with a degree of caution.

The Modified Thornthwaite Water Budget Model (Johnstone & Louie 1983) was used to estimate the water budget components. The Thornthwaite model runs with actual climate data from the Drummond Center climate station to verify the program and is then used with future climate data to estimate future water budget components. Finally, future streamflows in the Mississippi River were evaluated. In addition to long-term trends, cyclic pattern analysis of the historic mean annual streamflow records provided short-term streamflow forecasting and opportunities for wet-year/dry-year adaptive reservoir management operations in the watershed. Each step is described in greater detail below.

**Future climate for Mississippi River watershed (Ontario)**

The highest uncertainty in modeling climate change impact on water resources comes from the general circulation models (GCMs) component. Projections of eight prominent global climate change models for the subject site were compared: NORESM1-ME, MPI-ESM-MR, MIROC5, IPSL-CM5B-LR, HADCM3, GFDL-CM3, CNRM-CM5, and CGCM2.

**GCMs downscaling**

It is worth emphasizing that CGCM2 data are developed on a continental scale. For example, the unit grid size of CGCM2 is 3.75° longitude × 3.75° latitude, which has the regional size of around 417 × 342 km (Zhang et al. 2001). It is too coarse to be used directly for assessing climate change impacts on a watershed scale, thereby requiring a downscaling tool for further, local analysis. Generally, there are two downscaling methodologies widely used for GCMs: CF and SD.

CF downscaling is a common approach that has been well-documented in the literature. Several authors (Booty et al. 2005; Diaz-Nieto & Wilby 2005; Zhang 2005) used CF methodology for future climate change scenario development. Booty et al. (2005) defined CF for temperature as the monthly mean differences between the selected GCM outputs and the baseline temperature for 1961–1990, and the CF for precipitation as the monthly mean differences in percentage, relative to the baseline data. Diaz-Nieto & Wilby (2005) compared the two methods, CF and SD, and concluded that CF had the main strengths of being easy and quick to apply, but had problems in that with this method the downscaled and the baseline weather data only differed in terms of their respective means, maxima and minima; all other statistical properties of the data, such as the range and variability, remained unchanged. In this research, the ClimGen model was used to analyze the CGCM2 data to calculate the CFs.

**ClimGen model**

One model for weather generation that has been applied extensively in the United States is WGEN (Richardson & Wright 1984). This model generates estimates of daily precipitation, maximum and minimum temperatures, and solar radiation, and it is designed to preserve the interdependence between variables as well as the persistence and seasonal characteristics of each variable. ClimGen is a modified version of WGEN and generates daily maximum and minimum temperatures and precipitation from either daily weather data, if available, or from monthly summaries (Stöckle et al. 1999).

For the Mississippi watershed investigation, ClimGen was employed as the WG because there is sufficient information to allow parameterization (Stöckle et al. 1999).

Within the Mississippi watershed area grid (latitude 46.56° N, longitude 75.00° W), daily climate data forecasts of CGCM2 for the base period [1984–2003] and for future periods [2010–2039], [2040–2069], and [2070–2099] were compared to calculate the CFs, as presented in Table 2. Historic daily precipitation from the Drummond Center Climate station (ID 6102J13) located within the watershed was used as input for the ClimGen model. ClimGen was used in ‘data analysis mode’ to analyze the Drummond Center climate station data and calculate the CFs.
Center climate data to calculate local climate statistics. Then, ClimGen was used in ‘data generation mode’ to generate future climate data using the local climate statistics and the change rates for the three future periods, [2010–2039], [2040–2069], and [2070–2100].

**Water balance model**

The Modified Thornthwaite Water Balance Model from Environment Canada was used to estimate the water budget components. The model was run with actual climate data from the Drummond Center climate station to verify the program and then run with future climate data, precipitation and temperature, to estimate water budget components.

**Catchment rainfall–runoff model**

This study applied the MIKE 11/NAM rainfall–runoff model (Nielsen & Hansen 1973). The model forms part of the MIKE 11 River modeling system for simulation of the rainfall–runoff process in sub-catchments (Havnø et al. 1995). The NAM model represents the various components of the rainfall–runoff process, by continuously accounting for the water content in four different, but mutually interrelated storages, where each storage represents different physical elements of the catchment: (1) snow storage; (2) surface storage; (3) lower zone (root zone) storage; and (4) groundwater storage. The water discharge calculated by the model is released through three linear reservoirs to overland, intermediate and deep groundwater flow. Past studies and Danish Hydraulic Institute documents explain the model structure and description of model parameters. To set up the catchment water balance in the NAM model, the following parameters were calibrated: maximum water content in surface storage ($U_{max}$); maximum water content in root zone storage ($L_{max}$); overland flow runoff coefficient ($C_{QOF}$); time constant for interflow ($CK_{IF}$); time constants for routing overland flow ($CK_{1,2}$); root zone threshold value for overland flow ($TO_{IF}$); root zone threshold value for interflow ($T_{IP}$); ground water parameters ($T_{G}$); time constant for base flow ($CK_{BF}$); and snowmelt process parameters: degree-day coefficient ($C_{snow}$) and base temperature snow/rain ($T_{0}$).

Within the Mississippi River watershed (Ontario), the gauged sub-watershed by the Water Survey of Canada (WSC 02KF016) was considered for hydrologic modeling. The Marble Lake watershed, including the Shabomeka lake, Mazinaw lake and Little Marble lake sub-basins, was utilized in the analyses. Plotting the cumulative daily streamflow at four hydrometric gauges in the subject watershed normalized by the drainage area demonstrated that all the

<table>
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<th>Month</th>
<th>Max. temp. change rate (°C/year)</th>
<th>Min. temp. change rate (°C/year)</th>
<th>Precip. change rate (mm/year)</th>
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sub-watersheds have similar water balance scenarios in terms of precipitation and evaporation. For modeling purposes, the basin was divided into three lake drainage sub-basins named Shabomeka (41 km²), Mazinaw (297 km²), and Little Marble (21 km²).

The rainfall–runoff models were set up for a 6-year period (from August 1994 to December 1999). The first 5 years of daily streamflow data were used for calibration of the model parameters and 1 year of daily streamflow data (1999) was used for verification of the NAM model. This study used the auto-calibration tool in the MIKE 11/NAM model to match both streamflow volumes and peak daily flows. The MIKE 11/NAM model auto-calibration tool derived a set of 12 parameters based on the correlation factor between measured and simulated runoff along with improving the water balance to a best match. Up to 2000 Monte Carlo model simulations were completed in the model to reach an optimum calibration (Figure 3).

Runoff spectrum analysis

Spectrum analysis (Fourier analysis) was used for the exploration of cyclical patterns of streamflow data across the Mississippi River watershed. The modeling decomposes the original daily streamflow time series into underlying sine and cosine functions for different frequencies according to Equation (1):

$$Q_t = Q + \sum_{j=1}^{h} \left[ A_j \cos \left(\frac{2\pi j t}{\omega} \right) + B_j \sin \left(\frac{2\pi j t}{\omega} \right) \right]$$

where $$Q_t$$ = time series of mean annual streamflow; $$t = 1, 2, \ldots, \omega; A_j, B_j$$ = Fourier series coefficients, $$j =$$ the harmonic; $$h =$$ the total number of harmonic equal to $$\left(\frac{\omega}{2}\right)$$ or $$\left(\frac{\omega - 1}{2}\right)$$ depending on whether $$\omega$$ is even or odd.

By using the linear multiple regression model, the $$A_j$$ and $$B_j$$ coefficients were found. The final equation for streamflow in the Appleton gauge is

$$Q = 33.4 + 4.36 \sin \left(\frac{2\pi t}{12} - 1.95\right) + 2.9 \sin \left(\frac{2\pi t}{3} - 3.28\right)$$

A 30-year period (1974–2003) for runoff depth was used to develop the spectrum analysis. Depth of runoff was calculated by multiplying the mean streamflow at the station with the time step (to estimate volume), and dividing by the drainage area. The mean annual runoff at the stations ranged from 230 to 511 mm/year from 1974 to 2003.

RESULTS AND DISCUSSION

Future climate data and water budget components

Figure 4 presents precipitation projections of eight prominent global climate change models for the study area: NorESM1-ME, MPI-ESM-MR, MIROC5, IPSL-CM5B-LR, HadCM3, GFDL-CM3, CNRM-CM5, and CGCM2. The daily temperature and precipitation from the second generation Coupled Global Climate Model (CGCM2) were selected to characterize the potential climate change for the watershed during the 21st century.

Figure 5 presents historic and future mean minimum daily air temperature for the study area. The increases in minimum air temperature obtained using CGCM2 for the Mississippi River watershed are similar to the results obtained by Booty et al. (2005) for the Duffins Creek watershed near Toronto using the same model. It is evident that the winter months of December through March are warming significantly, resulting in precipitation falling more frequently as rain rather than snow.

Figure 6 summarizes annual average water balance components for the historic period [1985–2003] and for the three future periods [2010–2039], [2040–2069], and [2070–2099]. Comparisons of historic and future water budget components
indicate a gradual ‘annual rate of change’ as follows: 0.1% increase in total precipitation; 0.2% increase in rainfall; 0.7% decrease in snowfall; 0.2% increase in potential evapotranspiration (PE); 0.1% decrease in soil moisture; 1.4% increase in water deficit; 0.5% increase in streamflow during winter months, and 0.3% decrease in streamflow during the summer months.

These findings are similar to those of Whitfield & Cannon (2000) who reported increases in temperature and changes in precipitation and streamflow patterns.
Future runoff modeling

The potential effects of climate change on future runoff in the study watershed were investigated using a regional climate model coupled with a hydrologic model (NAM model) calibrated with historic streamflow data (Figure 3). As shown in Figure 3, flow peaks occur historically in the spring (April) during snowmelt. The NAM model estimated spring snowmelt timing and Julian day of maximum snow cover on the ground for the past and future periods, showing long-term increases in the temperature of the region have begun to severely affect both snowpack accumulation and snowmelt delivery time. The historic and projected precipitation, PE, and temperature for the study area, centered on the 2025s and 2085s, were considered in the calibrated hydrologic model to produce future runoff values. Figure 7 presents historic [1971–2003], near future [2010–2039], and far future [2070–2099] mean monthly streamflow rates at Shabomeka station.

To check the performance of the calibrated model with the optimal parameter set, fully independent sample events for the 1999–2000 period were used to perform this test. Model performance was assessed with the same coefficient of determination ($R^2_{\text{calibration}}$) used for calibration and $R^2$ for the 1999–2000 sample, denoted $R^2_{\text{1999–2000}}$ (Table 3). Table 3 also lists calibration statistics including mean, standard deviation and $R^2$ between observed and simulated flow during the model calibration and validation.

Sensitivity analysis

A sensitivity analysis was performed to examine how the variation in the produced runoff can be apportioned, qualitatively or quantitatively, to different variations in the NAM model parameters. A trial-and-error approach in the sensitivity analysis showed that variations in the $CK_{\text{BF}}$ and $CK_{\text{IF}}$ did not significantly impact the simulated flow. In contrast, maximum water storage at the upper surface of the basin ($U_{\text{max}}$), the maximum lower storage ($L_{\text{max}}$) and the coefficient of overflow runoff ($CQ_{\text{OF}}$) are the most sensitive parameters in the hydrological NAM model. Overland flow runoff coefficient ($CQ_{\text{OF}}$) and time constant for routing
overland flow ($C_{1,2}$) had direct impacts on the shapes and peaks of the discharge hydrographs. An increase of either $CQ_{OF}$ or $C_{1,2}$ raised peak flow, and an increase in $C_{1,2}$ changed the rising limb of the hydrograph.

**Annual streamflow cyclic analysis**

The influence of climate variability on streamflow plays an important role in reservoir management. Throughout the Mississippi River watershed, mean annual runoff (in mm) at different Water Survey of Canada gauges in the region were investigated for cyclic analysis. Figure 8 clearly demonstrated a significant and predictable 3-year cyclic pattern in streamflows measured at seven different Water Survey of Canada stations across the river basin.

This 3-year cycle is likely due to the El Niño and La Niña effects as they affect precipitation in the region. Annual streamflow, generated based on Fourier series (Equation (2)), have a good correlation ($R^2 = 0.74$) with observed flow during 1965-2009 (Figure 9). This equation illustrates that the long-term mean annual streamflow at Appleton gauge (02KF006) is 33.4 m$^3$/s with a 3-year cycle that adds/subtracts about 2.9 m$^3$/s and another 12-year cycle that adds/subtracts 4.36 m$^3$/s. As the 3-year and 12-year cycles coincide every 12 years, a large amplification of the combined effects of adding/subtracting 7.53 m$^3$/s from the 33.4 m$^3$/s (i.e. varying from 25.87 to 40.93 m$^3$/s) is observed.

This analysis demonstrates that streamflow in the Mississippi River watershed is cyclic in nature with 3-year and 12-year periods (Figure 8). This might be in agreement with the findings of Burn et al. (2004) and Woo & Thorne (2003) that streamflow frequency is related to ENSO.

**CONCLUSION**

This research, which assumed the IPCC business-as-usual emissions scenario for the climate change GCMs simulation, predicts statistically significant increases in the
minimum daily air temperatures in eastern Ontario water-sheds. This may result in increased precipitation occurring as rain (rather than snow) during the late fall and early spring seasons. Both historical records and projected future data predict a rate of change in the minimum daily temperature by 0.5–1.3 °C per decade in the months of January and February. The historical average annual precipitation of 849 mm (with a standard deviation of 31 mm) is expected to increase to 933 mm (with a standard deviation of 33 mm) by 2100. This increase in precipitation will mainly occur in the autumn months, resulting in significantly wetter autumn conditions.

The water balance model predicts a gradual ‘annual rate of change’ of 0.1% increase in total precipitation, 0.2% increase in rainfall, 0.7% decrease in snowfall, 0.2% increase in PE; 0.1% decrease in soil moisture; 1.4% increase in water deficit; 0.5% increase in streamflow during winter months; and 0.3% decrease in streamflow during the summer months in the study area. The low flows in summer months are expected to drop by 25% over the next few decades which is of major concern for maintaining instream flow needs and the health of the ecosystem. Moreover, a decreasing trend in the Julian date of occurrence of the annual major snowpack melting event is predicted. In
both cases, increased temperatures in the spring appear to be resulting in an earlier onset of snowmelt and therefore an earlier start to the spring freshet. This will shift the optimum timing for filling up the reservoirs in the early spring to address both flood risk management concerns as well as maintaining the minimum required active reservoir storage for augmenting summer low flows.

In addition to long-term trends, cyclic pattern analysis of the historic mean annual streamflow records indicates the existence of pronounced 3-year and 12-year cycles, which provides short-term streamflow forecasting opportunities for wet-year/dry-year adaptive reservoir management operations. In the dry years, the reservoirs must be filled up 4–6 weeks earlier than the wet years for optimum active flood control capacity and to capture enough water for summer low flow augmentation.

This study attempts to capture both predictable short-term cyclic wet-year/dry-year variability in streamflows as well as the gradual long-term trends due to climate change as part of an adaptive reservoir management strategy under variable and changing climate.

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