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Streamflow Forecast and Reservoir Operation Performance Assessment Under Climate Change

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Abstract This study attempts to investigate potential impacts of future climate change on streamflow and reservoir operation performance in a Northern American Prairie watershed. System Dynamics is employed as an effective methodology to organize and integrate existing information available on climate change scenarios, watershed hydrologic processes, reservoir operation and water resource assessment system. The second version of the Canadian Centre for Climate Modelling and Analysis Coupled Global Climate Model is selected to generate the climate change scenarios with daily climatic data series for hydrologic modeling. Watershed-based hydrologic and reservoir water dynamics modeling focuses on dynamic processes of both streamflow generation driven by climatic conditions, and the reservoir water dynamics based on reservoir operation rules. The reliability measure describes the effectiveness of present reservoir operation rules to meet various demands which are assumed to remain constant for the next 100 years in order to focus the study on the understanding of the structure and the behaviour of the water supply. Simulation results demonstrate that future climate variation and change may bring more high-peak-streamflow occurrences and more abundant water resources. Current

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reservoir operation rules can provide a high reliability in drought protection and flood control.

Keywords Climatic change · Streamflow · Forecast · Reservoir · Shellmouth Dam · Canada

1 Introduction

All existing global circulation models (GCMs) are projecting a warmer future with increasing greenhouse gases concentrations in the atmosphere (IPCC 2007). Potential impacts of global warming on hydrology include changes in the hydrologic cycle and the water availability (e.g. Douville et al. 2002). More significant impact may be expected in the Northern American Prairie region where the runoff is significantly contributed by seasonal storage of water in the snowpack. Snowfall in the prairie region accounts for about 30% of annual precipitation (Akinremi et al. 1999). Adding or removing snow in wintertime fundamentally changes the snowpack's ability to act as a reservoir for water storage (Nijssen et al. 2001). Total winter precipitation and spring air temperature play an important role in snow accumulation in winter and snowmelt in spring. Changes in the amount of precipitation tend to affect the volume of runoff, while air temperature changes mostly affect the timing of runoff (Barnett et al. 2005). Increasing air temperatures lead to less snow accumulation in the winter and an earlier peak runoff in the spring, and reduced flows in summer and autumn (Mote et al. 2005; Cayan et al. 2001; Stewart et al. 2004; IPCC 2007). The change in the streamflow regime results in a substantial impact on regional water resources and seasonal water supplies. Reduced storage of water in the snowpack and earlier melt due to air temperature increase translate to a lower fresh water pulse for recharge of soil moisture, lakes and reservoirs, and a greater potential for evaporation loss. This trend, coupled with increasing demand for water from human society, exacerbates competition for over-allocated water resources. Therefore, a serious re-examination of the performance of present reservoir operation rules, designed on the basis of the timing of runoff, is likely to have substantial implications for prairie regional water resources planning and management under future climate change.

Considerable efforts have been made to investigate the hydrological processes, water resources allocation and climate change impacts. Climate change scenarios can be generated by various techniques such as the paleoclimate analogue, the recent climate analogue and the general circulation modeling. The methods for predicting river discharge series include statistical approaches (Thomas and Megahan 1998), time series techniques (Jakeman and Hornberger 1993; Moore et al. 2008), complex physically-based runoff models (Bobba and Lam 1990; Kite et al. 1994; Lehning et al. 2006; Fang and Pomeroy 2008), neural networks (Hsu et al. 1995; Ehrman et al. 2000) and the combination of the above methods (Vicuna and Dracup 2007). System simulation is a powerful methodology linking climate change to hydrology for predicting the streamflow and assessing the performance of reservoir operations under climate changes. For example, Ahmad and Simonovic (2000) simulated the flood damage under different reservoir management strategies. An integration of the climate change model and hydrological model with reservoir operation assessment model will provide a solid basis for assessing the potential impacts of climate change on reservoir operation performance. Based on the analysis of limitations and constraints of existing hydrological models for prairie conditions, Li and Simonovic (2002) developed a hydrological model that uses the active air temperature (>0°C) accumulation to explain surface soil defrosting and refreezing processes and their impacts on streamflow generation. As a key part of a regional dynamic hydroclimatological assessment model (DYHAM) developed by Simonovic and Li (2003), the hydrological model was combined with climate change scenarios and flood protection assessment model to assess the reliability of a complex urban flood protection system. The streamflow series were calculated and predicted by the hydrological model under real time and climate change conditions, then fed to flood protection system assessment model.

Reasonable allocation of water resources by reservoir operation plays an important role in matching the requirements of sustainable water resources and mitigating the adverse impact of climate variations and changes. In the DYHAM (Simonovic and Li 2003), the reservoir was taken as a flood protection facility instead of a component of watershed-based hydrological system. The study focus is on the failure state of the reservoir flood water level and the peak streamflow. Other states, like the drought state of the low reservoir water level and low streamflow which is one of critical indicators for water resources management are not addressed in this work. This study attempts to view the reservoir as a component of watershed-based hydrologic and water resource management system, and integrate a watershed-based hydrologic model with a reservoir model to assess the performance of reservoir operation in a prairie region for a long term under the streamflow regime change caused by future climate change. The focus of the study is on understanding the water supply system structure and its dynamics. The paper first introduces the assessment methodology, then applies the methodology for a case study from North American prairie region, and finally ends with discussions and conclusions.

2 Methodology

The methodology developed by Simonovic and Li (2003) for assessing the long-term impact of climate change on an integrated urban flood protection system in the Red River Basin in Canada includes three steps: (1) development of the climate change scenarios; (2) modeling of the hydrologic processes; and (3) development and application of the system performance assessment model. In order to assess the impacts of climate change on long-term watershed water resources and reservoir operation performance, this study modifies the original methodology and integrates a watershed-based hydrologic model with a reservoir water dynamics model. The model links climate change scenarios to reservoir water resources assessment through hydrologic processes taking place in the watershed. This modified methodology for assessing long-term impacts of climate change includes three tasks: (1) extraction of climate data series from the climate change scenarios; (2) watershed-based hydrological and reservoir operation modeling; (3) reliability assessment of reservoir water resources under given reservoir operation rules. Climate change scenarios generate air temperature and precipitation data series, which are downscaled to use as input into the hydrologic model. The hydrological model then generates river discharges, which are used for assessing the reservoir operation performance. The demand is assumed to remain constant in order to focus on the main issues of the water supply system structure and its behaviour. One direction for future studies is to include in the model more detailed description of water demand.

2.1 Climate Change Scenarios Generation

There are different methods to generate climate scenarios, such as the paleoclimate analogue, the recent climate analogue and the general circulation modeling. The great development of Global Circulation Models (GCM) over the past 20 years has provided a tool for simulating past, current and future climate and the evolution of the atmosphere in response to external forcing mechanisms. Use of the data from multiple GCMs is able to diagnose uncertainty arising from climate model specification. Although most of GCMs use less than an hourly time step and save the results for every hour, daily air temperature and precipitation data series are not readily available for download from all scenarios by some GCMs, which brings a difficulty for a long-term daily-based comparison study. This study attempts to use different emission scenarios of the same GCM to test the uncertainty from boundary conditions specification. The Second Generation Coupled Global Climate Model (CGCM2; http://www.cccma.ec.gc.ca/models/cgcm2.html), developed at the Canadian Centre for Climate Modeling and Analysis (CCCma), British Columbia, Canada, was chosen to generate climate change scenarios with daily precipitation and temperature data. The CGCM2 is a fully coupled model, linking the atmosphere, ocean and land surface (Flato and Boer 2001). It divides the entire earth's surface as grid points, and each grid point has approximately $3.75^\circ \times 3.75^\circ$ size with ten vertical levels in the atmosphere and 29 vertical levels in the ocean. The model simulates the exchanges of energy and moisture among grid cells at an hourly time step. The CGCM2 produces output for 25 climatic variables including various measures of air temperature, pressure, wind speed, precipitation and humidity. A description of CGCM2 and a comparison of its response to increasing greenhouse-gas forcing can be found in Flato and Boer (2001). The model has been used to simulate both past climate (Kim et al. 2002) and future climate for the IPCC analyses out to 2100 (Flato and Boer 2001). The CGCM2 has more recently been run under a number of emissions scenarios taken from the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES; Nakicenovic et al. 2000) on the basis of various assumptions about technological development, fossil fuel use and social cohesiveness. Two scenarios (SRES A2 and SRES B2) were selected for assessing water resources and reservoir operation risk in this study because they are able to provide daily climate data series. The A2 scenario is a "business as usual scenario" which envisions population growth to 15 billion by the year 2100 and rather slow economic and technological development, while the B2 scenario is more optimistic and envisions slower population growth (10.4 billion by 2100) with a more rapidly evolving economy and stricter on environmental regulation. Therefore, the B2 produces lower emissions and less future warming than the A2 does. Detail discussion on climate change results from the A2 and B2 scenarios can be found in the IPCC Special Report on Emissions Scenarios and IPCC Fourth Advanced Report (IPCC 2007).

Since the resolution of CGCM2 is coarse and important mesoscale processes and surface features that control the regional precipitation are not addressed, a simple statistical downscaling method has been employed in this study. A local scaling method developed by Widmann et al. (2003) and (Salathé 2005) is used to downscale precipitation and temperature:

$$P_{ds}(x,t) = P_{mod}(x,t) * \frac{[P_{obs}]_{mon}}{[P_{mod}]_{mon}} \tag{1}$$

$$T_{ds}(x,t) = T_{mod}(x,t) + \{[T_{obs}]_{mon} - [T_{mod}]_{mon}\} \tag{2}$$

where $P_{ds}(x,t)$ and $T_{ds}(x,t)$ are the downscaled precipitation and temperature for the gridpoint containing a location x and at time t, $P_{mod}(x,t)$ and $T_{mod}(x,t)$ represent the simulated large-scale monthly-mean precipitation for the gridpoint containing a location x and at time t, $[P_{mod}]_{mon}$, $[P_{obs}]_{mon}$, $[T_{mod}]_{mon}$ and $[T_{obs}]_{mon}$ are the monthly mean taken over the fitting period (i.e. the overlap of the observed data set and the historic run of GCM).

2.2 Development of Watershed-based Hydrologic and Reservoir Water Dynamics Model

In order to reflect the dynamic characteristics of watershed-based water resources system, the System Dynamics, a feedback-based theory to study the relations between system structure and behaviour, is used to model watershed-based hydrologic behaviour and reservoir water dynamics. A feedback system with a closed-causal-loop structure brings results from its past actions of the system back to control its own future behaviour. A negative feedback loop in the system seeks a goal or brings the system to equilibrium, while a positive feedback loop generates a growth process which causes the system to diverge or move away from the goal or equilibrium. Based on the dynamic processes of the hydrologic cycle occurring in a watershed, Li and Simonovic (2002) developed a hydrological model using system dynamics approach to explore hydrological processes in the Red River Basin where the main contribution to flooding comes from the snowmelt. The model is able to generate much more accurate soil moisture storages of different layers and the overland flow on the basis of comparison with the data from the Penman method and Bowen ratio (Elshorbagy et al. 2005). Ahmad and Simonovic (2000) developed a reservoir operation model using system dynamics theory for assessing the flood damage under different reservoir management strategies. This study integrated the above two models together, and developed a new dynamic hypothesis which links the watershed hydrological structure, as well as the climate factors, to the streamflow generation and the change of water volume in the reservoir (Fig. 1). The purpose was to link the natural hydrological process with artificial man made system and evaluate the performance of the reservoir.

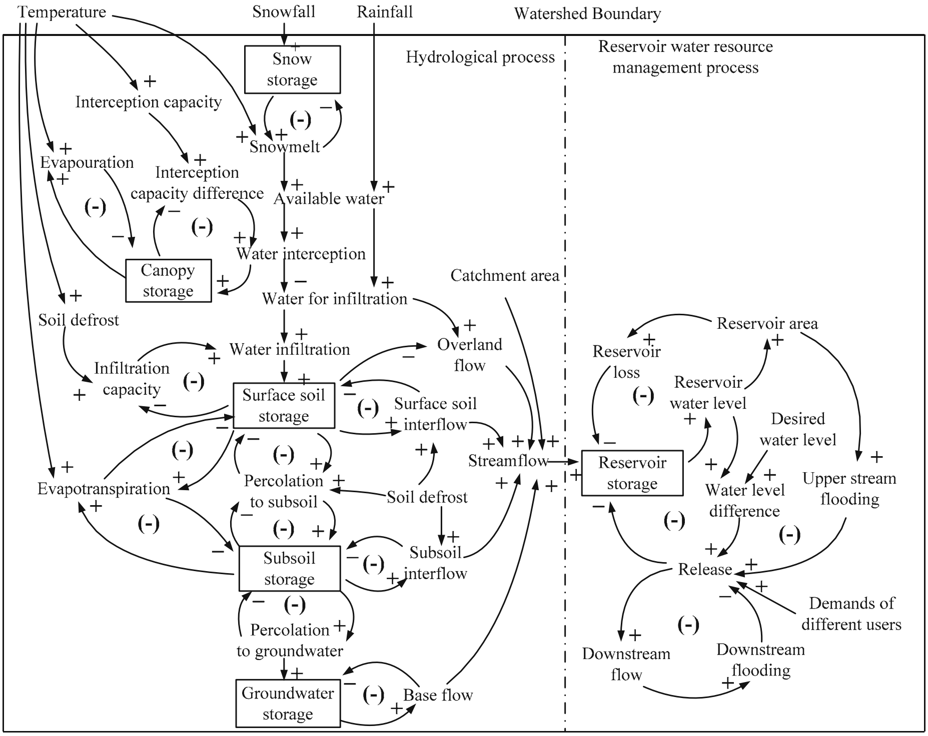

Fig. 1 Basic dynamic hypothesis for watershed-based hydrologic-reservoir water dynamics

The '+' and '−' signs used in Fig. 1, represent the positive or negative relationships between the first variable and the next one. Figure 1 indicates that the streamflow is determined by the interaction among climatic factors, vegetation interception, physical properties of soil (frozen or defrost), and soil moisture saturation. The snow is accumulated in the winter. Snowmelt water and/or rainfall in the spring will be partially intercepted by vegetation, and some infiltrated into the soil. Surplus water after interception and infiltration together with interflows from surface soil and subsoil, and baseflow from groundwater is routed as streamflow flowing into the reservoir. The water in the reservoir may be discharged to meet the demands of both different stakeholders and/or alleviation of drought or flood. The essential dynamics of streamflow generation is captured by a vertical water balance using five tanks representing snow, canopy, surface soil, subsoil and groundwater storage, while the change of reservoir water volume is determined by its inflow from streamflow and existing reservoir water storage as well as its outflows. Precipitations as snowfall or rainfall positively bring external water into the watershed hydrologic-reservoir system, while hydrological processes such as water interception, infiltration, percolation, evapotranspiration and release from reservoir, become negative feedback loops to control the moisture storage in canopy, surface soil, subsoil, groundwater and reservoir (Fig. 1). Since the hypothesis is designed to explain both the impact of canopy interception and soil physical state (frozen and defrost) on streamflow generation, and the reservoir water dynamics under reservoir operation, the main feedback loops linking states and processes can be identified as follows:

1. Water interception +> canopy storage −> interception capacity difference +> water interception
2. Water infiltration +> surface soil storage −> infiltration capacity +>water infiltration
3. Surface soil storage +> percolation to subsoil −> surface soil storage
4. Surface soil storage +> surface soil interflow −> surface soil storage
5. Percolation to subsoil +> subsoil storage −> percolation to subsoil
6. Subsoil storage +> subsoil interflow −> subsoil storage
7. Reservoir storage +> reservoir water level +> reservoir area +> upper stream flooding +> release −> reservoir storage
8. Release +> downstream flow +> downstream flooding −> release
9. Reservoir storage +> reservoir water level +> water level difference +> release −> Reservoir storage

Loop 1 shows that water interception by canopy increases water in the canopy storage, which reduces the interception capacity, and finally limits water interception rate. Loop 2 describes the source of water for surface soil storage through water infiltration process, while loops 3 to 6 explain the water loss through the processes of soil interflow and percolation of water from surface soil storage to the subsoil storage. Loops 3 to 6 are influenced by the soil water content and strongly regulated by air temperature during snowmelt active periods. Frozen surface soil limits water infiltration rate and water availability for percolation and interflow. The streamflow is routed from overland flow, interflows from surface soil and subsoil, and baseflow flows into the reservoir. Loops 7 to 9 are three negative feedback loops to control the water storage in the reservoir. Above dynamic hypothesis shows that the rainfall and the snowmelt are the most important external water sources affecting the water balance between the soil layers and the groundwater storage, while reservoir water dynamics is dependent upon watershed streamflow and water release under reservoir operational rules. On the mass conservative balance, an integration of watershed hydrological model (Li and Simonovic 2002) and reservoir water management model (Ahmad and Simonovic 2000) can be mathematically expressed as follows:

$$\frac{\mathrm{d}S1}{\mathrm{d}t} = P_{\mathrm{SF}} - R_{\mathrm{SM}} \tag{3}$$

$$\frac{\mathrm{d}S2}{\mathrm{d}t} = R_{\mathrm{CI}} - R_{\mathrm{EC}} \tag{4}$$

$$\frac{\mathrm{d}S3}{\mathrm{d}t} = R_{\mathrm{I}} - R_{\mathrm{E1}} - R_{\mathrm{F1}} - R_{\mathrm{P1}} \tag{5}$$

$$\frac{\mathrm{d}S4}{\mathrm{d}t} = R_{\mathrm{P1}} - R_{\mathrm{E2}} - R_{\mathrm{F2}} - R_{\mathrm{P2}} \tag{6}$$

$$\frac{dS5}{dt} = R_{P2} - R_{BF} \tag{7}$$

$$\frac{dSR}{dt} = Q - R_{out} - R_{loss} \tag{8}$$

$$R_{of} = (R_{SM} + P_r) - R_{CI} - R_I \tag{9}$$

$$R = R_{of} + R_{F1} + R_{F2} + R_{BF} \tag{10}$$

$$Q = \text{SMTH3}\,(R * A, t_d, Q_i) * r \tag{11}$$

where S1, S2, S3, S4 and S5 represent the water storages (cm) in snowpack, canopy, upper soil layer, subsoil layer and groundwater, respectively; P_{SF} is precipitation water (cm/day) in term of the snowfall; R_{SM} is snowmelt water (cm/day); R_{CI}stands for canopy interception rate (cm/day); R_{EC}, R_{E1} and R_{E2} are water losses (cm/day) due to evaporation in canopy and evapo-transpiration in upper soil and subsoil layers; R_I is the rate of upper soil infiltration (cm/day); R_{F1} and R_{F2} are interflow rate (cm/day) in upper soil and subsoil layers; R_{P1} and R_{P2} are percolation rate (cm/day) in upper soil and subsoil layers; R_{BF} stands for baseflow (cm/day); R_{of} (cm/day) is the overland flow; P_r is precipitation water (cm/day) in term of the rainfall; R (cm/day) is total water available for routing as streamflow; Q (m^3/s) is the streamflow responding to R with a travel time delay in which a third-order exponential smooth function (High Performance Systems 1997) is used; A is catchment drainage area (km^2); r is unit conversion coefficient; t_d represents average delay time (day) and Q_i stands for initial streamflow (cm km^2/day); SR is the water storage in the reservoir (m^3); R_{loss} is water loss rate due to evaporation and leakage from reservoir (m^3/day) and R_{out} is flow-out rate from reservoir (m^3/day).

The calculations for the hydrological flow rates among the stocks are based on Li and Simonovic (2002), while reservoir water release and evaporation loss rates for the selected reservoir are calculated on the basis of Ahmad and Simonovic (2000). Interception capacity by canopy is subject to seasonal change of vegetation. Vegetation growth within a year is for biomass to accumulate in time and space until achieving maximum biomass and cover which is consistent with the local physical environment (Gutierrez and Fey 1980). Vegetation increases exponentially during spring as accumulation of active temperature (>0°C) increase, then reaches its maximum value and eventually decreases as the growth rate approaches zero (Li and Simonovic 2002). During soil frozen season, infiltration rate and surface storage capacity depend on the soil physical conditions which are affected by the period of time during which the air temperature remains above and below the active temperature (Li and Simonovic 2002). This phenomenon results in exponential soil defrosting and refreezing processes with accumulation of active air temperature. The soil refreezes again if air temperature drops below 0°C for a number of days. The active temperature accumulation will be lost and starts again from zero. Accordingly, the influence of active temperature accumulation on the canopy size and soil physical state can be written as (Li and Simonovic 2002):

$$C_{tc} = \begin{cases} \left[\left(\sum T\right)/T_{C\max}\right]^{c_c} & \text{if} \quad \sum T < T_{C\max} \\ 1 & \text{if} \quad \sum T \geq T_{C\max} \end{cases} \tag{12}$$

$$C_{ti} = \begin{cases} \left(T_I/T_{I\max}\right)^{c_i} & \text{if} \quad T_I < T_{I\max} \\ 1 & \text{if} \quad T_I \geq T_{I\max} \end{cases} \tag{13}$$

$$T_I = \begin{cases} \sum T & \text{if} \quad T > 0 \quad \text{and } N < N_n \\ 0 & \text{if} \quad N \geq N_n \end{cases} \tag{14}$$

$$N = \begin{cases} \sum N_0 & \text{if} \quad T < 0 \\ 0 & \text{if} \quad T \geq 0 \end{cases} \tag{15}$$

$$N_0 = \begin{cases} 1 & \text{if} \quad T < 0 \\ 0 & \text{if} \quad T \geq 0 \end{cases} \tag{16}$$

where C_{tc} and C_{ti} are the influence of air temperature on the canopy size and soil physical state (dimensionless), c_c is an exponential coefficient of active air temperature accumulation on the canopy growth, and $T_{C\max}$ is the maximum active air temperature accumulation point at which canopy storage reaches maximum, $T_{I\max}$ is a maximum T_I point at which surface soil is fully defrosted (°C), c_i is an exponent for describing the influence of T_I on soil defrosting (dimensionless), N is the number of continuous days with air temperature below active point (days), N_n is a maximum N after which T_I will be lost and surface soil will refreeze again, and N_0 is a logical variable to identify the day in which air temperature is higher or lower than the active air temperature.

2.3 Water Resources Assessment

The purposes of reservoir operation are to match the various demands on water from flood control, recreation and water supply for residential life and industrial production. As the water demand will be changed mainly due to exogenous factors, such as the increase of the population, economic growth and policies, in the meanwhile, the main objective of this study is to investigate the potential impact of climate change on water resources availability under existing reservoir operation rules. As a result, the water demand is assumed to be constant over the years to make the study focus on the examination of the supply performance. A reliability criterion is commonly used to assess reservoir system performance in water resource practice (Hashimoto et al. 1982; Klemes 1985; Burn and Simonovic 1996). Reliability (R) is defined as the probability of success:

$$R = \text{Prob}\,(S) \tag{17}$$

S is defined in various ways for the different reservoir purposes, but generally corresponds to matching desired demands. The practice form of the reliability measure used in this study is given as the probability of the reservoir being in a reference state and defined as:

$$R = \frac{1}{T}\sum_{t=1}^{T} z_t \tag{18a}$$

$$z_t = 1 \quad \forall z_t \in S \tag{18b}$$

$$z_t = 0 \quad \forall z_t \in F \tag{18c}$$

where R is the reliability for a state, $z_{t,}$; z_t represents the state of the reservoir system in the time interval t; S stands for the satisfactory state; F is the failure state; and T is the duration of operating period (day). For the purpose of reservoir system performance assessment, the daily reliability (within a year), R_{d}, and the total reliability (calculated over the simulation horizon of 100 years), R_t, are calculated. R_{d} is calculated using T as the total number of days of a year (day), while R_t is calculated using T as the total number of days within the simulation period of 100 years (day).

2.4 Model Implementation and Calibration

The two climate change scenarios were based on A2 and B2 emission scenarios, with daily precipitation and air temperature data extracted from the CGCM2 for watershed-based hydrologic and reservoir modeling. The watershed-based hydrologic and reservoir model was developed and implemented using the STELLA II development tool (High Performance Systems 1997). STELLA II provides a modeling environment for defining the objects and the functional relationships by using the basic building blocks including stocks, flows, converters and connectors. Stocks are used to represent storage, which can be changed with flows. Flows are defined and regulated by converters. Converters are used to store algebraic relationships, define external input to the model and hold values for constants. Connectors indicate the cause–effect relations among the model elements. The model is represented by differential and difference equations that can be solved with either Euler's or Runge–Kutta method.

The calibration process of the model includes the determination of model parameters and initial values for all state variables. Input data set for the hydrological model used includes all calibrated parameters, daily air temperature series, daily precipitation and a set of initial values for the state variables. Parameters are selected from a range of feasible reference values, then tested in the model. Original hydrological model was designed to simulate the streamflow generation and flood events in the snowmelt-dominated river basins. Therefore, the major parameters related to the temperature impacts, such as degree-day factor for snowmelt (α), maximum active temperature accumulation for canopy capacity (T_{Cmax}) and soil defrosting (T_{Imax}), exponential coefficient of active temperature accumulation on the canopy growth (C_{c}) and soil defrosting (C_{i}), maximum canopy interception capacity (C_{max}) etc., were changed during the calibration process. In order to deal with change in multiple parameters, the sensitivity analysis has been used to guide the selection of parameters during calibration, i.e. starting with most sensitive parameter, and following with less sensitive parameters later. Parameter adjustment process continues until satisfactory agreement is obtained between the predicted and the observed values. The model has been calibrated and verified for the hydrological year of 1979 and 1995 from the Upper Assiniboine River Basin, Saskatchewan and Manitoba of Canada, and in 1996 and 1997 from the Red River Basin, shared by Canada and the USA (Li and Simonovic 2002). The upper Assiniboine river flows to north-eastern direction with a relative small catchment area, so it was lumped into one catchment. Since the catchment area of the Red River Basin flows from south to north with a very large catchment area, a division into three sub-catchments was made, i.e. the upper reach, middle reach and lower reach, and simulated and measured river discharge series at Grand Forks, Emerson and Ste Agathe were compared. The results show that the simulated streamflow reflects the variation in air temperature and precipitation as well as the moisture interaction between the surface soil, subsoil and the groundwater storages. Sensitivity analysis indicates that parameters related to the surface soil storage and the temperature are not sensitive to the selected-parameter variations with ±10%, while the statistical comparison using coefficient of efficiency, coefficient of determination and square of the residual mass curve coefficient reveals that the simulation error is unsystematic and random, and the model can well reproduce the observed flood starting time, peak and the flood duration (Li and Simonovic 2002). The model was also successfully applied to simulate the soil moisture storages of different layers and the overland flow in Alberta watersheds by Elshorbagy et al. (2005), and to assess the sensitivity of complex flood protection system to future climate change in the Red River Basin by Simonovic and Li (2004). The main output includes simulated discharge series at the reservoir which is fed to calculate reservoir storage and release. The reservoir water dynamics model was quantitatively calibrated and tested by Ahmad and Simonovic (2000) on the basis of the operation rules to control water outflow from the reservoir.

3 Application of Watershed-Based Hydrologic and Reservoir Water Dynamics Model

3.1 Description of the Study Area

The Upper Assiniboine River Basin and Shellmouth reservoir in prairie Canada are taken as a case study (Fig. 2). The Assiniboine River originates out of the Porcupine Hills, northwest of Preeceville in eastern Saskatchewan. A major tributary, the Whitesand River, rises out of the Beaver Hills, northwest of Yorkton and joins the Assiniboine River at the town of Kamsack. The River drains the area from eastern part of Saskatchewan to the western part of Manitoba, and meets the Qu'Appelle River approximately 70 km downstream from Shellmouth Dam. The Basin has a drainage area of 21,000 km^2, of which 79% is located in Saskatchewan. Topographically, the Assiniboine River basin undulates gently to moderately with higher relief evident in the Northeast portion. Climatologically, the basin is continental sub-humid characterized by long, cold winter and short, warm summer. Based on the climate data for the ecoregions within the Upper Assiniboine River Watershed study area, mean annual precipitation ranges from 440 to 500 mm, 27% of which is snow, while mean annual temperature ranges from 0.6°C to 2.8°C (Smith et al. 1998). The

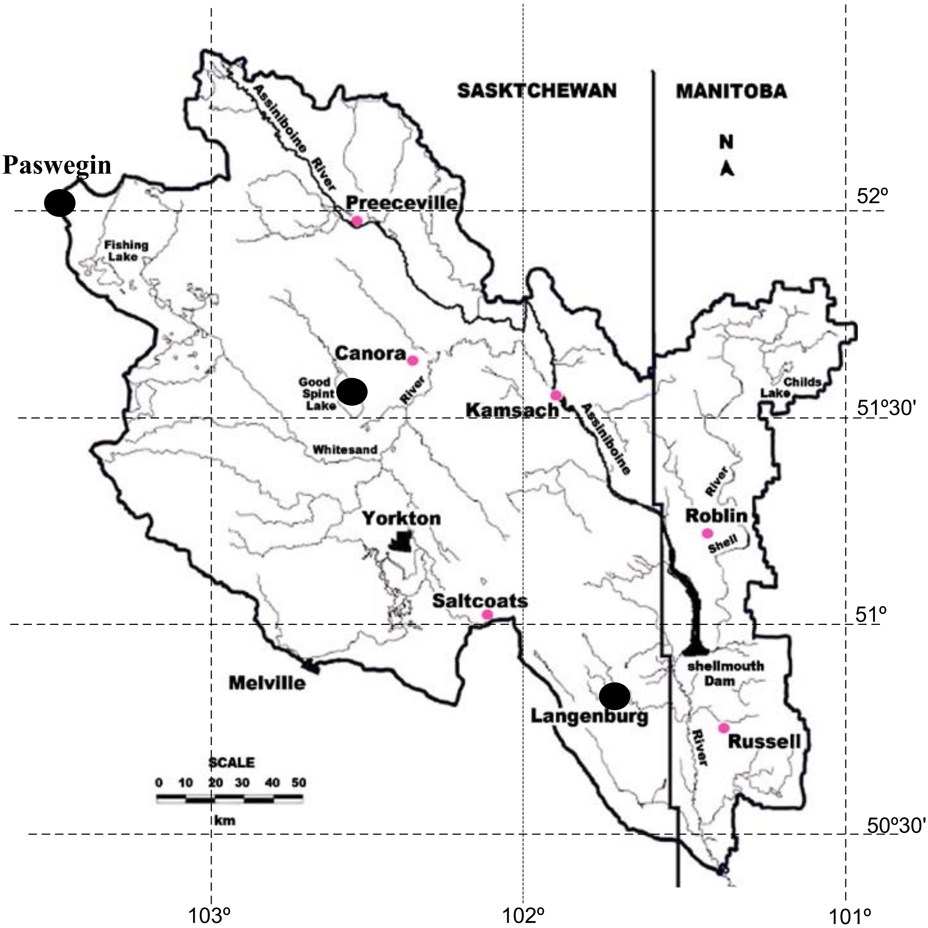

Fig. 2 Study area and location

frost-free season varies from 90–110 days. The streamflow in the basin is highly variable on daily basis. During spring, water levels on the Assiniboine River reach peak due to snowmelt, and rapidly decline to a base level. About 63% of annual total flow is contributed by the mouths of April and May, while only 3% by December to March.

The Shellmouth Dam created in 1970 is approximately 1,319 m long and 19.8 m high with earth-fill embankment. A gated concrete conduit with discharge capacity of 198.2 m^3/s on the east abutment and a concrete chute spillway on the west abutment control water outflows from the dam (Water Resources Branch 1992). The reservoir is 56 km in length, 1.28 km in average width and covers a surface area of 61 km^2 when it is full. The elevation of top of the dam is 435 m above mean sea level with a dead storage elevation of 417 m. The minimum water level controlled by the conduit is 422.5 m. The spillway crest elevation is 12.32 m higher, at 429.32 m. The volume of inactive pool below the conduit invert elevation is 12.3×10^6 m^3. The difference between volume of reservoir at active storage (370×10^6 m^3) and crest level of natural spillway (477×10^6 m^3) is flood storage capacity of reservoir, i.e. 107×10^6 m^3. Current operating rules specify that the reservoir should be brought to 185×10^6 m^3 at about water level 423.98 m by March 31 to accommodate floods and a reservoir volume of 370×10^6 m^3 at about 427.5 m is a goal during the summer months. Maximum reservoir outflows from the conduit and spillway are limited to 42.5 m^3/s to prevent flooding downstream and the outflow must be greater than 0.71 m^3/s to avoid damage to fish and aquatic life in the river system (Water Resources Branch 1995).

3.2 Results

3.2.1 Climate Data Series from CGCM2

Daily air temperature and precipitation data series generated by CGCM2 by the year 2100 are used to represent climate variability and change and to predict streamflow values at Shellmouth reservoir. Since the spatial grid size of the CCC GCM2 was 3.75° × 3.75°, whole basin is located within a CCC GCM2 grid (Fig. 2). Climate data series were extracted from one grid point located at approximately 101.25° W, 50.10° N for the Assiniboine River basin. Average precipitation and temperature from three meteorological Stations within or near to the basin, including Paswegin, Good Spirit Lake and Langenburg (Fig. 2), were selected for downscaling purposes. The period 1966–2000 is used for fitting the downscaling method. The downscaled precipitation and temperature were fed into hydrological model for simulation.

Figure 3 shows the trend of simulated annual air temperature and precipitation from two climate scenarios of CGCM2 for simulation period. The results indicate that annual mean air temperature varies over time, but it tends to increase in two

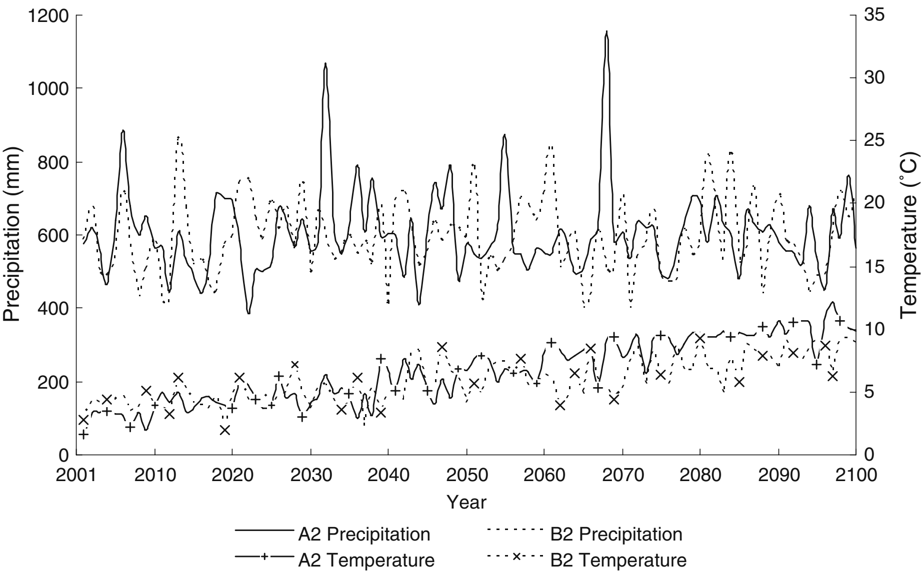

Fig. 3 The trend of annual precipitation and mean temperature from CGCM2 A2 and B2

scenarios toward the year 2100. The comparison shows that scenario A2 generates higher annual average air temperature than scenario B2 does (Fig. 3). Average daily air temperature from simulation years reaches 6.6°C in scenario A2 and 5.8°C in scenario B2, which are 5.3°C and 4.5°C higher than the average historical daily air temperature (1.3°C) observed at selected three meteorological Stations within or near to the basin. Figure 4 compares the average monthly air temperature calculated from 100 years of simulated data. The result shows that climate scenario based on A2 generates higher spring air temperature than climate scenario based on B2. Average daily air temperature from February to May in scenario A2 and B2 are 5.7°C and 1.1°C higher than the average historical daily air temperature in the same period. Higher air temperature in early spring influences snowmelt timing and annual streamflow patterns.

Simulated annual precipitations from two scenarios vary over time, but they exceed the historical average (471.5 mm) with a range from 140 mm in 1961 to 550 mm in 1981 (Fig. 3). The average annual precipitations over the 100-years simulation horizon generated from emission scenarios A2 and B2 are 605 mm and 588 mm, respectively. Annual precipitation ranges from 385 mm to 1158 mm in scenario A2 and from 405 mm to 858 mm in scenario B2. Historical extreme daily precipitation observed is 128.4 mm at Cote station in 1982, while simulated extreme daily precipitations from scenario A2 and B2 are 92 and 132 mm, respectively. The results show that the global warming will bring more precipitation to this region, and that emission scenario A2 will generate more annual precipitation.

3.2.2 The Assessment of Water Resources and Reservoir Operation

Streamflow Series A long-term assessment of streamflow includes streamflow pattern within each year and annual streamflow generated by two climate scenarios. Figure 5 presents the simulated daily streamflow series at Shellmouth hydrological station on the Assiniboine river at the entrance into the reservoir under two climate change scenarios. The results show little difference in peak streamflow magnitude

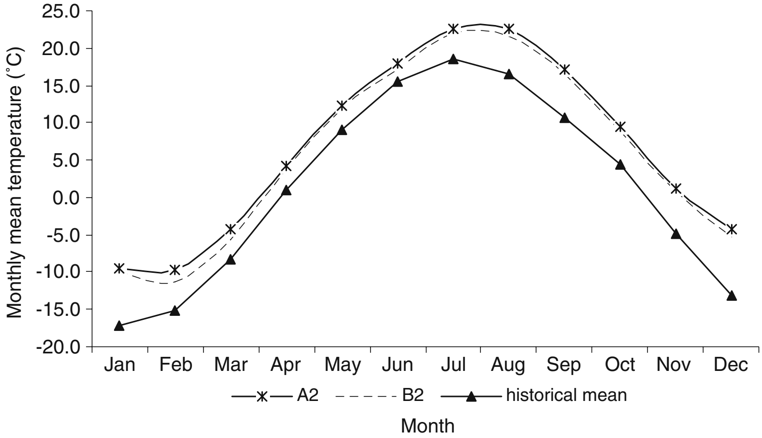

Fig. 4 Comparison of simulated mean monthly temperature by CGCM2 scenarios A2 and B2 with historical records

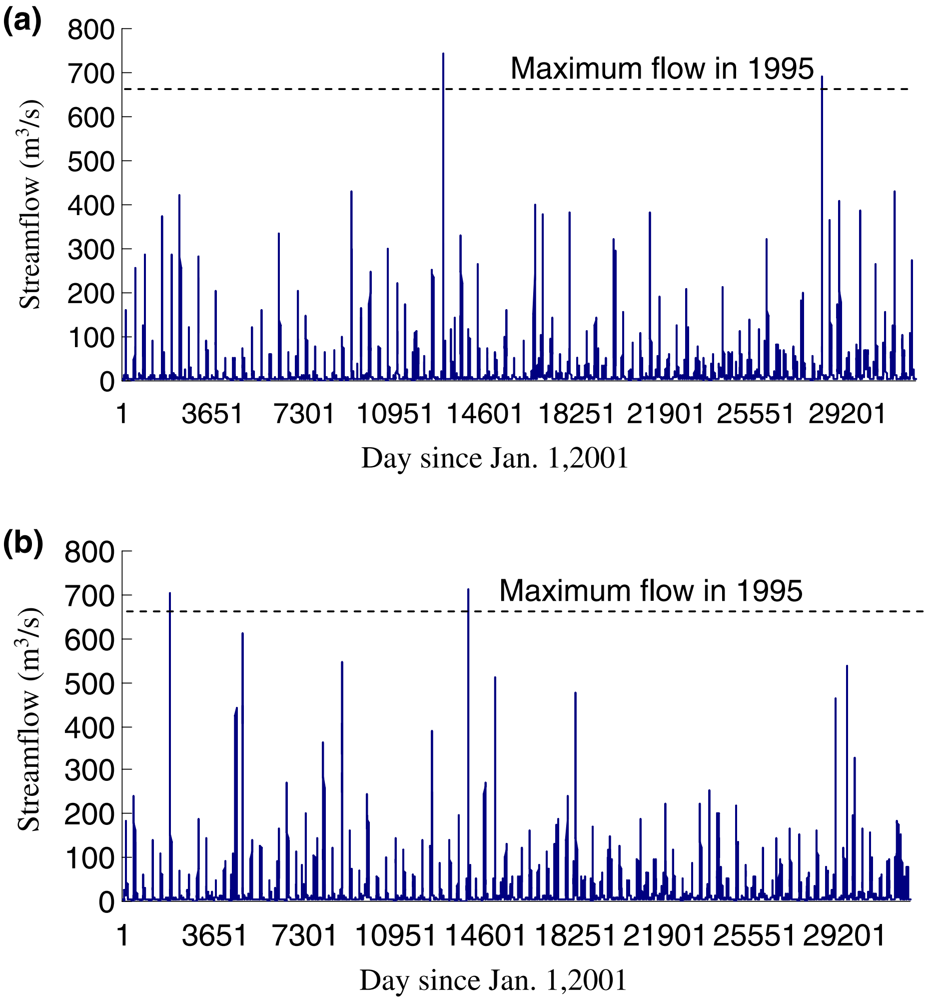

Fig. 5 Comparison of simulated streamflow at Shellmouth hydrological station from CGCM2 scenarios A2 and B2. **a** Simulated streamflow at Shellmouth hydrological station from the emission scenario A2. **b** Simulated streamflow at Shellmouth hydrological station from the emission scenario B2

between two scenarios when the peak values are less than 100 m^3/s, but there exists a clear difference in the cases when the peak values are greater than 100 m^3/s (Table 1). Scenario B2 generates more years with the peak values from 100 to 200 m^3/s than

Table 1 Distribution of simulated peak flows for next 100 years (%)

Scenarios	Peak flow ranges (m^3/s)					
	<100	100–200	200–300	300–400	>400	>1,995 peak flow
A2	34	28	17	14	7	2
B2	33	41	12	3	11	2

scenarios A2 does. In the cases with higher peak streamflows, in 38% instances stream flow generated in scenario A2 is greater than 200 m^3/s, while it is only 26% higher in scenario B2. Results also demonstrate that both scenarios A2 and B2 will twice generate peak streamflows greater than historical record with 661 m^3/s in 1995. The highest peak streamflows generated from two scenarios are 745.1 m^3/s in scenario A2 and 713.0 m^3/s in scenario B2. The results show that climate change may more frequently result in peak streamflows greater than historical record.

Annual total streamflow values generated from two scenarios are shown in Fig. 6. Annual total streamflow values vary over years, but around 80% of annual total streamflow values from scenario A2 and scenario B2 during simulation period are greater than historical average. Simulation results show that incidences of total annual streamflow values greater than historical record in 1995 occur twice in each scenario during simulation period, and minimum total annual streamflow values simulated from scenario A2 and scenario B2 will not be lower than the historical record in 1989. The result also demonstrates that scenario A2 generates more total annual streamflow than scenario B2 does. The maximum, minimum and mean annual streamflow values generated by the scenario A2 are 4.1%, 7.8% and 6.8% higher than those generated by scenario B2, respectively. Mean annual streamflow values from scenarios A2 and B2 are mainly contributed by the mouths of April and May with 54.5% and 55.7%, respectively, but they are less than the historical contribution of about 63% in the same period (Fig. 7). Meanwhile, streamflow values from December to March under two scenarios reach to 10.3% and 7.8%, respectively, which are higher than historical share with about 3% in the same period. This change is mainly caused by higher mean air temperature in spring from future climate change scenarios. Higher air temperature in spring results in two phenomena: more precipitation, and earlier snowmelt. Both phenomena will directly or indirectly contribute to an increase in streamflow in the spring. The results indicate that climate

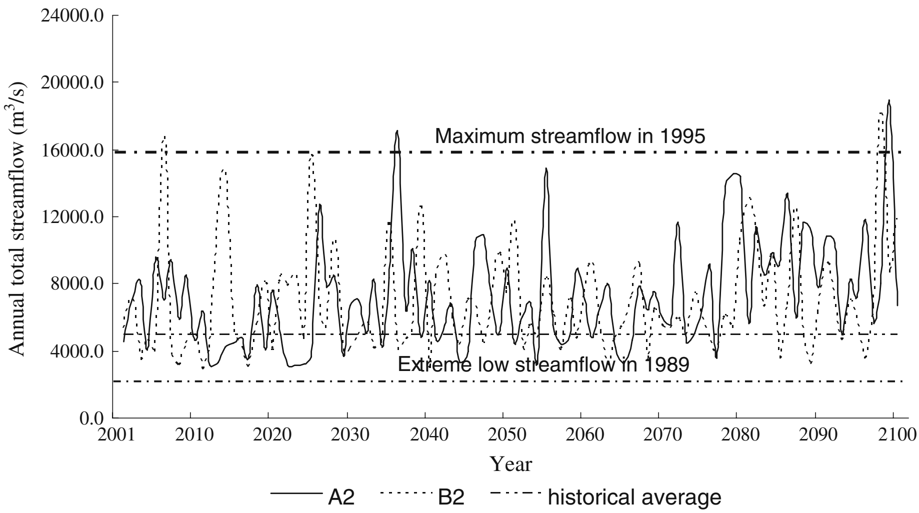

Fig. 6 Comparison of simulated streamflow at Shellmouth hydrological station from CGCM2 scenarios A2 and B2

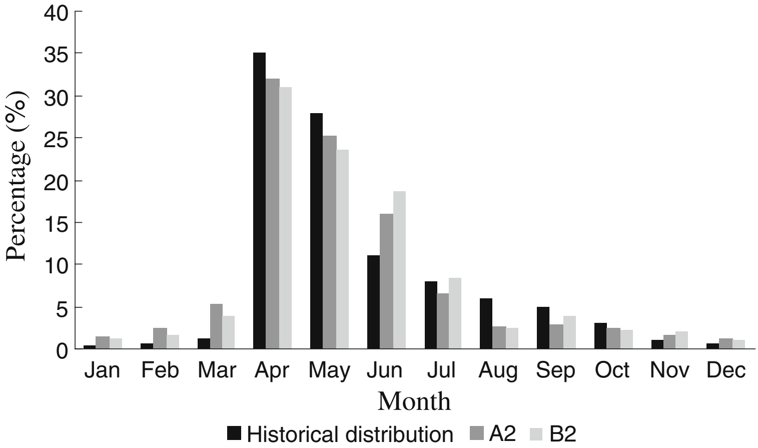

Fig. 7 Monthly percentage of simulated annual streamflow at Shellmouth hydrological station from emission scenarios A2 and B2

change not only influence the annual total streamflow values, also change its monthly distribution pattern within a year. The information provides an important base for reasonable allocation of water resources within a year and between years.

Reliability of Reservoir Operation: Water Resources and Flood Since the Shellmouth Dam created in 1970, only one severe flood in 1995 and one extreme low flow period in 1989 took place. The reservoir performed well for protecting the water system during those two events. This study concentrates on the impact of future climate change on the performance of the Shellmouth Reservoir as operated for seasonal water allocation and flood control under current operational rules. Water levels in the reservoir are applied to measure the satisfactions of reservoir operations. The reference criteria used to address the water resource state are based on the reservoir winter target level (423.98 m), summer target level (427.50 m) and spillway crest level (429.32 m), and classified as four status: scarcity (water level less than winter target at 423.98 m), normal (water level between winter target at 423.98 m and summer target at 427.50 m), abundance (water level greater than summer target at 427.50 m, but less than spillway crest level at 429.32 m), and flood (water level greater than spillway crest level at 429.32 m).

Figure 8 shows the probabilities of water resource status at the Shellmouth reservoir and their distribution for each year during simulation years under two climate change scenarios. The plots shown in Fig. 8 highlight that the variability in the reservoir performance can be expected under the two scenarios applied. The reservoir water level stays between normal and abundance level in the most simulation years under two scenarios conditions. The most of scarcity incidents take place in first half simulation period, while few occur in the last 50 simulation years. Reservoir water level also reaches the spillway crest level in some simulation years. A comparison of reservoir operation performance from two scenarios demonstrates that scenarios A2 generates higher abundance and flooding possibilities as well as fewer scarcity possibilities than B2 does. There are 31 years in which reservoir water level generated from scenarios A2 can reach flood level, but only 21 years

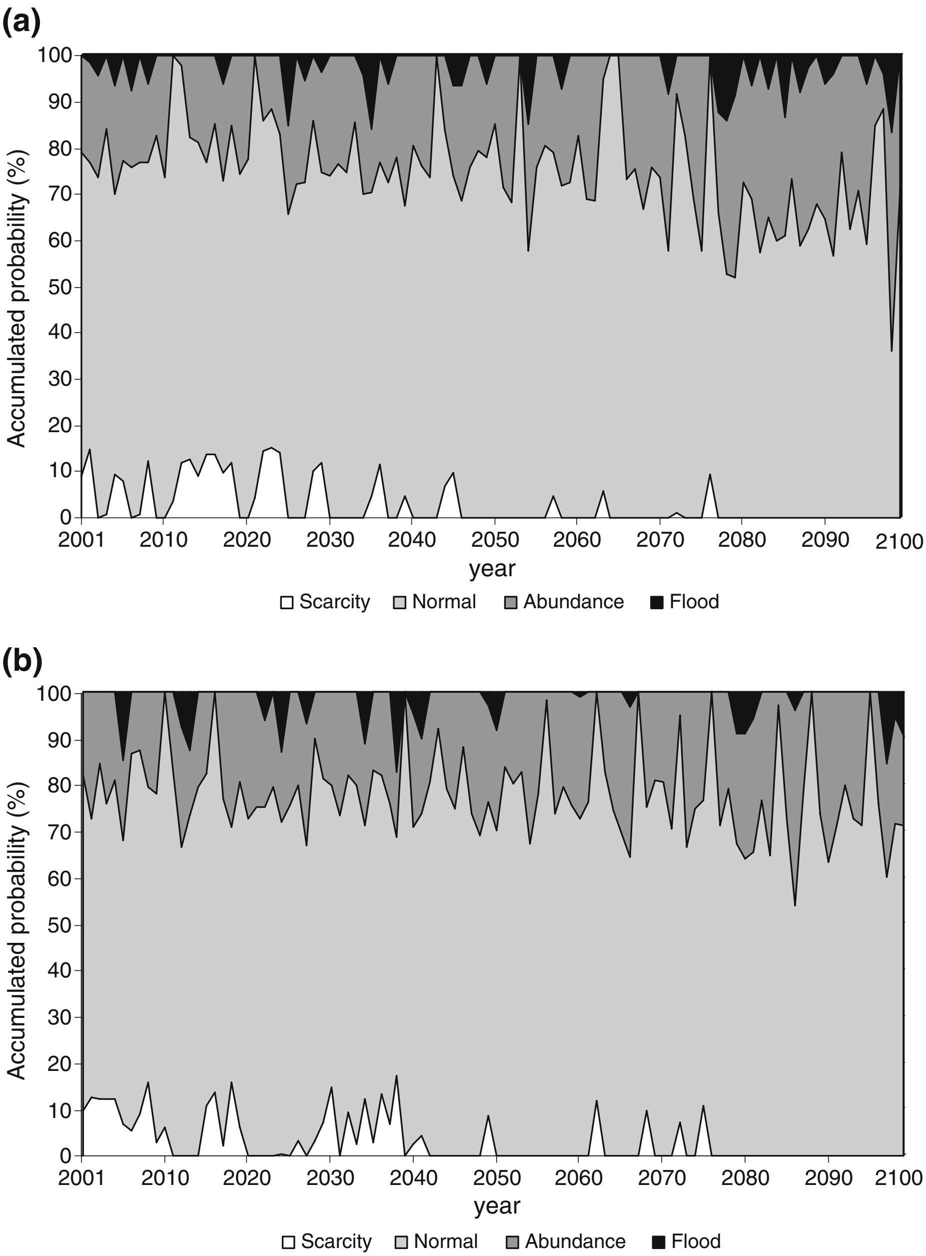

Fig. 8 Annual accumulated probability distribution of water resources under CGCM2 scenarios A2 and B2. **a** Annual accumulated probability distribution under the emission scenario A2. **b** Annual accumulated probability distribution under the emission scenario B2

from scenario B2. On the other hand, compared to 35 scarcity years under scenario B2 conditions, only 30 scarcity years take place under scenario A2 conditions. Meanwhile, a wider variance of abundance and flooding possibilities also can be observed from scenario A2, especially in last decades of simulation period. This trend is consistent to peak streamflows and annual total streamflows discussed in "Streamflow Series" in Section 3.2.2.

As discussed above, reliability measures are designed to assess the ability of the reservoir for drought protection and flood control through seasonal water allocation. For the purpose of differentiation from scarcity and flood, the probabilities of normal and abundance are added together for calculating water secure reliability because normal water level represents the recreation demand in summer and abundance water level strands for flood water storage during raining seasons. A quantitative comparison of summary statistics for reservoir operation performance from two scenarios is shown in Table 2. The information in Table 2 reveals that the reservoir is highly reliable for the simulation period with an average reliability from 94.91% to 98.26% for different purposes under two climate change scenarios. The highest reliabilities are associated with flood control and scarcity protection, while the lowest ones are related to the satisfaction of secure water level. The high reliability for flood control and scarcity protection reflects the fact that the reservoir was initially designed to protect the reaches of reservoir downstream from flooding and drought through reasonable seasonal water allocation, and the priority of the current reservoir operation policy is also based on this purpose. The low water secure reliability may not be so critical because it may just reduce the possibilities for human recreation, but will not influence water supply for the downstream users. Compared to scenario B2, scenario A2 generates higher reliability for drought protection and less reliability for flood control and recreation under current reservoir operation rules. Higher annual total streamflow from scenario A2 is responsible for these results. However, the range of reliability from scenario B2 is greater than that from scenario A2.

According to the information shown in Fig. 8 and Table 2, a high variability in water resource reliability can be expected under both climate change scenarios. However, scenarios generate a very similar trend, i.e. scarcity probability declines and normal and abundance probability increases, which means reliability for protecting drought increases. The result occurs due to an increase in annual total streamflow as a response to climate change scenarios in last simulation decades. The result brings some potential room for re-evaluating the current operating rules for this system. Potential benefits may be obtained from reducing the current high priority on drought protection and increasing the priority on water secure aspects, such as water supply and recreational purposes, because occurrence frequency of scarcity conditions are expected less under future climate change conditions. This adjustment may reduce the range of water secure reliability, and finally increase water secure reliability.

Table 2 Summary of reservoir reliability measures (%)

Scenarios	Scarcity		Secure		Flooding	
	A2	B2	A2	B2	A2	B2
Mean	97.34	96.95	94.91	95.21	97.57	98.26
Standard deviation	4.71	4.96	5.95	6.45	4.28	3.93
Max	100.00	100.00	100.00	100.00	100.00	100.00
Min	84.93	82.74	79.73	65.75	83.29	83.01

4 Discussions and Conclusions

Decisions regarding reservoir operations are especially important for seasonally balanced water supplies and the protection of reservoir downstream from drought or flooding in the North American prairie where snow accumulation and snowmelt act as an important water source for streamflow generation. Global warming may bring a more uncertain change in air temperature and precipitation which seriously influence the hydrological processes and water supply. In order to investigate the potential impact of climate change on the hydrological processes and water resources in the region, this study applies system dynamics as an effective methodology to organize and integrate existing information available on climate change scenarios, watershed hydrologic processes, reservoir operation and water resource assessment system. As a result, demand is assumed to remain constant for the next 100 years. The global climate model CGCM2 is applied to generate the climate change scenarios showing a clear picture of climate change in a large scale with daily climate change data series for hydrologic modeling. Watershed-based hydrologic and water volume dynamics modeling focus on the dynamics process of both streamflow formation within the watershed driven by climatic parameters, and the reservoir water volume change under reservoir operation rules. The selected hydrologic model explains the interactions among the surface and subsurface storage, and reflects the phenomena of dynamic change in vegetation canopy and soil physical state as active temperature changes in the winter as well as the contribution of snowpack accumulation and snowmelt to streamflow. The reservoir water volume dynamics modeling follows the reservoir operation rules which are based on the demands from the different stakeholders. The reliability measure describes the effectiveness of present reservoir operation rules to meet the demands on drought protection, water security and flood control. The results indicate that fast global population growth with rather slow economic and technological development may accelerate an increase in the temperature in the prairie region, which may bring more high-peak-streamflow occurrences and more water resources in terms of annual total streamflow in the region. Reliability assessment demonstrates that current reservoir operation rules can provide a high reliability in drought protection and flood control for the reservoir downstream under two selected climate change scenarios. More water resources from climate variation and change imply a shifting of current high priority of reservoir operating rules from drought protection to water secure aspects. Different stakeholder may benefit more from this priority adjustment.

Watershed-based hydrological-reservoir water dynamics model focuses on long-term impact of climate change on water resources reliability. It provides a bridge to link the climate change to watershed water resources assessment. Future studies may extend the model to reflect the spatial variation of climate and watershed soil and topographic characteristics for the purpose of increasing the model's predicting ability. In order to reduce the risk from future flood events, it is also recommended to study the performance of current reservoir operation rules in terms of vulnerability and resiliency. Also, assumption of the constant demand for the continuous 100 years can be released to generate more realistic scenarios. One of the limitations of the system dynamics is the limitation in the spatial analysis. A spatial system dynamics will improve the model's ability to predict future drought and flood events.

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