Water Resources Management **18:** 89–110, 2004.

Sensitivity of the Red River Basin Flood Protection System to Climate Variability and Change

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(Received: 16 September 2002; in final form: 8 October 2003)

Abstract. An original modeling framework for assessment of climate variation and change impacts on the performance of complex flood protection system has been implemented in the evaluation of the impact of climate variability and change on the reliability, vulnerability and resiliency of the Red River Basin flood protection system (Manitoba, Canada). The modeling framework allows for an evaluation of different climate change scenarios generated by the global climate models. Temperature and precipitation are used as the main factors affecting flood flow generation. System dynamics modeling approach proved to be of great value in the development of system performance assessment model. The most important impact of climate variability and change on hydrologic processes is reflected in the change of flood patterns: flood starting time, peak value and timing. The results show increase in the annual precipitation and the annual streamflow volume in the Red River basin under the future climate change scenarios. Most of the floods generated using three different climate models had an earlier starting time and peak time. The assessment of the performance of Red River flood protection system is based on the flood flows, the capacity of flood control structures and failure flow levels at different locations in the basin. In the Assiniboine River Basin, higher reliabilities at downstream locations are obtained indicating that Shellmouth reservoir plays an important role in reducing downstream flooding. However, a different trend was identified in the Red River Basin. The study results show that flood protection capacity of the Red River infrastructure is sufficient under low reliability criteria but may not be sufficient under high reliability criteria.

Key words: climate change impacts, flood protection system, reliability

1. Introduction

Climate variability and change may alter hydrologic conditions and result in a variety of possible impacts on water resource systems. Those potential impacts may include changes in the availability of water supply (Revelle and Waggoner, 1983), runoff production (Lettenmaier and Gan, 1990), the timing of hydrologic events (Lettenmaier and Gan, 1990; Burn, 1994), and the frequency and severity of floods (Hurd *et al.*, 1999). Increased annual precipitation could produce a large increase in annual runoff and a greater and more intense freshet spring runoff in Northern Canada (Singh, 1988). Therefore, serious consequences may be expected in the ability of existing large-scale flood protection systems to serve their function (Klemes, 1985; Burn and Simonovic, 1996). Red and Assiniboine Rivers in Manitoba are the two main rivers flowing through the City of Winnipeg. Floods in both river basins often occur in the spring. The well-known causal parameters producing floods in Manitoba include: (a) soil moisture at freeze-up time (previous autumn); (b) total winter precipitation; (c) rate of snowmelt; (d) spring rain amount; and (e) timing factor (Warkentin, 1999). Temperature and precipitation are the two major variables that affect the above five parameters. Annual distribution patterns of the temperature and precipitation have significant influence on the flood starting time, flood magnitude and occurrence interval of floods.

The current flood control works for the Red River valley consist of the Red River Floodway, the Portage diversion and Shellmouth Dam on the Assiniboine River, the primary diking system within the City of Winnipeg, and community diking in the Red River valley. Following the 1950 flood on the Red River, the federal government and the Province of Manitoba set up a fact-finding commission to appraise the damages and make recommendations. The commission recommended in 1958 the construction of the Red River Floodway (completed in 1966), the Portage Diversion (completed in 1970) and the Shellmouth Reservoir (completed in 1972). As a consequence of the concern over flood protection for the Red River Valley, a federal-provincial agreement led to the construction in early 1970s of a series of ring dikes around communities in the Valley. Moreover, financial aid programs encouraged rural inhabitants to raise their homes, as well as to create individual dikes around their properties. All the decisions regarding the capacity of current flood control works were based primarily on economic efficiency, getting the largest return for the investment. Existing facilities effectively protected the City from the floods in last decades. However, there still exists an uncertainty on their ability to protect the City from floods under the future climate change.

In order to assess the performance of complex flood protection system under climate variability and change, taking into consideration the way continuous atmospheric variations will influence basin hydrology, requires modeling both, climatic factors (temperature and precipitation) and river flow. Under the leadership of the Intergovernmental Panel on Climate Change (IPCC) a considerable progress has been made in developing high-resolution forecasts of temperature and precipitation using General Circulation Models (GCM). Use of GCM forecasts is of assistance in assessing possible impacts of climate change on the regional level. Using available GCMs a number of different climate change scenarios have been developed providing yearly, monthly and daily temperature and precipitation data for the next 100 years (Simonovic, 2001).

A large body of knowledge exists that allows sophisticated modeling of hydrologic processes on the watershed-scale. There are many existing models that have been developed to analyze the hydrologic processes and predict the runoff. Integration of climate change scenarios obtained by GCMs with hydrologic models that can predict river flow on the watershed-scale often provides sufficient information that can be utilized by water resources management models (Bicknell *et al.*, 1997; Leavesley *et al.*, 1983; Manley, 1978; Kite, 1998; Ahmad and Simonovic, 2000) in order to assess the impact of climate change on the performance of existing water resources management infrastructure.

Specific characteristics of the basin and the complexity of the existing flood protection infrastructure call for 'tailored' assessment methodology (and model). Specific characteristics of the basin and specific needs of the assessment process are addressed through: (a) the understanding of specific characteristics of the basin and the flood protection system; (b) the development of climate change scenario generator; (c) the development of an original hydrologic model using system dynamics simulation; (d) the development of an assessment model using reliability, resiliency and vulnerability as the main indicators of system performance; and (e) the integration of all components into the regional dynamic hydroclimatologic assessment model named DYHAM (Simonovic and Li, 2003). Developed assessment modeling framework is data intensive and can be easily adopted for the assessment of climate change and variability impacts in different regions as well as for the assessment of performance of different water resources systems.

The next section of the paper provides more details on the impact assessment approach for constructing climate change scenarios, predicting streamflows and assessing the effectiveness of flood protection system. The following section presents the results of the assessment of impacts of the climate variability and change on to Red River flood protection system at Winnipeg. A summary of the results ends the paper.

2. Climate Variability and Change Impact Assessment Approach

Assessment of climate variability and change impacts on the performance of a large-scale flood protection system is conducted in three steps: (a) Development of climate change scenarios; (b) Modeling of hydrologic processes in the Red River Basin; and (c) Development and implementation of the system performance assessment model. In the first step, temperature and precipitation data was generated that are used as input into the second step. Hydrologic modeling task generates river flows for assessing the performance of flood protection system in the third step. A schematic presentation of the assessment framework is shown in Figure 1.

2.1. DEVELOPMENT OF CLIMATE CHANGE SCENARIOS

The effect of climate variability and change, although gradual, is having an increasing impact on the weather experienced in Canada, Zhang *et al.* (2001). On a regional scale, such as the Prairies where the Red River Basin is, climate variability and change has definite impacts on areas such as crop production, forestry, energy sector, and water resources sector, to name a few. It is therefore crucial to be able to determine what climate scenarios can be expected in the future.

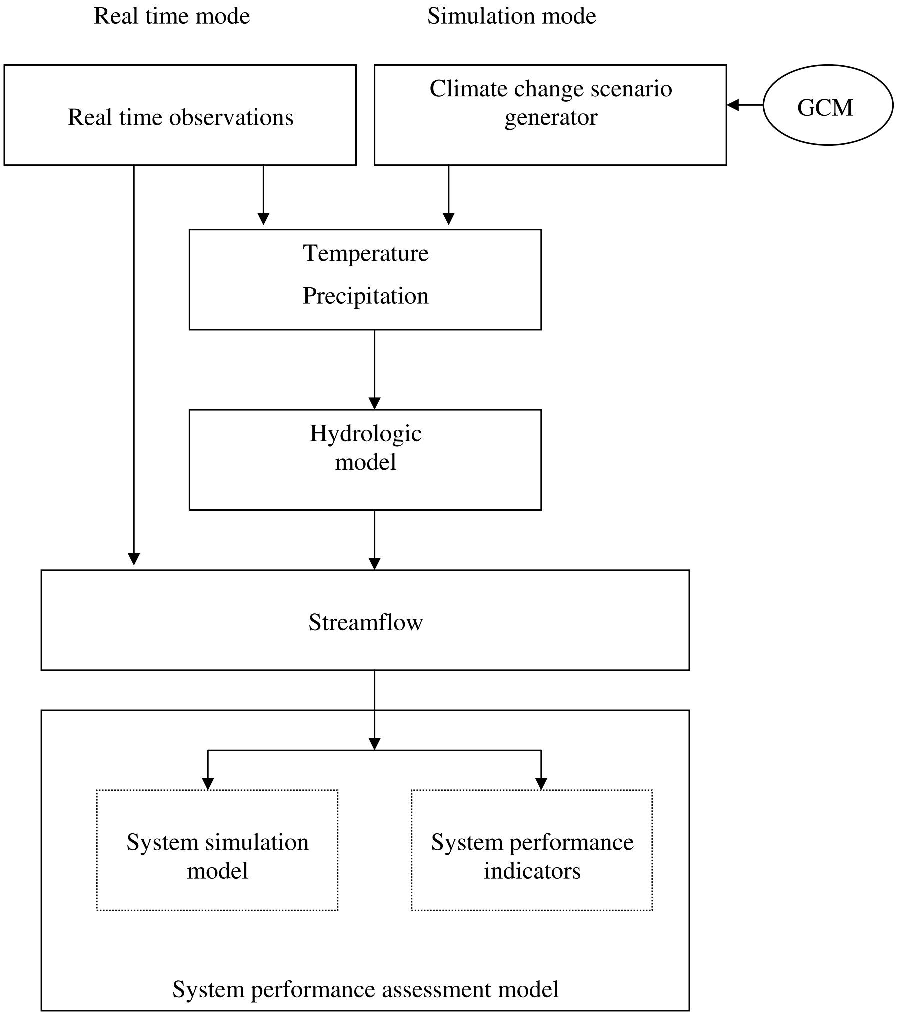


Figure 1. Schematic presentation of the assessment model DYHAM (after Simonovic and Li, 2003).

Different techniques are used to predict the climatic change, including the paleoclimate analogue, the recent climate analogue and the general circulation modeling (GCM). GCM models provide a digital-analogue way to predict the climatic change. These models simulate the evolution of the atmosphere through time from some initial state. GCMs have the ability to model the evolution of the atmosphere in response to external forcing mechanisms – for example, a doubling of carbon dioxide. In order to construct scenarios and generate precipitation and temperature data, this assessment methodology is based on the three climate change models: HadCM3 (http://ipcc-ddc.cru.uea.ac.uk/dkrz/hadcm2_index.html) which was developed at the Hadley Centre, Bracknell, U.K., CGCM1 (http://ipcc-ddc.cru.uea.ac.uk/dkrz/cccma_index.html) which was developed at the Canadian Centre for Climate Modeling and Analysis, and ECHAM4 (http://ipcc-ddc.cru.uea.ac.uk/dkrz/echam4_index.html) which was developed in co-operation between the Max-Planck-Institut für Meteorologie (MPI) and Deutsches Klimatechenzentrum (DKRZ) in Hamburg, Germany. Three models are used in order to evaluate the reliability of the predictions and to eliminate bias associated with data simulated from a sole model (Simonovic and Li, 2003).

Although a large number of variables are simulated by the global circulation models (i.e., soil moisture, evaporation, wind speed), this study focuses on two variables: temperature and precipitation. These variables are considered to be the major climatological variables affecting the hydrology/water resources sensitivity of the Red River Basin.

Two general scenarios are examined for effects on precipitation and temperature. Scenario 1 (S1) assumes 1% increase in CO_2 concentration, while Scenario 2 (S2) assumes 1% increase in CO_2 concentration plus Sulphate Aerosols. As a reference, a control scenario with constant CO_2 is used. Unfortunately, daily temperature and precipitation are not readily available for all scenarios. Therefore, only limited comparative analysis is possible to assess the choice of GCM model and its impact on the system performance assessment. Simulation horizon of 100 years is used for all models starting with year 2000 and ending with year 2099.

2.2. HYDROLOGIC MODELING

In the Red River Basin, temperature is presented as an important climate factor that influences snowpack accumulation and snowmelt as well as the soil and water physical states. An original hydrologic model has been developed for the purpose of assessment methodology that uses system dynamics approach to explore hydrological processes in the Red River Basin where the main contribution to flooding is coming from the snowmelt (Li and Simonovic, 2002). Model structure captures a vertical water balance using five tanks representing snow, interception, surface, subsurface and groundwater storage. Mathematical formulation of the system dynamics hydrologic model based on the vertical water balance and five tank representation includes a set of five nonlinear differential equations describing each storage in the system. Calibration and verification results show that temperature change and snowmelt play a key role in flood generation (Li and Simonovic, 2002; Simonovic, 2001). Results indicate that simulated values match observed data very well. The model is capable of capturing essential dynamics of streamflow formation.

Input data set for the hydrologic model use includes all calibrated parameters, daily temperature, daily precipitation and a set of initial values for the state variables. The main output includes simulated (and observed in calibration and verification stages) discharge at different locations in the study area on both rivers. However, every system dynamics model is capable of showing easily temporal

Figure 2. Location of the major flood control structures in the Red River Basin (after Ahmad and Simonovic, 2000).

variations in all state variables. In the process of model calibration and verification Li and Simonovic (2002) quite often used moisture dynamics in the surface and subsurface soil storage together with the precipitation data.

Temporal and spatial resolution of hydrologic model input data has been adjusted to match the resolution of climate data used in this study. This eliminated the need for downscaling procedure. Size of the Red River Basin (116 500 km^2) allowed for the use of four grid points from the global circulation models as presented later in this paper.

2.3. SIMULATION OF FLOOD PROTECTION SYSTEM PERFORMANCE

Red River flood protection system, as shown in Figure 2, is fairly complex (Simonovic and Li, 2003; Simonovic and Carson, 2003). The performance of this complex system is dependent on the: (a) Flow from the upper Assiniboine river into the Shellmouth Reservoir; (b) Outflow from the Shellmouth Reservoir; (c) Local inflow along the Assiniboine River between the Shellmouth Reservoir and the Portage diversion; (d) Operation of Portage diversion; (e) Red River flow upstream from the floodway; (f) Floodway operation; and (g) Total Red River flow in Winnipeg downstream from the Assiniboine River.

The hydrologic model (Li and Simonovic, 2002) predicts the river flow at Shellmouth Reservoir on the Assiniboine River and at Emerson and Ste Agathe on the Red River. Outflow from the Shellmouth Reservoir depends on the used reservoir operating rules. Portage diversion and the floodway are also controlled by the operating rules. Local inflow along the Assiniboine River and the Red River can be estimated using the available data (Ahmad and Simonovic, 2000). A regional system dynamics simulation model is used at this stage to allow for investigation of system behavior in response to different climate change scenarios. Three statistical indices: system reliability, vulnerability and resiliency, are employed to assess the performance of the flood protection system under different climatic conditions. The assessment simulation model contains two major sectors: (a) Shellmouth Reservoir operations sector; and (b) Red River flood protection system indices sector. Both sectors are integrated within the model for seamless simulation of the flood protection system performance (see Figure 1).

Simulation of Shellmouth Reservoir performance (calculation of reservoir storage and release) depends on the reservoir inflow, flooding potential upstream and downstream from the dam, and demand for water from the reservoir for different uses. Control variable for reservoir operation is the water release rate, which is determined from the demand structure, desired reservoir level, and upstream and downstream flooding conditions.

Upstream flooding is triggered by a combination of streamflow and the current reservoir level. It is represented in the model using the flooded area and the duration of flooding conditions measured in days. Each of them is expressed as a function of reservoir inflow and reservoir level. The number of days is also calculated when upstream area is flooded.

Downstream flooding is triggered by the reservoir operation and the local inflow. Individual flooded area and duration of flooding at selected locations between the dam and the final disposal points of the river is calculated from the reservoir outflow and the local inflow. The downstream flooded area is divided into five sub-areas (Figure 2). Rating curves are provided for each of them by Manitoba Conservation. Total downstream flooded area is also calculated.

The Red River section of the simulation model includes the calculation of water level and flooding along the river using stage-discharge relationships available for different sections of the river. Flooding in this portion of the model is triggered by the operation of the Red River floodway. Current floodway operating rules are incorporated in the model as obtained by Manitoba Conservation (IJC, 2000). Combined flow from both rivers is calculated within the City of Winnipeg as a consequence of combined operation of all main flood protection structures: the Shellmouth Reservoir, the Portage Diversion and the Red River Floodway.

Assessment methodology is using risk-based criteria for the evaluation of flood protection system performance. Hashimoto *et al.* (1982) formulated three criteria for evaluating the possible performance of water resource systems, including reliability, resiliency and vulnerability. The reliability is defined, after Hashimoto *et al.* (1982), Moy *et al.* (1986), Burn *et al.* (1991) and Simonovic *et al.* (1992), as the likelihood of system failure; vulnerability is used to describe the severity of the failure; and resiliency measures how quickly the system recovers from the failure state. These three criteria were adapted and modified in this study for the assessment of performance of the Winnipeg City flood protection system.

The reliability is defined as the probability of system being in a satisfactory state. It is expressed as a ratio of the number of non-failure time intervals to the total number of time intervals in the period under consideration, i.e.:

$$\alpha = \frac{1}{\mathrm{NS}} \sum_{t=1}^{\mathrm{NS}} z_t \tag{1}$$

$$z_t = 1 \qquad \forall x_t \in S \tag{2}$$

$$z_t = 0 \qquad \forall x_t \in F \ , \tag{3}$$

where α is the reliability; z_t is the state of the flood control system in the time interval t; S is the satisfactory state; F is the failure state; and NS is the duration of the operating period.

Failure states are considered to be the time intervals during which flow exceeds the channel capacity at different control locations along the river. In the case of Shellmouth Reservoir the failure state is determined on the basis of reservoir water level and its relationship to the rule curve. For the purpose of system performance assessment, the yearly reliability and the total reliability (calculated over the simulation horizon of 100 years) are calculated.

Vulnerability measures the severity of failure. It is simply defined as the maximum difference between the reference and the calculated values of a certain variable (river flow or reservoir water elevation). It is calculated on the yearly basis as:

$$\beta_y = \begin{cases} 0 & \text{if} \quad V_t \le V_f \\ \max[V_t - V_f] & \text{else} \end{cases} \tag{4}$$

where β_y is the notation for vulnerability; V_t is the reference level of river flow or reservoir water elevation at the time t; V_f is the calculated value of river flow or reservoir water elevation. If it is used as the long-term indicator, vulnerability is defined as the mean normalized value of yearly vulnerability:

$$\beta_m = \frac{\sum_{f=1}^{\mathrm{NF}} \beta_y}{\mathrm{NF}} \tag{5}$$

$$\beta_n = \frac{\sum_{f=1}^{\mathrm{NF}} \beta_y}{V_f * \mathrm{NF}} \ , \tag{6}$$

where β_m is the mean vulnerability; f is the counter of failure states; NF is the total number of failure states during the operating period; and β_n is the normalized mean vulnerability.

Resiliency describes system's ability to bounce back from the failure state. It is evaluated in the assessment methodology on a yearly basis. An original formulation for measuring resiliency of water resources systems was developed by Simonovic *et al.* (1992):

$$\gamma = \frac{1}{\left(\dfrac{\mathrm{MD}}{\mathrm{NST}}\right) * \mathrm{FN}}, \tag{7}$$

where γ is the resiliency indicator; MD is the maximum number of consecutive time intervals of failure state in a year; NST is the number of days in a year; FN is the number of failure state time internals in a year.

The DYHAM model can be used in real time and simulation mode (Figure 1). Real time mode uses observed temperature and precipitation data as inputs into the hydrologic model for streamflow simulation, or directly employs observed streamflow as input into the assessment process. Therefore, three components of DYHAM can be separately applied for different purposes. Flexibility of the programming environment used in the development of DYHAM allows for easy use of the model in different modes.

A system dynamics simulation approach has been used for the development of the assessment model. It relies on understanding complex inter-relationships existing between different elements within a system (Forrester, 1968; Sterman, 2000). This is achieved by developing a model that can simulate and quantify the behavior of the complex flood protection system. Simulation of the model over time is considered essential to understand the dynamics of the system. Understanding of the system and its boundaries, identifying the key variables, representation of the physical processes or variables through mathematical relationships, mapping the structure of the model and simulating the model for understanding its behavior are some of the major steps that are carried out in the development of a system dynamics model. System dynamics, a feedback-based methodology, is applied in the development of the hydrologic model that represents the dynamics of hydrologic processes described above. System dynamics provides a conceptual framework useful in the assembly of nonlinear differential equations with complex feedback and recognizes that the dynamic behavior of systems is controlled by the feedback loop structure.

3. Assessment of the Performance of Red River Flood Protection System

3.1. FLOOD PROTECTION SYSTEM DESCRIPTION

Situated in the geographic centre of North America, the Red River originates in Minnesota and flows north with a drainage area of 116 500 km^2 of which nearly 103 600 km^2 are in the United States. The basin is remarkably flat and the slope of the river averages less than one-half foot per mile. The basin has a sub-humid to humid climate with moderately warm summers, cold winters and rapid changes in daily weather patterns. When the conditions are right and the river floods, nothing holds it back. During major floods, the entire valley becomes the floodplain. In 1997, the Red River spread to a width of about 40 km in Manitoba. The main tributary of the Red River is the Assiniboine River. It originates in the middle northwest Saskatchewan and drains the area from eastern part of Saskatchewan to the western part of Manitoba. Its major tributaries include Qu'Appelle River and Souris River. The Assiniboine River flows from Northwest to Southeast and enters into the Red River at Winnipeg in Manitoba. Since the lower reach is below Shellmouth Dam that can significantly reduce flow rates and downstream water levels, our study area for the Assiniboine River focuses on its surface basin from headwaters to the Shellmouth Reservoir, and covers 16 496 km^2. 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 months of April and May, while only 3% by December to March. Variation of year-to-year flows is also high due to climate variability.

Most of the flood management planning in Manitoba was initiated after the 1950 flood. The current flood control works for the Red River valley consist of the Red River Floodway, the Portage diversion and Shellmouth Dam on the Assiniboine River, the primary diking system within the City of Winnipeg, and community diking in the Red River valley. Following the 1950 flood on the Red River, the federal government and the Province of Manitoba set up a fact-finding commission to appraise the damages and make recommendations. The commission recommended in 1958 the construction of the Red River Floodway (completed in 1966), the Portage Diversion (completed in 1970) and the Shellmouth Reservoir (completed in 1972). As a consequence of the concern over flood protection for the Red River Valley, a federal-provincial agreement led to the construction in early 1970s of a series of ring dikes around communities in the Valley. Prior to 1997, those flood protection infrastructure had performed well to protect Winnipeg and other cities between the Shellmouth dam and Winnipeg along the Assiniboine River from the flooding. Even in 1997 when the flood protection system was stretched to its limits, Winnipeg suffered comparatively much less damage due to extensive flood control infrastructure that has been in place since early 1970s (IJC, 2000).

The general design criteria used in the planning and construction of the Red River flood protection system was to provide protection for the City of Winnipeg for the 1:160 yr flood with a capacity of 4786 m^3 s^{-1} at Redwood Bridge downstream from where the Assiniboine and the Red River merge. Capacity of the existing flood protection structures has been evaluated by many engineering studies (KGS, 2000; IJC, 2000; Simonovic and Carson, 2003). Based on the current operating rules, total capacity is about 4986 m^3 s^{-1} with high reliability, and about 6059 m^3 s^{-1} with low reliability (Table I).

Table I. Capacity of the Red River flood protection system ($m^3\ s^{-1}$) (modified after International Joint Commission, 2000)

Component	Design capacity	1997 peak flow	High reliable capacity	Low reliable capacity
Shellmouth Dam	198	113	198	198
Portage Division	708	337	708	708
Red River Floodway	1700	1900	2070	2520
Diking System	2180	2260	2010	2633
Total	**4786**	**4610**	**4986**	**6059**

4. Climate Change Scenarios

Temperature and precipitation data for selected climate variability and change scenarios have been processed by the hydrologic model to provide streamflow value at different locations in the Assiniboine and the Red River basins. Streamflow scenarios are used as input for the assessment model simulations to evaluate the performance of the flood protection system.

Results of the assessment process in this paper will be presented to only two climate change scenarios generated by the HADCM3 model: (a) control run (named CONTROL) and (b) 1% increase in CO_2 greenhouse gas (named S1). They provide daily temperature and precipitation data for our study. We used data for three grid points in the Red River basin (located approximately at 45.5–50.5°N, 94–100.5°E), and one grid point for the Assiniboine River basin (which is located approximately at 51.0–52.1°N, 101.5 to 103.6°E). Readers interested in the analysis of all other scenarios generated by the HADCM3, ECHAM4 and CGCM1 models are directed to the final report to Natural Resources Canada by Simonovic (2001) that is available from the http://www.engga.uwo.ca/research/iclr/simonovic/documents/CCAF_FinalReport.pdf.

Temperature and precipitation patterns generated by HADCM3 model are affecting streamflow generation and the Red River flood protection system performance. Since floods in the basin normally occur during the spring, analysis of temperature change focuses on the period between January and May. HADCM3 model projected temperature and precipitation for next 100 years for two scenarios are shown in Tables II and III. The results of average daily temperature calculated from 100 years of simulated data for two scenarios clearly show higher spring temperature for both rivers (Table II). Meanwhile, comparison of the predicted annual precipitation indicates that precipitation generated by scenario S1 of HADCM3 exceeds in most years the predicted annual precipitation generated by the control scenario. In the Assiniboine River basin, the average annual precipitation over the 100-year simulation horizon from the HADCM3 control run and S1 run is 19.35%

Table II. Comparison of monthly-averaged daily temperature for two climate scenarios generated by the HADCM3 model (°C)

	Assiniboine River		Red River					
			Downstream		Middle section		Upstream	
	Control	S1	Control	S1	Control	S1	Control	S1
January								
Min	–34.9	–28.8	–37.1	–32.0	–34.3	–30.9	–22.5	–19.4
Max	–18.8	–16.4	–25.4	–20.3	–21.2	–16.0	–8.1	–1.3
Mean	–27.1	–22.7	–29.6	–25.6	–27.0	–23.4	–15.1	–10.9
February								
Min	–31.3	–26.0	–30.0	–26.0	–29.1	–24.8	–21.7	–18.3
Max	–14.2	–11.0	–18.5	–14.4	–15.4	–10.8	–6.9	–0.1
Mean	–23.4	–18.6	–24.5	–20.3	–22.7	–18.8	–13.1	–9.5
March								
Min	–22.0	–16.4	–19.1	–15.3	–18.6	–15.0	–15.0	–10.2
Max	–4.6	1.7	–8.2	–2.4	–2.2	1.9	2.4	5.5
Mean	–13.0	–7.9	–13.9	–9.7	–12.4	–7.5	–6.4	–2.7
April								
Min	–5.3	–2.5	–6.0	–3.6	–4.5	–1.2	–1.3	2.2
Max	5.6	8.7	5.3	7.5	6.7	9.5	13.1	16.0
Mean	1.0	4.9	–1.2	2.9	1.3	5.2	5.8	8.8
May								
Min	8.6	10.5	8.5	9.5	8.9	10.8	9.7	10.1
Max	13.8	19.3	12.3	16.8	13.1	17.7	19.8	23.4
Mean	11.0	14.3	10.3	12.8	10.6	13.9	14.3	17.1

and 28.57% higher than the historical average (450 mm), respectively. The average annual precipitation from the S1 run is 11.43% higher than the average annual precipitation from the control run (Table III). In the Red River basin, generated annual precipitation in different sections of the basin from the HADCM3 control and S1 simulation is higher than the historic basin average of 500 mm. Scenario S1 produces higher minimum, maximum and average annual precipitation than the control run does in all sections of the basin (Table III).

Table III. Comparison of average annual precipitation for two climate scenarios generated by the HADCM3 model (mm)

	Assiniboine River		Red River					
			Downstream		Middle section		Upstream	
	Control	S1	Control	S1	Control	S1	Control	S1
Max	851.1	1036.4	1341.0	1469.6	935.2	1084.3	1425.7	1427.4
Min	347.4	336.1	671.9	765.9	497.8	551.3	624.9	661.2
Mean	558.0	630.2	908.1	1080.9	720.9	815.7	927.3	994.6

Table IV. Comparison of annual streamflow for two climate scenarios generated by the HADCM3 model (m^3 s^{-1})

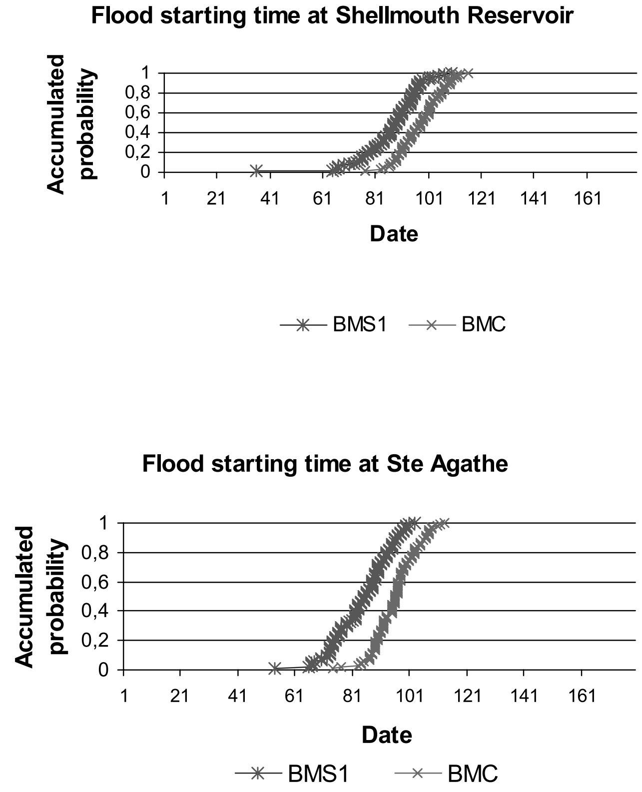
Location	Shellmouth dam		Ste Agathe		Floodway entrance	
	Control	S1	Control	S1	Control	S1
Max. streamflow	14594.3	13158.1	134739.5	180947.0	161659.7	217091.5
Min. streamflow	3102.9	2380.8	57118.8	56274.6	68452.2	67502.8
Mean streamflow	6410.8	6279.5	91580.9	96674.5	109894.5	116005.8

4.1. HYDROLOGIC MODEL SIMULATION OF STREAMFLOW

4.1.1. *Annual Streamflow*

Hydrologic model simulations are performed to generate streamflow in the basin using the temperature and precipitation data generated by the global HADCM3 model. Calibration and verification results of the hydrologic model are presented in Li and Simonovic (2002). Simulated streamflow at Shellmouth dam location in the Assiniboine River basin, and at Ste Agathe and Floodway entrance in the Red River basin are analyzed in this study.

In the Assiniboine River basin, the maximum and the average annual streamflow at the Shellmouth dam generated by HADCM3 control run and scenario S1 do not show significant difference. However, the minimum annual streamflow generated by the scenario S1 is lower for 30.3% than the minimum streamflow generated by control run (Table IV). In the Red River Basin, there is no significant difference in minimum and mean annual streamflow obtained from the two climate change scenarios. However, scenario S1 generates much greater maximum annual streamflow at both locations (Ste Agathe and floodway entrance) compared to the control run.


Flood starting time at Shellmouth Reservoir

Flood starting time at Ste Agathe

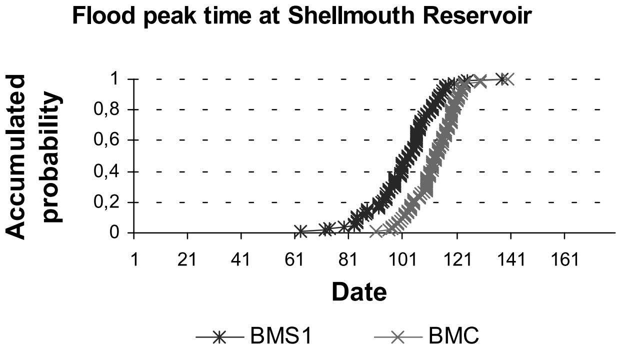
Figure 3. Comparison of the flood starting time for two climate change scenarios generated by the HADCM3 model.

4.1.2. *Analysis of Flood Patterns*

The most important impact of climatic change on hydrologic processes within a watershed should be demonstrated through the change of flood patterns: flood starting time, flood peak value and flood peak timing. Probability distributions of simulated flood starting time, flood peak value and flood peak timing are employed to assess the flood patterns. Shellmouth dam on the Assiniboine River and Ste Agathe on the Red River were selected as locations for analyses of flood patterns. Starting time and peak time at other locations can be estimated using mean travel time between different locations along the river.

4.1.3. *Flood Starting Time*

The temperature and the river flow are used to identify flood starting time. In this research, the point in time, when the daily mean temperature reaches above 0 °C and after that the streamflow continuously increases, is identified as the flood starting time. Probability distributions of flood starting time obtained from the control and S1 runs of HADCM3 are shown in Figure 3. Floods at the Shellmouth



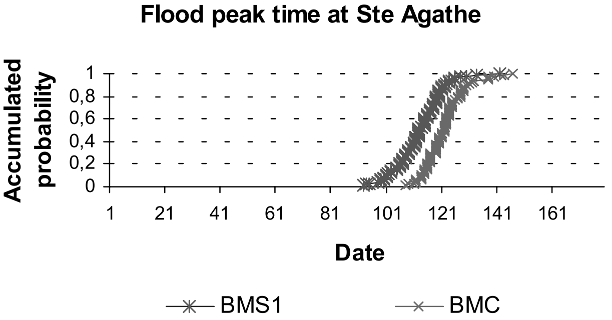
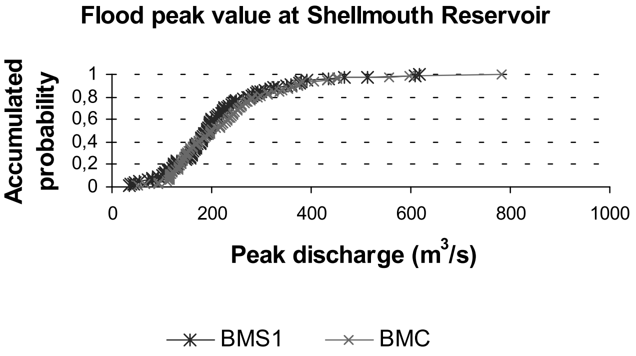


Figure 4a. Comparison of flood peak time and magnitude for two climate change scenarios generated by the HADCM3 model.

dam and at the Ste Agathe generated from the scenario S1 start earlier than those generated by the control scenario. In more than 90% cases, the flood starting time at both locations for the scenario S1 is between early March and early April, while those from the control scenario are between late March and late April. The higher temperature that may be the consequence of climatic change results in an earlier flood starting time in both river basins.

4.1.4. *Flood Peak Flow and Timing*

The timing of flood peak and the flood peak magnitude assessed impact of climatic change on the flood peak. Figure 4 shows the impact of climate variability and change on flood peak time and magnitude at the selected locations in the basin. At the Shellmouth dam, flood peak time from the scenario S1 falls between late March and late April, while that from the control run occurred from early April to early May (Figure 4a). The same pattern is observed at the Ste Agathe. More than 90% of simulated floods from the scenario S1 occurred from early April to early May, while that from the control run from mid April to mid May (Figure 4a). Presented



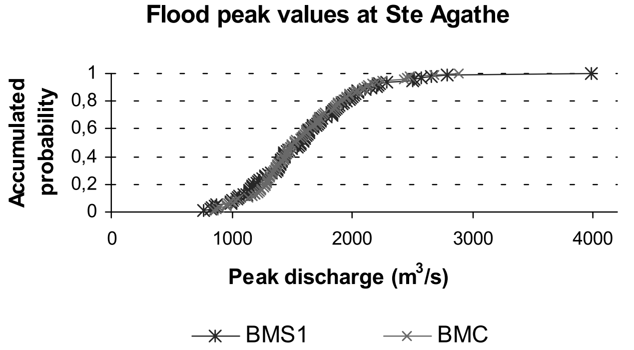


Figure 4b. (continued).

results demonstrate that in both river basins the climate change might cause the earlier occurrence of flood peaks.

The distribution of flood peak magnitude at both locations (Shellmouth dam and Ste Agathe) did not show the significant difference between different scenarios (Figure 4b). However, the large floods may occur. More than 90% of flood peak values at the Shellmouth dam are lower than 400 m^3 s^{-1}. Scenario S1 generated two times more often floods greater than 600 m^3 s^{-1}, while control run generated one flood greater than 600 m^3 s^{-1}. The control scenario generated one flood with a peak flow of 781.41 m^3 s^{-1} which exceeds the great flood of 1995 at the Shellmoth dam. At Ste Agathe, scenarios S1 and control run generated about 85% of flood peak values below 2000 m^3 s^{-1}, and almost all flood peak values were below 3000 m^3 s^{-1}. Only one flood from scenario S1 exceeded the 1997 flood, with the peak value of 3988.38 m^3 s^{-1}.

4.2. RED RIVER FLOOD PROTECTION SYSTEM PERFORMANCE ASSESSMENT

The assessment of the performance of Red River flood protection system is based on the flood flow, the capacity of flood control facilities and the failure flow at each location within the system. The reliability, vulnerability and resiliency are

Table V. Reliability of the Red River flood protection system

Locations	Control			S1		
	Flood years	Min. yearly reliability	Total reliability	Flood years	Min. yearly reliability	Total reliability
Assiniboine River						
Shellmouth Reservoir	26	0.8417	0.9834	23	0.8806	0.9847
Channel Capacity	25	0.8444	0.9861	23	0.8833	0.9879
Russell	25	0.8472	0.9862	22	0.8833	0.9881
St. Lazare	25	0.8444	0.9861	23	0.8833	0.9879
Miniota	5	0.9306	0.9978	4	0.9472	0.9984
Griswold	5	0.9306	0.9978	4	0.9472	0.9984
Brandon	5	0.9361	0.9981	4	0.9528	0.9986
Holland	5	0.9333	0.9980	4	0.9528	0.9986
Portage	5	0.9389	0.9983	4	0.9556	0.9988
Red River						
Ste Agathe	59	0.8972	0.9727	65	0.8472	0.9625
Winnipeg	0	1.0000	1.0000	1[a]	0.9996[a]	1.0000[a]

[a] Calculated with high reliability criteria.

calculated at the selected locations within the system under different climate variability and change scenarios generated using the HADCM3. Statistical measures of performance are determined by comparing simulation results for two climate change scenarios with the current capacity of the flood protection infrastructure at different locations in the basin. Current values are taken from the Table I.

4.2.1. *Reliability*

Evaluation of the system reliability, a probability of the system being in a satisfactory state, is conducted using the relationships (1) to (3) presented earlier. A number of flood events defined as flow exceeding the current flood protection system capacity as defined in Table I and the system reliability at the selected locations in the basin are shown in Table V. Comparison of the number of flood events for two climate change scenarios in Assiniboine River basin indicates that there is no significant difference between the scenarios. However, the results for the Red River are different. Scenario S1 and control scenario resulted in 65 and 59 flood events at Ste Agathe, respectively. Under high reliability criteria as established by International Joint Commission (2000), Scenario S1 generated one flood at Winnipeg greater than 1997 flood. The results show that the mechanisms of flood generation under climate change in two river basins are different. One of the significant factors may be the direction of flow: for the Assiniboine River – west to east; and for the Red River – south to north.

Under the simulated climate change regime, the total reliability generated by scenario S1 at selected locations in the Assiniboine River basin ranges from 0.9847 at the Shellmouth Reservoir to 0.9988 at Portage, while the range for control scenario is from 0.9834 to 0.9983. Table V shows that there is no significant difference in minimum and mean reliability at selected locations between the two scenarios. Along the Assiniboine River, at the locations downstream from the reservoir, a more reliable system performance is observed (expressed in higher total and minimum yearly reliability). This indicates that the Shellmouth reservoir plays an important role in reducing downstream flooding. At Ste Agathe in Red River basin, scenario S1 generates more flood events and lower reliability than the control scenario. Under the current floodway operation rules, total floodway operation time over 100 years is 6.02% for scenario S1 and 5.77% for control scenario. Maximum yearly operation time is 16.67% for scenario S1 and 14.44% for control scenario. The results indicate that Scenario S1 will increase the frequency of floodway operation . At Winnipeg, one flood event occurred in the scenario S1 simulation under high reliability criteria. However, the results of analysis show that the flood protection capacity for the city is sufficient under low reliability criteria as established by the International Joint Commission (2000).

4.2.2. *Vulnerability*

The vulnerability measure is used to assess the flood severity. Table VI presents the minimum, maximum and mean vulnerabilities for flood events calculated using Equations (4) to (6). Under the current Shellmouth reservoir operation rules there is no significant difference in vulnerability due to the upstream flooding between the two scenarios. For downstream locations along the Assiniboine River, vulnerability generated by the scenario S1 is lower than that generated by the control scenario. In Red River basin, the S1 scenario generates higher vulnerability at the Ste Agathe than the control scenario. Scenario S1 also results in one flood event in Winnipeg under high reliability criteria. The peak flood flow of 5668.86 $m^3\ s^{-1}$ exceeds high reliability flow by 682.86 $m^3\ s^{-1}$, but is still 391.14 $m^3\ s^{-1}$ smaller than the low reliability flow as established by the International Joint Commission (2000). The results clearly demonstrate that the current capacity of the Red River flood protection system is sufficient under the low reliability criteria, but there is some risk under the high reliability criteria.

4.2.3. *Resiliency*

Resiliency represents the ability of flood protection system to recover from a failure state. Mean, yearly minimum and maximum resiliency calculated using Equation (7) are shown in Table VII. At the Shellmouth reservoir location, the mean resiliency and the range of yearly resiliency generated from the control scenario are

Table VI. Vulnerability of the Red River flood protection system

Locations		Control			S1		
		Min.	Max.	Mean	Min.	Max.	Mean
Assiniboine River	Upstream flooded area (m^2)	4477.0	72700.0	63957.0	2729.0	72700.0	68225.0
	Shellmouth Reservoir (m)	0.07	12.77	3.43	0.08	11.56	3.23
	Downstream flooded area (m^2)	25702.0	6149724.0	767692.0	2668.0	5511116.0	629481.0
	Channel Capacity (m^3 s^{-1})	1055.54	14199.80	2366.63	1054.88	10817.07	2093.93
	Russell (m^3 s^{-1})	1091.19	15161.99	2493.19	1092.83	11481.82	2248.53
	St. Lazare (m^3 s^{-1})	267.65	16441.65	1880.94	266.83	12279.20	1545.38
	Miniota (m^3 s^{-1})	2218.34	17666.11	7679.64	1180.83	12799.09	6790.34
	Griswold (m^3 s^{-1})	2410.17	19402.72	8417.60	1268.92	14049.00	7439.38
	Brandon (m^3 s^{-1})	2071.19	20763.00	8679.36	815.81	14873.89	7603.31
	Holland (m^3 s^{-1})	2899.41	27168.97	11487.47	1259.76	19639.32	10127.09
	Portage (m^3 s^{-1})	1970.80	28700.08	11420.49	175.61	20278.67	9881.74
Red River	Ste Agathe (m^3 s^{-1})	3.22	1452.64	429.53	13.45	2588.38	457.59
	Winnipeg (m^3 s^{-1})	/	/	/	682.86	682.86	682.86

Table VII. Resiliency of the Red River flood protection system

Locations		Control			S1		
		Min.	Max.	Mean	Min.	Max.	Mean
Assiniboine River	Shellmouth Reservoir	6.32	72.00	23.20	8.37	51.43	19.53
	Channel Capacity	6.43	180.00	41.62	8.57	360.00	48.10
	Russell	6.55	360.00	46.44	8.57	120.00	30.93
	St. Lazare	6.43	180.00	41.62	8.57	360.00	48.10
	Miniota	14.40	36.00	26.02	18.95	45.00	27.91
	Griswold	14.40	36.00	26.02	18.95	45.00	28.20
	Brandon	15.65	51.43	31.72	21.18	72.00	37.10
	Holland	15.00	45.00	29.64	21.18	60.00	33.42
	Portage	16.36	60.00	35.90	22.50	180.00	66.05
Red River	Ste Agathe	9.73	360.00	34.33	6.55	120.00	26.09
	Winnipeg	/	/	/	24.00	24.00	24.00

greater than those obtained from the scenario S1. This is the indication that, under the climate change conditions, the ability of the reservoir to return to a satisfactory state declines. However, for the downstream locations, the same scenario S1 results in a much higher mean resiliency and minimum yearly resiliency compared to the control scenario. The firm conclusion is that the Shellmouth reservoir greatly increases the resiliency of flood protection at the downstream locations along the Assiniboine River.

In the Red River basin, the scenario S1 generates lower mean resiliency and minimum yearly resiliency at Ste Agathe than the control scenario (Table VII). At the City of Winnipeg, the scenario S1 resulted in one flood with the resiliency of 24 under the high reliability criteria.

5. Conclusions

DYHAM, a regional dynamic hydroclimatologic assessment model has been implemented to investigate the effectiveness of large-scale flood protection system under changing climatic conditions, and determine the impact of climate variability and change on flood protection system in the Red River basin. The model involves projected climate variability and change scenarios, hydrologic processes modeling, and the assessment of the performance of flood protection system using statistical indicators of reliability, vulnerability and resiliency.

The global climate model HADCM3 is used to generate possible climate change scenarios. HADCM3 is a digital analogue to the real climatic system. Although the realistic simulation of climatic phenomena is limited due to its coarse grids

(Li and Simonovic, 2002) and the assumptions of static or unchanging boundary conditions, it still provides the clearest picture of climate change at large scale and generate daily climate change data under different climate variability and change scenarios. The hydrological model selected in this study was developed using System Dynamics approach. It clarifies the interactions among surface-subsurface storage and the role of temperature change on canopy size, physical state of the soil and flood generation in a watershed. The model predicts streamflows under different climate change scenarios for the assessment of performance of flood protection system. Three measures of effectiveness of flood protection systems used in this study include reliability, vulnerability and resiliency. Those measures describe system failure frequency (reliability), severity (vulnerability), and system effectiveness in recovery from a failure state (resiliency).

In summary, the climate variability and change may cause an increase in annual discharge and shift ahead in flood starting time and peak occurrence time in both, the Assiniboine and the Red River basins. The two scenarios of HADCM3 model did not produce a significant difference in the distribution of flood peak values in the Assiniboine River upstream from the Shellmouth Reservoir and at Ste Agathe in Red River basin. The results are confirming that the different mechanisms drive the flood generation in these two rivers. Analysis of reliability shows that the Shellmouth Reservoir increases downstream reliability. The present level of flood protection for the city of Winnipeg is sufficient under the low reliability even that the scenario S1 resulted in one flood larger than that of 1997.

This study bridges the gap between climate variability and change and assessment of effectiveness of large-scale flood protection system. Due to the coarse grid of the selected global circulation model and the lumped hydrological model structure that ignore the spatial variation of climate, mantle and soil properties, further studies taking spatial variations into account are warranted to improve the model's ability to predict future flood events.

Acknowledgements

This work was made possible by a financial support from the Natural Resources Canada through the Climate Change Action Fund. The authors would like to thank the Department of Water Resources, Manitoba Conservation for providing watershed characteristics, and Hadley Centre of U.K. for providing predicted daily climate change data.

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