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Modelling of climate-induced hydrologic changes in the Lake Winnipeg watershed

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ABSTRACT

The hydrologic regime of the Lake Winnipeg watershed (LWW), Canada, is dominated by spring snowmelt runoff, often occurring over frozen ground. Analyses of regional climate models (RCMs) based on future climate projections presented in a companion paper of this special issue (Dibike et al., 2011) show future increases in annual precipitation and temperature in various seasons and regions of this catchment. Such changes are expected to influence the volume of snow accumulation and melt, as well as the timing and intensity of runoff. This paper presents results of modelling climate-induced hydrologic changes in two representative sub-catchments of the Red and Assiniboine basins in the LWW. The hydrologic model, Soil and Water Assessment Tool (SWAT), was employed to simulate a 21-year baseline (1980–2000) and future (2042–2062) climate based on climate forcings derived from 3 RCMs. The effects of future changes in climatic variables, specifically precipitation and temperature, are clearly evident in the resulting snowmelt and runoff regimes. The most significant changes include higher total runoff, and earlier snowmelt and discharge peaks. Some of the results also revealed increases in peak discharge intensities. Such changes will have significant implications for water availability and nutrient transport regimes in the LWW.

Introduction

The hydrologic regime of the Lake Winnipeg watershed (LWW), Canada, is dominated by spring snowmelt runoff, often occurring over frozen ground. In the Prairie regions of Canada, where the LWW is primarily located, snowmelt runoff accounts for more than 80% of the total annual surface runoff, despite the fact that snowfall only contributes one third of total annual precipitation (Gray, 1970; Gray and Landine, 1988). Thus, spring snowmelt runoff plays an important role in the agricultural water supply of the region. Specifically, water consumption for agricultural purposes constitutes almost 50% of total water use, which is mainly drawn from surface water (Gan, 2000). Spring snowmelt runoff is also responsible for most floods in the region, such as events typically seen in the Red and Assiniboine rivers in the province of Manitoba (Simonovic and Li, 2003).

A number of previous studies have analyzed hydro-meteorological trends of the Canadian Prairies. For example, Gan (2000) observed that the Prairies have become warmer and drier in the last 4–5 decades. However, in the LWW there has been an overall increasing long-term trend in mean annual streamflow in the Red (between 1905 and 2005; Novotny and Stefan, 2007) and Winnipeg (between 1924 and 2000; George, 2007) rivers. Seasonally, trend analysis of streamflow data from 26 hydrometric stations from the Canadian Prairies for the periods 1966–2005, 1971–2005, and 1976–2005 showed significantly earlier timing of the spring freshet (Burn et al., 2008). An evaluation of how such discharge trends will be modified under future climate scenarios will help to assess the implications on overall water availability—a critical issue in the typically dry Prairie region.

Climate change is generally expected to lead to an intensification of the global water cycle as a result of changes in hydrologic variables such as precipitation and temperature (Huntington, 2006). For snow-dominated regions, the timing, volume, and extent of snowpack, and the associated snowmelt runoff, are intrinsically linked to seasonal climate variability and change (Stewart, 2009). Changes in precipitation principally affect maximum snow accumulation and runoff volume while temperature changes mostly affect runoff timing (Barnett et al., 2005). The potential future impacts in snowmelt-dominated catchments may include a reduction in snowpack volume and an earlier onset of melt (e.g., Stewart et al., 2004; Dibike and Coulibaly, 2005; Merritt et al., 2006; Rauscher et al., 2008; Choi et al., 2009b). These model-predicted changes are already evident in twentieth and early twenty-first century trends, such as a general decline of snowpack volume (e.g., Mote et al., 2005; Stewart, 2009) and earlier occurrence of snowmelt (e.g., Adam et al., 2009; Stewart et al., 2005). These alterations of the hydrological cycle in snowmelt-dominated regions could have major implications, such as regional water shortages where built storage capacity is inadequate to cope with seasonal shifts in streamflow (Barnett et al., 2005).

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Given that a variety of hydrologic characteristics have been found to control nutrient transport, any climate-induced changes in such characteristics are likely to also affect nutrient delivery to lakes such as Lake Winnipeg. For example, runoff from rainfall and snowmelt events is known to drive nitrate transport processes (e.g., Creed et al., 1996; Shrestha et al., 2007), and snowmelt in combination with frozen soils has been found to be especially important in the transport of phosphorus in the Canadian Prairies (Salvano et al., 2009).

The potential impacts of climate change on the hydro-meteorological regime in the Great Lakes basins have been the subject of recent investigations (e.g., Lofgren et al., 2002; Cherkauer and Sinha, 2010; Wuebbles et al., 2010). In a companion manuscript in this special issue, Dibike et al. (this issue) analyzed future climate projections from three regional climate models (RCMs) corresponding to the IPCC's SRES A2 scenario for the entire LWW. The analysis indicated that the total annual precipitation would increase by 5.5%–7.7% in the future period (2041–2070) compared to the "current" baseline period (1971–2000) while mean air temperature in the region would increase by 2.1–2.8 °C over the same interval. In addition, the analysis showed significant differences between the RCMs in terms of spatial and seasonal variability. Due to these differences, hydrologic scenarios simulated from different RCMs might produce significantly different results, as seen in previous ensemble RCM-driven hydrologic model simulations (e.g., Graham et al., 2007; Hagemann and Jacob, 2007). It was therefore considered essential to follow an ensemble modelling approach, using multiple RCMs for this assessment of climate-change projections.

This study is a part of Environment Canada's Lake Winnipeg Basin Initiative project and the main objective of the study is to assess the potential impacts of climate change on the hydrologic and nutrient transport regimes in selected basins of the LWW. The research focuses on the simulation of climate-induced hydrologic changes between a baseline (1980–2000) and a future (2042–2062) period, building on the analysis of three RCM outputs by Dibike et al. (this issue). The Soil and Water Assessment Tool (SWAT) was employed for the simulation of hydrologic scenarios in two representative sub-catchments of the Red and Assiniboine basins in the LWW. Based on RCM-driven model simulations, projected changes in the hydrologic regimes were identified.

Study area

Previous studies on nutrient loading in the Lake Winnipeg watershed indicate that the Red and Assiniboine river basins are the most significant sources of nitrogen and phosphorus loading to Lake Winnipeg (Bourne et al., 2002). Therefore, two representative sub-catchments, the Morris catchment in the Red River basin and the Upper Assiniboine catchment in the Assiniboine River basin (Fig. 1) were selected for this study. Both catchments are dominated by agricultural land use and therefore, are considered appropriate for understanding the climate impacts on non-point nutrient loadings.

The Upper Assiniboine catchment covers an area of about 13,500 km^2 and is located upstream of the Lake of the Prairies (Shellmouth reservoir) in the province of Saskatchewan (Shrestha et al., 2009). The topography is gently to moderately undulating with elevation ranging from 427 to 723 m. Annual precipitation over the timeframe 1979–2003 was about 460 mm (sourced from Gridded Climate Dataset for Canada; Hutchinson et al., 2009). Major tributaries of the Assiniboine River include the Whitesand River, Shell River, Lilian River and Yorkton Creek. The catchment is dominated by agricultural land use (about 55%) with mixed grain and wheat as primary crops (Environment Canada, 2000). The Morris River, with a catchment area of about 4300 m^2, is a tributary of the international trans-boundary Red River (Shrestha et al., 2009). Located in southern Manitoba with headwaters at the north-eastern edge of the Pembina Hills region (Jones and Armstrong, 2001), its relief varies from 228 to 535 m. Average annual precipitation in the Morris catchment is about 440 mm (1979–2003; Hutchinson et al., 2009). The Boyne River and Tobacco Creek are the major tributaries, which drain into a network of constructed channels before flowing into Morris River. The catchment is dominated by agricultural land use (about 80%) and the river water is used extensively for irrigation.

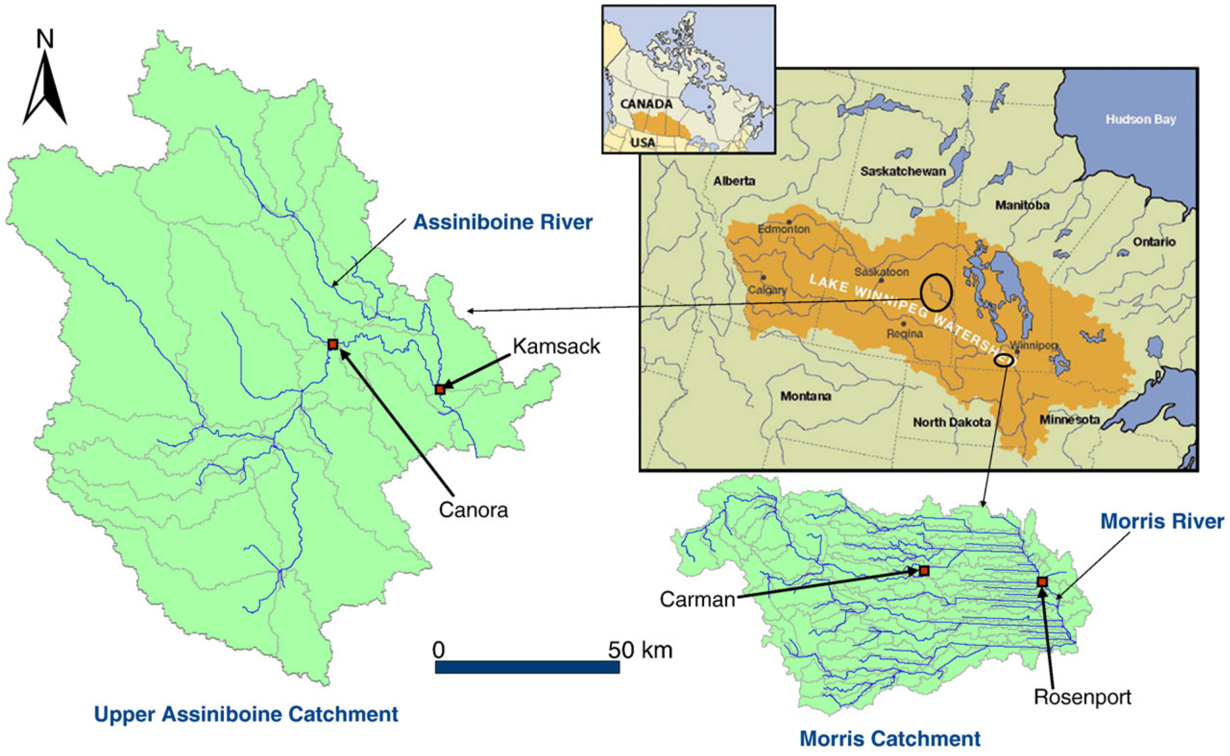

Fig. 1. Location of Upper Assiniboine and Morris Catchments in the Lake Winnipeg Watershed.

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Hydrologic modelling using SWAT

Model description of SWAT

The Soil and Water Assessment Tool (Arnold et al., 1998; Neitsch et al., 2005) was employed to simulate hydrologic processes in the two sub-catchments of the LWW. Since the overall long-term objective of the program is to assess the potential impacts of climate change on the hydrologic and nutrient transport regimes, the SWAT model which contains both the hydrologic and nutrient transport modules was selected. SWAT is also considered appropriate for the LWW as it has been extensively and successfully used in other snowmelt-dominated regions to simulate hydrologic response (e.g., Abbaspour et al., 2007; Ahl et al., 2008; Levesque et al., 2008) and nutrient transport (e.g., Grizzetti et al., 2003; Gollamudi et al., 2007; Panagopoulos et al., 2007). It has also been extensively used around the world for the assessment of climate impacts on hydrologic response (e.g., Jha et al., 2004; Marshall and Randhir, 2008; Abbaspour et al., 2009; Ficklin et al., 2009; Franczyk and Chang, 2009) and nutrient transport (e.g., Bouraoui et al., 2002; Bouraoui et al., 2004; Marshall and Randhir, 2008).

SWAT is a semi-distributed, continuous watershed modelling system, which simulates different hydrologic responses using process-based equations. The model computes the water balance from a range of hydrologic processes such as evapotranspiration, snow accumulation, snowmelt, infiltration and generation of surface and subsurface flow components. Spatial variability within a watershed is represented by dividing the area into multiple sub-watersheds, which are further subdivided into hydrologic response units (HRUs) based on soil, land cover and slope characteristics.

SWAT uses a temperature-index approach to estimate snow accumulation and melt. Snowmelt is calculated as a linear function of the difference between average snowpack maximum temperature and threshold temperature for snowmelt. Snowmelt is included with rainfall in the calculation of infiltration and runoff. SWAT does not include an explicit module to handle snow melt processes in the frozen soil, but includes a provision for adjusting infiltration and estimating runoff when the soil is frozen (Neitsch et al., 2005). Despite this limitation, SWAT was considered to be the most appropriate integrated model currently available for application in this cold-regions environment. SWAT computes actual soil water evaporation using an exponential function of soil depth and water content. The model generates surface runoff using a modified Soil Conservation Service (SCS) curve number method based on local land use, soil type, and antecedent moisture conditions. The influence of plant canopy infiltration and snow cover is incorporated into the runoff calculation. The soil profile is subdivided into multiple layers to support soil water processes such as infiltration, evaporation, plant uptake, lateral flow, and percolation to lower layers. Downward flow occurs when field capacity of a soil layer is exceeded and the layer below is not saturated. Percolation from the bottom of the soil profile recharges the shallow aquifer. Lateral sub-surface flow in the soil profile is calculated simultaneously with percolation. Groundwater flow contribution to total stream flow is simulated by routing the shallow aquifer storage component to the stream. Runoff is routed through the channel network using the variable storage routing method or the Muskingum method (Neitsch et al., 2005).

Model set up and calibration

The hydrologic and nutrient transport models for both catchments were set up using the ArcSWAT (Winchell et al., 2007) interface for SWAT2005 (Neitsch et al., 2005). The model was set up with: a) a 90-m resolution digital elevation model from the Consultative Group for International Agriculture Research-Consortium for Spatial Information, CGIAR-CSI (Jarvis et al., 2008); b) 1-km resolution land use data from Land Cover of Canada (LCC; Cihlar and Beaubien, 1998); and c) $1{:}1\times10^{6}$ resolution soil data from Soil Landscapes of Canada (SLC; SLC Working Group, 2007). The LCC and SLC databases were reclassified to match the SWAT database requirement.

SWAT requires daily precipitation, maximum and minimum air temperature, solar radiation, wind speed and relative humidity as forcing data. In the present study, the SWAT model was forced with gridded datasets from the North America Regional Reanalysis, NARR (Mesinger et al., 2006) and Gridded Climate Dataset for Canada, GCDC (Hutchinson et al., 2009). The gridded datasets were employed instead of relatively sparse data from climate observing stations because of their more detailed spatial coverage and their similarity to the RCMs datasets, which are also available in gridded format. This helps to retain consistency of inputs for model calibration/validation as well as climate-change scenario simulation using RCMs. Suitability of this approach for this region is supported by the work of Choi et al. (2009a), who have demonstrated that a hydrologic model can be suitably calibrated in a Prairie environment using gridded NARR data.

NARR is a long-term, consistent, climate dataset for the North American domain. Data are available at a 32-km spatial resolution for the period 1979–2005. Along with the use of the National Centers for Environmental Prediction (NCEP) Eta Model and its Data Assimilation System (at 32 kilometers per 45 layer resolution with 3-hourly output), the hallmarks of the NARR are incorporation of hourly assimilation of high quality and detailed precipitation observations, the inclusion of a recent version of the Noah land surface model, and the use of numerous other data sets that are additional or improved compared to the earlier Global Reanalysis products (Mesinger et al., 2006). The GCDC consists of daily precipitation and maximum and minimum air temperature datasets south of 60° N latitude in Canada for the period 1961–2003. The dataset is based on daily Environment Canada climate station observations, interpolated at 10-km spatial resolution using a thin-plate smoothing spline-surface fitting method (Hutchinson et al., 2009).

The SWAT models were set up for both catchments with forcings from: a) NARR precipitation, maximum and minimum air temperature, solar radiation, wind speed and relative humidity; and b) GCDC precipitation, maximum and minimum air temperature, and NARR solar radiation, wind speed and relative humidity. Based on results of previous successful studies in snow-dominated catchments (Abbaspour et al. 2007; Ahl et al. 2008; Levesque et al. 2008), a set of 13 parameters were chosen for calibration of the SWAT model. These included seven

Table 1
Minimum and maximum range of SWAT parameters and the best parameters values.

Parameter	Description	Min	Max	Best parameter	
				U. Assiniboine	Morris
CN2	SCS runoff curve number	−35%	35%	−13.4%	−13.1%
SURLAG	Surface runoff lag coefficient	0.01	10	0.50	0.15
TIMP	Snowpack temperature lag factor	0.01	1	0.23	0.32
SMTMP	Snowmelt base temperature	−3	3	−0.95	1.43
SMFMX	Maximum melt factor	0	10	5.42	8.79
SMFMN	Minimum melt factor	0	10	0.40	6.05
SNO50COV	Areal snow coverage threshold at 50%	0.01	1	0.16	0.02
SNOCOVMX	Areal snow coverage threshold at 100%	0	400	81.80	121.10
SFTMP	Snowfall temperature threshold	−3	3	2.13	−2.97
ALPHA_BF	Baseflow factor for bank storage	0.01	0.5	0.21	0.49
GW_DELAY	Groundwater delay time	10	100	53.50	12.00
CH_N	Manning *n* for the main channel	0.01	0.2	0.11	0.19
CH_K2	Effective hydraulic conductivity in main channel	2	20	17.30	3.83

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parameters controlling snowpack accumulation and melt, and six others that affect runoff generation. The description and range of parameters used in the SWAT calibration is given in Table 1. Calibration was performed using the procedures of the Parameter Solutions (ParaSol; van Griensven and Meixner, 2006), which is available in the SWAT-CUP2 toolbox (Abbaspour et al., 2007). ParaSol is a global optimization algorithm based on the Shuffled Complex Evolution (SCE-UA; Duan et al. 1992). The method uses threshold value given by χ^2-statistics to define a set of "good parameter". Using this set, the output uncertainty can be quantified in terms of a 95% confidence interval.

Observed daily discharge data from the Canora and Kamsack hydrometric stations in the Upper Assiniboine catchment and the Carman and Rosenort stations in the Morris catchment (Fig. 1) were used for model calibration. Unfortunately, discharge data during November–February are missing for the Canora station in the Upper Assiniboine catchment, and for both stations in the Morris catchment, most likely due to effects of river freeze-up. Such missing data were excluded from model calibration and validation. Ten years of data (1986–1995) were used for model calibration and 8 years of data (1996–2003) for model validation. A warm-up period of 1 year was employed so that the initial conditions did not affect the model calibration. Five independent calibration runs between 5000 and 10,000 simulations were performed for each of the SWAT calibration setups. Discharge simulations from 2 hydrometric stations were combined into a single objective function for optimization of the 13 parameters. The sum of the squares of the residuals between observed and simulated discharge were used as objective functions for model optimizations. In addition, the Nash–Sutcliffe coefficient of efficiency (NSCE), coefficient of determination (R^2), and mean absolute error (MAE) were used for independent evaluation of model performance. The formulae for the model performance measurements used in this study are summarized in Table 2.

Modelling of climate-induced hydrologic changes

The model forcings for the simulation of climate-induced hydrologic changes were derived from the North American Regional Climate Change Assessment Program (NARCCAP) database (Mearns, 2004), as presented in the companion paper in this issue (Dibike et al., this issue). NARCCAP produces climate data based on a set of regional climate models (RCMs) driven by a set of atmosphere–ocean general circulation models (GCMs) over a domain covering the conterminous United States and most of Canada. The RCMs are nested within the GCMs for baseline (1971–2000) and future (2041–2070) periods with forcings from observed emission and SRES A2 emission scenarios for the 21st century, respectively. The RCM runs are available at a spatial resolution of 50 km. Climate forcings from the Canadian CGCM3/CRCM (Music and Caya, 2009), the UK HadCM3/HRM3 (Hudson and Jones, 2002), and the NOAA GFDL/RCM3 (Pal et al., 2007) were used as inputs to the SWAT model for the simulation of climate-induced hydrologic changes.

It is to be noted that RCM outputs typically have some systematic biases, which is partly due to the fact that the climate models are not calibrated/validated at the watershed scale. For example, precipitation bias of the three RCMs ranges between −7% and 28% (−7% and 23%) for the Upper Assiniboine (Morris) catchment. Minimum and maximum temperature biases of the three RCMs range between −2.6 to 0.5 °C (−2.9 to 0.5 °C) and −4.1 to 0.6 °C (−4.2 to 0.7 °C) for Upper Assiniboine (Morris) catchment, respectively. Such biases can lead to considerable deviation when a hydrologic model is forced with a biased RCM (Graham et al., 2007). Two transfer methods, delta-change and bias-correction, both of which are commonly used methods to account for the biases from the GCM/RCM outputs (Graham et al., 2007) were employed in this study to deal with such model biases.

In the application of the delta-change method, changes in the mean monthly values between baseline and future periods were calculated for each RCM. The delta changes were calculated in terms of fraction changes for precipitation, wind speed, relative humidity and solar radiation, or differences for minimum and maximum air temperature (Eq. 1a). The calculated delta changes were applied to the baseline observations datasets ($\mathrm{OBS_{baseline}}$) to obtain the corresponding future projections ($\mathrm{SCEN_{future}}$) (Eq. 1b).

$$\mathrm{RCM_{future}} \div \mathrm{or} - \mathrm{RCM_{baseline}} = \Delta_\mathrm{m} \tag{1a}$$

$$\mathrm{SCEN_{future}} = \mathrm{OBS_{baseline}} \times \mathrm{or} + \Delta_\mathrm{m} \tag{1b}$$

In the application of the bias-correction method, monthly systematic biases were calculated for the baseline period by comparing RCM outputs with the observations. The monthly mean biases were calculated for each RCM in terms of fractional change for precipitation, wind speed, relative humidity and solar radiation, or difference for minimum and maximum air temperature (Eq. 2a). The calculated biases were then applied to the corresponding baseline and future RCMs to obtain the unbiased values (Eq. 2b).

$$\mathrm{RCM_{baseline}} \div \mathrm{or} - \mathrm{OBS_{baseline}} = \delta_\mathrm{m} \tag{2a}$$

$$\mathrm{RCM_{unbiased\,(baseline\ /future)}} = \mathrm{RCM_{biased\,(baseline\ /future)}} \times \mathrm{or} + \delta_\mathrm{m} \tag{2b}$$

There is one fundamental difference between the delta-change and bias-correction methods. The delta-change method applies the changes in monthly mean values between the baseline and future periods onto the observed baseline data without considering the changes in variability during these two periods. On the other hand, the bias-correction method only removes the calculated monthly biases from both the baseline and future period while preserving the changes in variability in the projected climate data.

Table 2
Error measurement formulae.

Error measurement	Name	Formula
Nash–Sutcliffe coefficient of efficiency	NSCE	$1-\frac{\sum_{i=1}^{n}(y_{\mathrm{obs}}-y_{\mathrm{cal}})^2}{\sum_{i=1}^{n}(y_{\mathrm{obs}}-\overline{y}_{\mathrm{obs}})^2}$
Coefficient of determination	R^2	$\left\{\frac{\sum_{i=1}^{n}(y_{\mathrm{obs}}-\overline{y}_{\mathrm{obs}})(y_{\mathrm{cal}}-\overline{y}_{\mathrm{cal}})}{\left[\sum_{i=1}^{n}(y_{\mathrm{obs}}-\overline{y}_{\mathrm{obs}})^2\right]^{0.5}\left[\sum_{i=1}^{n}(y_{\mathrm{cal}}-\overline{y}_{\mathrm{cal}})^2\right]^{0.5}}\right\}^2$
Mean absolute error	MAE	$\frac{1}{n}\sum_{i=1}^{n} y_{\mathrm{obs}}-y_{\mathrm{cal}}$

Where n is the number of observations, y_{obs} and y_{cal} are the observed and calculated values, and $\overline{y}_{\mathrm{obs}}$ and $\overline{y}_{\mathrm{cal}}$ are the mean of the observed and calculated values, respectively.

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Table 3
Relative changes in mean annual precipitation between baseline (1980–2000) and future (2042–2062) periods.

	Changes in mean annual precipitation (%)			
	CRCM	RCM	HRM3	Mean RCMs
Upper Assiniboine	11.0	17.5	16.0	14.8
Morris	6.6	14.0	10.9	10.5

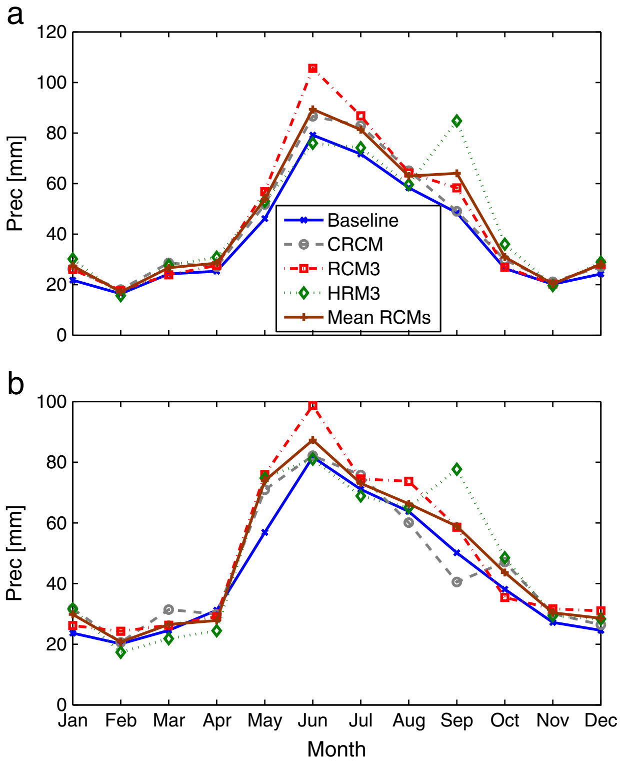

Fig. 2. Comparison of baseline (1980–2000) and future (2042–2062) mean monthly precipitation from different RCMs for the: a) Upper Assiniboine and b) Morris catchment.

For the analysis of climate-induced hydrologic changes in both catchments in the LWW, climate forcings from baseline and future periods were employed as inputs to the SWAT model. Since the NARR dataset begins only in 1979, a 22-year period (1979–2000) that also overlaps with the RCM data was used for the baseline hydrologic simulation (with GCDC precipitation, maximum and minimum air temperature, and NARR solar radiation, wind speed and relative humidity). Climate forcings obtained from delta-change and bias-correction methods were employed to simulate an equal number of years (2041–2062) in the future period. Changes in the simulated discharge and snowmelt signals in the catchment were compared between the baseline (1980–2000) and the future (2042–2062) periods, excluding the first years for the model warm-up period. Future hydrologic simulations are conducted for the SRES A2 emissions scenario because NARCCAP RCM outputs are only available for this emissions scenario. The IPCC A2 emissions scenario, which represents a high rate of population growth and a slower adaptation to new technologies (Nakicenvoic et al., 2000), is one of the "marker" scenarios commonly used in many impact studies.

The analysis of changes in bias-corrected RCM-derived precipitation between the baseline and future periods are presented in Table 3. The results show substantial differences between different RCMs, as well as between the two sub-catchments. The RCMs' projected precipitation for the future period depicts differences with the baseline period characterized by sharp peaks (Fig. 2a and b). For example, in comparison to the baseline period, June precipitation for the future RCM3 projections exhibits 33% and 21% increases in the Upper Assiniboine and Morris catchments, respectively. By contrast, the HRM3 projection exhibits sharp peaks in September, with mean monthly increases of 75% and 55% for the Upper Assiniboine and Morris catchments, respectively. To reduce the uncertainty in the future projection, an ensemble mean of monthly changes for each of the climate variables was calculated from the three RCMs. These ensemble means of delta-change values were used to calculate additional input to the SWAT model (employing Eq. 1a and 1b) for the simulation of average future changes (herein referred to as mean RCMs).

Results

SWAT calibration results

Based on the statistical performance of five independent model calibration runs for each catchment, the results with best overall performance were identified (Table 4). The results indicate that the SWAT models using GCDC precipitation and temperature produce better overall results compared to that using only NARR inputs. This could be due to the coarser spatial resolution (32 km) of the NARR datasets. In addition, the NARR data are based on assimilated observations, so the data may not fully represent the temporal dynamics at the sub-catchment scale required for the SWAT model. In comparison, the GCDC is a gridded observation dataset of 10 km spatial resolution, so it better represents spatial and temporal variability at the sub-catchment scale. The differences in the SWAT model performances are especially evident in model validation, where the models driven by GCDC show far better results for all three performance criteria considered (see Table 3).

Fig. 3 shows the best prediction results using the ParaSol procedure for both catchments with GCDC precipitation and temperature inputs. ParaSol also produced a narrow band (not shown in Fig. 3) of 95% confidence interval from a set of "good parameters". As suggested by Yang et al. (2008), the narrow band of uncertainty may be because ParaSol only considers parameter uncertainty (does not consider model structure and input uncertainties). However, the "best parameter" set (Table 1) selected from the multi-modal response surface showed good performance with good reproduction of the runoff dynamics for the calibration and validation periods. Specifically, for the Kamsack station for the Upper Assiniboine catchment

Table 4
Statistical performance of SWAT model for the Upper Assiniboine and Morris catchments.

Input dataset	Catchment (station)	Calibration			Validation		
		MAE [m^3/s]	R^2	NSCE	MAE [m^3/s]	R^2	NSCE
NARR + GCDC	Assiniboine (Kamsack)	3.67	0.87	0.81	4.23	0.72	0.65
NARR	Assiniboine (Kamsack)	3.83	0.82	0.73	5.48	0.68	0.19
NARR + GCDC	Morris (Rosenort)	3.16	0.70	0.69	5.27	0.62	0.62
NARR	Morris (Rosenort)	3.08	0.68	0.66	6.28	0.52	0.45

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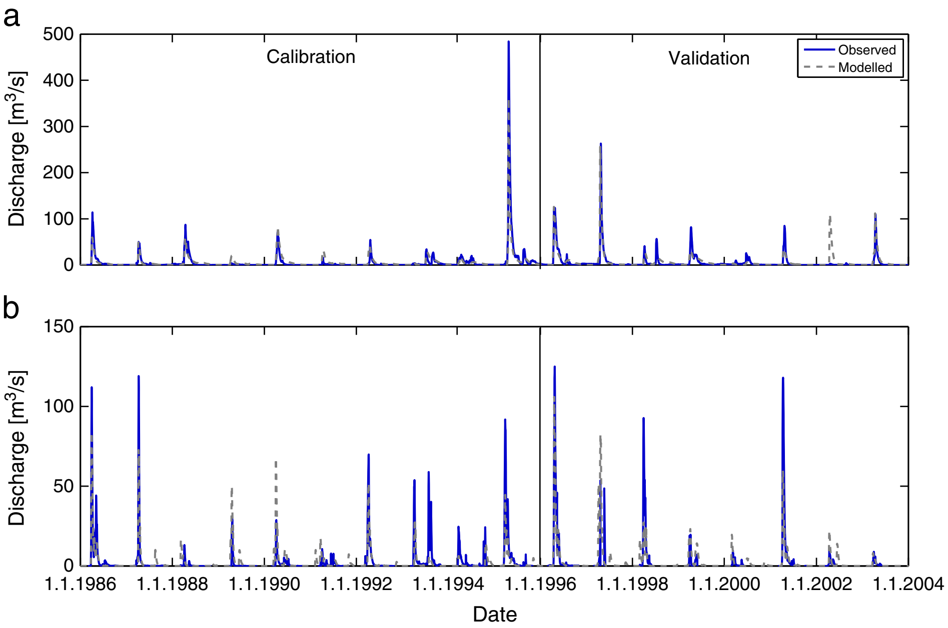

Fig. 3. Comparison of observed and simulated discharge for: a) Kamsack hydrometric station in Assiniboine River and b) Rosenort hydrometric station in Morris River, using climate inputs from NARR and GCDC datasets.

(Fig. 3a), the peaks in discharge during the April–May snowmelt season are replicated reasonably well for most years. The SWAT model driven by NARR precipitation and temperature inputs misses the secondary peaks after initial snowmelt (not shown in Fig. 3a), the model driven by GCDC precipitation and temperature is able to better reproduce the secondary peaks. Similarly, for the Morris catchment, the SWAT model calibrated with GCDC precipitation and temperature has a better overall statistical performance. Therefore, based on the statistical performance and graphical representation of the results in both catchments, the quality of precipitation and temperature inputs are found to be important factors determining the quality of the SWAT model performance.

In a catchment with multiple gauges, calibration of upstream discharge can affect downstream discharge (Shrestha and Rode,

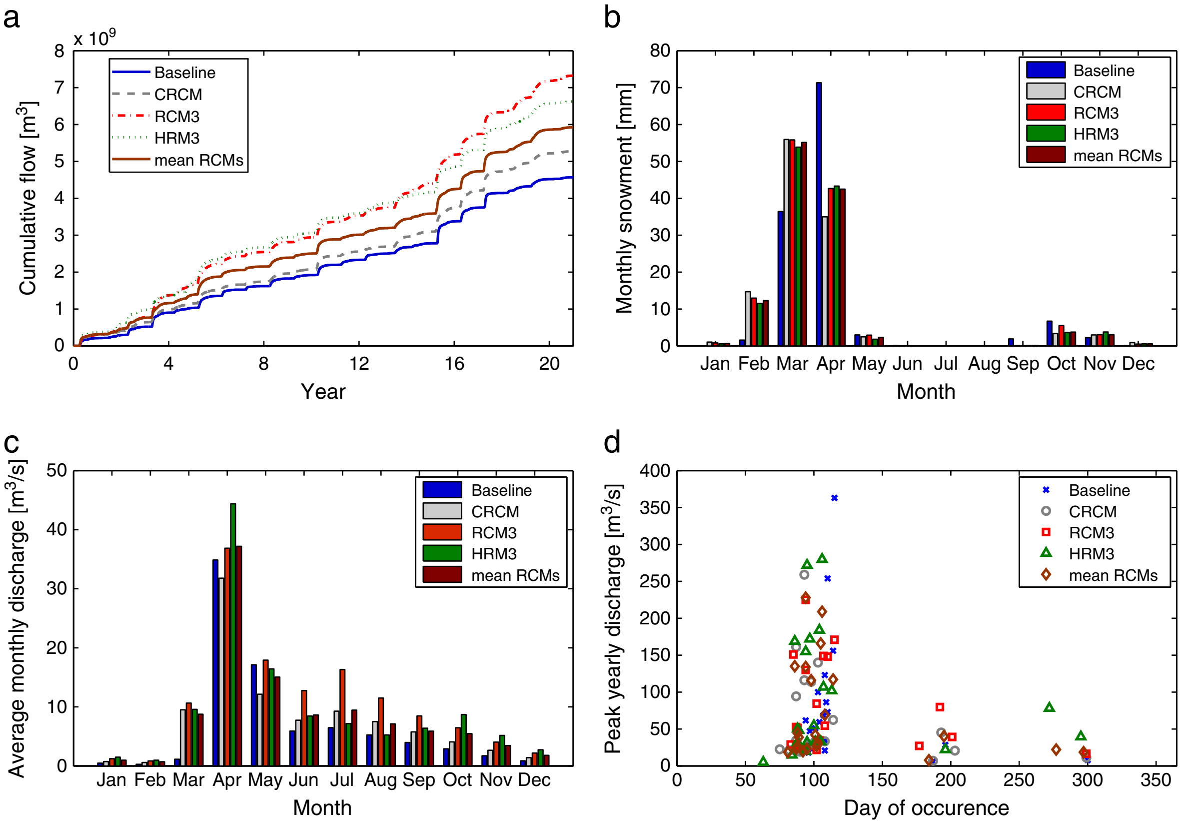

Fig. 4. Comparison of simulated future (2042–2062) and baseline (1980–2000) hydrologic regimes for the Upper Assiniboine catchment using the delta-change method. Illustrated are changes in: a) cumulative flow, b) monthly total snowmelt, c) monthly average discharge, and d) magnitude and Julian day of occurrence of annual peak discharge.

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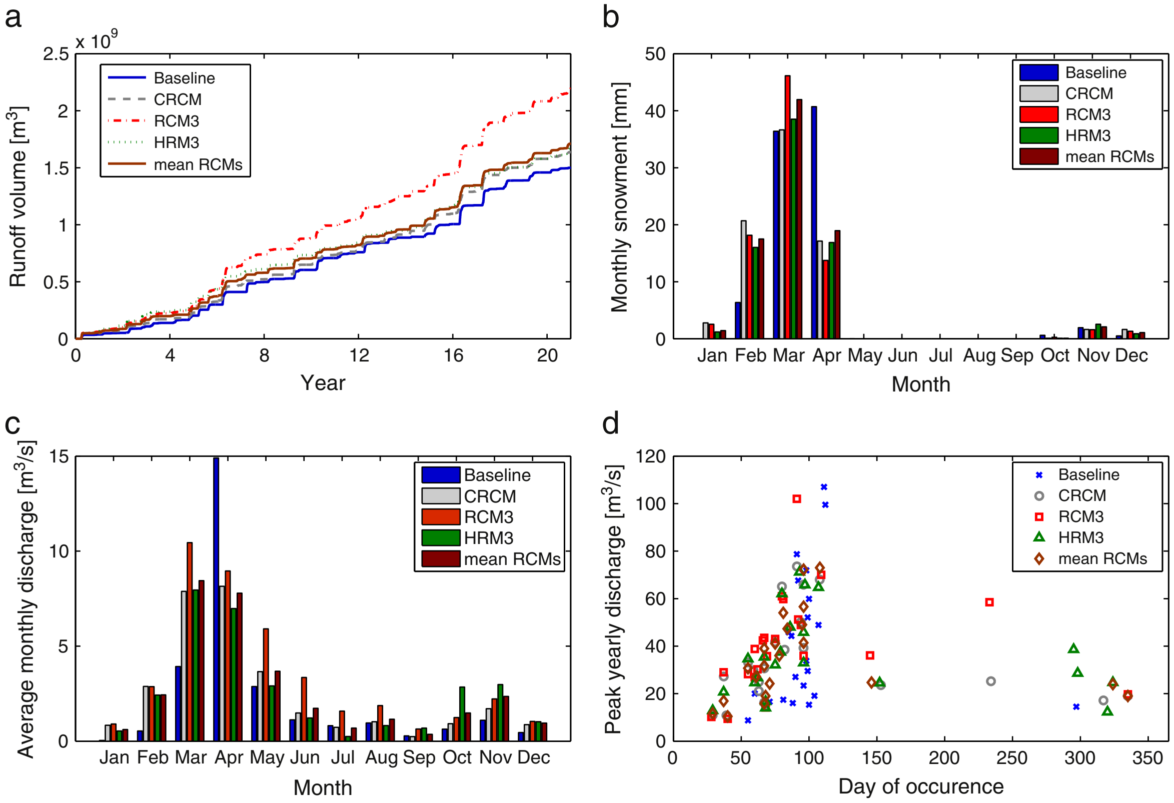

Fig. 5. Comparison of simulated future (2042–2062) and baseline (1980–2000) hydrologic regimes for the Morris catchment using the delta-change method. Illustrated are: a) cumulative flow, b) monthly total snowmelt, c) monthly average discharge, and d) magnitude and Julian day of occurrence of annual peak discharge.

2008). In this study, the flows between the upstream and downstream gauging stations are highly correlated for both catchments (Upper Assiniboine calibration: 0.89, validation: 0.92; Morris, calibration: 0.90, validation: 0.85). As expected, the upstream and downstream discharge residuals (difference between observed and simulated outputs) were also found to be highly correlated for both catchments (Upper Assiniboine, calibration: 0.55, validation: 0.79; Morris, calibration: 0.70, validation: 0.49), which suggests that calibration of downstream gauge is highly influenced by upstream gauge. However, better results in the downstream gauge compared to the upstream gauge in both catchments (not shown) imply an overall improvement of the model performance by the downstream calibration.

The results of the SWAT model calibration may also be affected by a number of other factors, such as river-ice, which can affect the quality of discharge records, especially during break-up (e.g., Pelletier, 1990; Hamilton, 2008). These discharge uncertainties influence the model calibration and validation results. For example, no discharge peak is present in the observation data of the Upper Assiniboine catchment during the 2002 snowmelt while the SWAT simulation produced a discharge peak of about 100 m^3/s. Such discrepancy may be due to problems in the observation dataset, thereby affecting statistical results for the model validation. In the Morris catchment, an additional source of uncertainty in the discharge values is the lack of accounting of water withdrawal for irrigation, which would also affect model statistics.

Hydrologic scenarios based on RCM climate projections

Delta-change method

The comparison of modelled baseline (1980–2000) and future (2042–2062) hydrologic scenarios for the Upper Assiniboine and Morris catchments based on the delta-change method are shown in Figs. 4 and 5, respectively. The SWAT model simulations indicate significant changes in the future runoff and snowmelt regimes for both catchments. All four hydrologic scenario simulations (each based on projections obtained from CRCM, RCM3, HRM3 and the ensemble mean of the three RCMs) depict higher future runoff volumes (Figs. 4a

Table 5
Comparison of changes in mean annual runoff volume, and magnitude and day of occurrence of average annual peak snowmelt discharge between baseline (1980–2000) and future (2042–2062) periods using delta-change method.

	Upper Assiniboine			Morris		
	Mean runoff vol. change (%)	Av. annual peak discharge [m^3/s]	Av. day of occurrence	Mean runoff vol. change (%)	Av. annual peak discharge [m^3/s]	Av. day of occurrence
Baseline	–	76	104	–	42	92
CRCM	15.4	60	93	9.2	34	71
RCM3	60.3	72	96	46.1	41	70
HRM3	45.0	88	95	11.0	35	74
Mean RCMs	29.6	71	96	14.1	35	72

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and 5a). The results also show, however, large differences among hydrologic change signals from the multiple RCMs. Specifically, the largest (smallest) increase in runoff volume from the four RCM scenarios (Table 5) is produced by the RCM3 (CRCM) projection. Overall, the percent increase in mean annual runoff (Table 5) exceeds the related increase in mean annual precipitation (Table 3) for scenarios. The hydrologic simulation based on the RCM3 projection is characterized by the largest deviations from the baseline period in both catchments. This can largely be attributed to higher summer runoff produced by greater summer precipitation (Fig. 2a and b).

Significant changes in the timing of snowmelt runoff are also evident for the future simulations, perhaps due to increases in minimum and maximum air temperatures. In comparison to the baseline period, higher monthly snowmelt volumes are observed in February and March for all RCM simulations in both catchments (Figs. 4b and 5b). These are followed by substantially lower April snowmelt volumes in both catchments, mostly due to snowpack depletion in the previous winter months. The effects of these shifts in the snowmelt regime are evident in the simulated seasonal hydrographs. Specifically, under future climatic conditions, higher average March discharge is observed in the Upper Assiniboine catchment (Fig. 4c), and higher future February and March runoff, together with lower April discharge is observed in the Morris catchment (Fig. 5c). The effects of earlier snowmelt can also be seen in the peak yearly discharges, which show shifts towards earlier events (Figs. 4d and 5d). These shifts are around 10 and 20 days in the Upper Assiniboine and Morris catchments, respectively (Table 5). In the case of average peak yearly discharge, small decreases in the future values are projected for both catchments (except for the HRM3 simulation in the Upper Assiniboine catchment).

Temporal variability of the forcing RCM datasets is also believed to have produced differences in some seasonal runoff simulations. Higher increases in summer and autumn precipitations in the RCM3 and HRM3 projections, respectively, led to higher runoffs in those seasons (Figs. 4c and 5c). The influence of these sharp changes in the precipitation of individual RCMs are averaged out in the ensemble simulations using mean monthly delta value (mean RCM) simulations, thereby resulting in lower changes for future seasonal runoff.

Bias-correction method

The comparison of simulated baseline (1980–2000) and future (2042–2062) hydrologic scenarios with the future climate data derived from the bias-correction method are shown in Figs. 6 (Upper Assiniboine catchment) and 7 (Morris catchment). These scenarios also depict significant changes in the runoff and snowmelt regimes for both catchments. Again, the spatial and temporal variability between the different RCMs produced differences in simulated runoff volumes for both catchments. Results of the simulations exhibit large variations in total runoff volume, with the HRM3 (CRCM) future scenarios producing the largest (smallest) deviations from the baseline periods in both catchments (Figs. 6a and 7a).

Monthly runoff trends show general increases in both catchments, with only the CRCM results showing slight decreases for the Morris catchment. Once again, the seasonal differences in precipitation among the three RCMs led to differences in the hydrologic response. Since runoff in the Prairies is dominated by snowmelt (Gray and Landine, 1988), changes in autumn and winter precipitation have the highest influence on total runoff. Specifically, in the HRM3 simulation, greater autumn and winter precipitation (Fig. 2a and b) led to higher autumn and spring runoff, and higher overall runoff volume. In the case of the RCM3 simulation, although the increase in mean annual precipitation is greater in the Upper Assiniboine catchment compared to the Morris catchment (Table 3), the runoff volume increase is lower in the former catchment (Table 6). This is mainly due to differences in the September–March precipitation (Fig. 2a and b) for the two catchments. A relatively small change in September–March precipitation resulted in a smaller runoff increase in the Upper Assiniboine

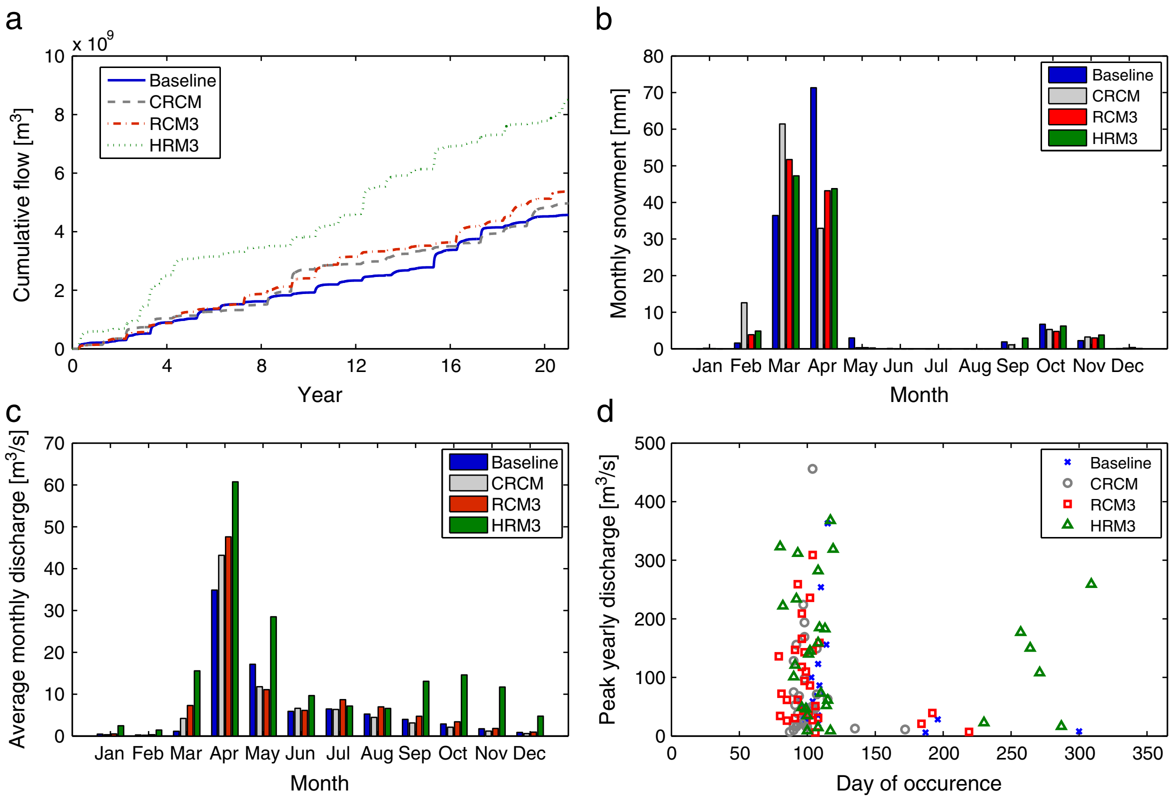

Fig. 6. Comparison of simulated future (2042–2062) and baseline (1980–2000) hydrologic regimes for the Upper Assiniboine catchment using the bias-correction method. Illustrated are changes in: a) cumulative flow, b) monthly total snowmelt, c) monthly average discharge, and d) magnitude and Julian day of occurrence of annual peak discharge.

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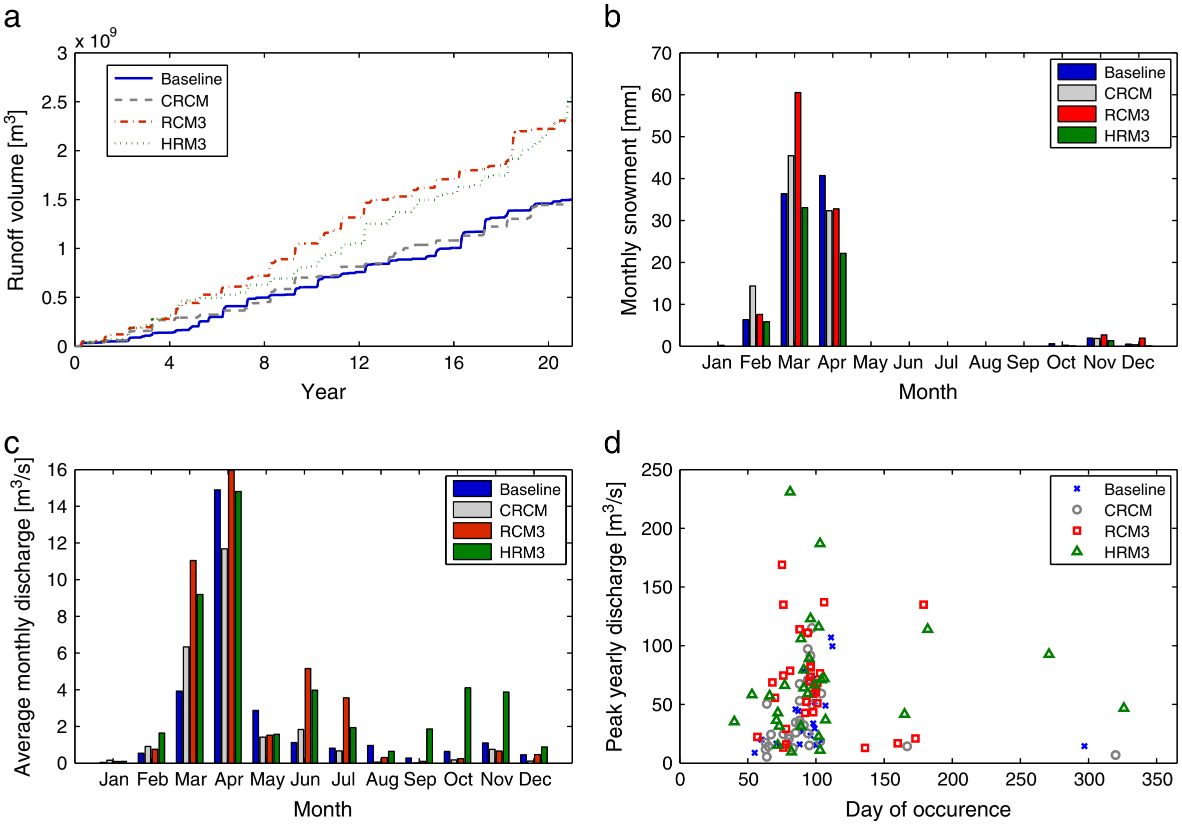

Fig. 7. Comparison of simulated future (2042–2062) and baseline (1980–2000) hydrologic regimes for the Morris catchment using bias-correction method. Illustrated are: a) cumulative flow, b) monthly total snowmelt, c) monthly average discharge, and d) magnitude and Julian day of occurrence of annual peak discharge.

catchment while a greater change in November–March precipitation led to a higher spring runoff increase in the Morris catchment. These results demonstrate the importance of temporal variations in precipitation on seasonal and total catchment runoff.

Significant differences between baseline and future simulations of snowmelt timing are also observed in the results of this analysis. The effect of a temperature-change driven shift in the snowmelt regime can be seen in future discharge simulations for all three RCMs. In comparison to the baseline period, higher monthly snowmelt in February and March, together with lower monthly snowmelt in April are evident in all future simulations (Figs. 6b and 7b). Earlier snowmelt is accompanied by higher March and April discharge in the Upper Assiniboine catchment (Fig. 6c), and higher February and March discharge in the Morris catchment (Fig. 7c). Earlier snowmelt also translated into earlier peak annual discharge values (Figs. 6d and 7d; Table 6). Seasonal shifts of 2–19 days in the Upper Assiniboine catchment and 5–7 days in the Morris catchment are observed (Table 6). In addition, the results of the RCM3 and HRM3 simulations show higher mean annual snowmelt peaks. This differs from the delta-change simulations, which produced lower peak values (Table 5). Since the bias-correction method preserves the variability of the future RCMs, the higher snowmelt peaks are likely due to differences in variability of the forcing datasets.

Discussion

Based on the above results, climate change is likely to bring significant changes to the snowmelt-driven runoff regime in the LWW. Specifically, the effects of projected future changes in climatic variables, specifically precipitation and temperature, are clearly evident in the resulting future snowmelt and runoff regimes. The simulated hydrologic scenarios based on SRES A2 climate forcings show general increases in runoff volume. The projections are consistent with similar studies undertaken in the northern Manitoba basin (Choi et al., 2009b) that also projected increasing future runoff volume. The earlier future snowmelt and runoff peaks as projected by this study also correspond with general historical trends in Canadian Prairies (Burn et al., 2008).

The spatial and temporal differences between the different RCM projected changes also led to significant differences in corresponding runoff simulations for the two catchments. For precipitation increases ranging between 6.6% and 17.5%, changes in catchment runoff ranged

Table 6
Comparison of changes in mean annual runoff volume, and magnitude and day of occurrence of average annual peak snowmelt discharge between baseline (1980–2000) and future (2042–2062) periods using bias-correction method.

	Upper Assiniboine			Morris		
	Mean runoff vol. change (%)	Av. annual peak discharge [m^3/s]	Av. day of occurrence	Mean runoff vol. change (%)	Av. annual peak discharge [m^3/s]	Av. day of occurrence
Baseline	–	76	104	–	42	92
CRCM	8.6	80	85	−6.1	40	85
RCM3	17.6	99	96	48.9	68	87
HRM3	89.9	137	102	65.9	69	78

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widely between −6.1% and 89.9%. Seasonal differences in precipitation in the three RCMs led to such discrepancies in hydrologic responses. Since runoff regime in the catchment is dominated by the snowmelt, changes in the autumn and winter precipitation cause considerable changes in the snow accumulation and melt as well as runoff generation processes. Hence, increase in the autumn and winter precipitation led to a higher increase in the total runoff volume while an increase in summer precipitation led to relatively low increases.

The projections of future hydrologic changes are also affected by the method used to account for the systematic biases inherent in the RCM data. The differences between the results of the delta-change and bias-correction methods are evident in the scenario simulations, especially in the case of the RCM3 and HRM3 results. For instance, the RCM3 simulations depict the highest change in overall hydrologic response using the delta-change method while the HRM3 simulations depict the highest change using the bias-correction method. The results also show that for the same increase in mean precipitation (Table 3), the increase in the corresponding runoff volume (Tables 5 and 6) could be quite different based on the method used. Since the variability of the future RCM scenarios is preserved only in the bias-correction method, the projections based on this method can be considered to provide a more plausible representation of possible future changes.

The results also show that the seasonal differences of the changes in the projected precipitation between the three RCMs led to large variations in hydrologic response, especially when considering the resulting effects on the critical snowmelt response. In summary, such uncertainties in modelling some aspects of future hydrologic regimes using single RCM forcings reinforce the need to use an ensemble approach that relies on multiple RCMs, and provides a range of possible future changes. Such an approach facilitates the consideration of a range of possible impacts and aids in developing appropriate adaptation strategies that can consider these uncertainties.

Climate-induced hydrologic changes as noted above are expected to also produce changes in regional water availability. Overall, the modelled results project increase in monthly runoffs (except for CRCM outputs using bias-correction method for Upper Assiniboine catchment) and annual runoff volume. Such increases in total runoff volumes can be considered positive for general water availability in the dry Prairies that feeds Lake Winnipeg. However, a shift in the hydrologic regime to an earlier occurrence of the snowmelt runoff peaks will lead to changes in the agricultural water supply for the region and may require changes to storage capacity, water delivery, and/or cropping practices. Climate-induced hydrologic changes may also bring about negative impacts in the region, such as an increase in flood hazards due to increases in peak snowmelt discharge. This may be especially important given the flood history of the Red and Assiniboine rivers. Moreover, the above noted hydrologic changes can also influence nutrient transport processes—a major concern as earlier noted for Lake Winnipeg. Nutrient responses in snowmelt-dominated catchments exhibit strong relationships with hydrologic response for both nitrate (Creed et al., 1996) and phosphorus (Prepas et al., 2003). Therefore, changes in the hydrologic response, such as earlier occurrence of discharge peaks, can be expected to lead to earlier nutrient responses. Further changes may occur in the N:P ratios and thereby amplify the risk of eutrophication (Marshall and Randhir, 2008). Detailed research to investigate the potential impacts of climate change on related hydrologic-nutrient cycle interactions is currently in progress.

The main limitation of this hydrologic impact study is that it does not take into consideration the possible changes that may occur in the frozen soil regime. Although the temperature index approach in the present version of SWAT (SWAT2005) provides a reasonable simulation of snow accumulation and melt processes, the model does not include an explicit methodology to take into account frozen-soil dynamics and infiltration processes. Application of hydrologic models/algorithms that explicitly consider frozen soil processes (e.g., Variable Infiltration Capacity (VIC) model, Cherkauer and Lettenmaier, 2003; Canadian Land Surface Scheme (CLASS), Verseghy, 2008) is currently in progress and the results of such research, together with comparison to output from current versions of the SWAT model, will be presented in subsequent papers. The lack of accounting for changes in sub-daily precipitation intensities also likely affects simulations of, for example, extreme events. As the SWAT model is run at a daily time step, average precipitation intensity over the 24 h period must be used. Hence, this study was unable to account for potential changes in the effects of intense, short-term precipitation events. But this should be a focus of future research since such events are likely to be important to runoff generation, particularly in frozen ground situations where runoff is very rapid.

Conclusions

The climate-induced hydrologic changes in two snowmelt-driven catchments in the LWW were investigated using the hydrologic and agricultural chemical yield model SWAT. After a successful calibration of the SWAT model, hydrologic simulations were conducted for a baseline (1980–2000) and a future (2042–2062) climate scenario by employing the forcings derived from three RCMs and their ensemble mean delta values. Since the snowmelt-driven spring runoff plays an important role in the agricultural water supply in the region, the potential climate-induced changes to the spring runoff regime were investigated in detail.

The hydrologic scenarios simulated using the delta-change and bias-correction methods (to take into account the systematic biases in the RCM datasets) generally led to similar results. These showed consistent changes in future snowmelt-driven runoff, characterized by an earlier onset of spring snowmelt and peak discharges. These trends are consistent with past trends observed in this part of the Prairie regions. In addition, overall increases in runoff volumes projected by this study correspond with past trends in the Red River.

The results of this study also show that simulated future hydrologic scenarios depend upon the climate projection from a particular RCM and upon the method used to correct systematic biases. The three RCM datasets used in the scenario simulations exhibited different spatial and temporal variability, which led to significant differences in the runoff simulations for the two catchments. For a precipitation increase of 6.6%–17.5% in the two catchments, the changes in the runoff are found to be between −6.1% and 89.9% depending on the RCM and the method used to correct the systematic biases in the RCM forcings. Seasonal differences in precipitation and temperature among the RCMs, especially in the critical snowpack accumulation and melt seasons, led to such differences in hydrologic responses. The bias-correction method generally led to increases in peak discharge while the delta-change method led to decreases in peak discharges. The bias-correction method preserves the change in both the mean magnitude and variability projected for future scenarios from the RCMs while the delta-change method only considers the change in mean magnitude of the future climate. Therefore, it seems more appropriate to use the bias-correction method for climate impact simulation.

The results also indicated that projected changes in hydrologic regimes simulated with different RCM forcings can be subject to appreciable uncertainties. Hence, until specific RCMs are proven to be superior in application, it is considered appropriate to employ multiple RCMs to project a full range of possible climate-change effects. Such an approach facilitates the consideration of different plausible forcing scenarios and the development of appropriate climate-change adaptation strategies.

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