Methodology for Assessment of Climate Change Impacts on Large-Scale Flood Protection System

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Abstract: An original modeling framework for the assessment of climate variation and change impacts on the performance of a complex flood protection system has been developed for the city of Winnipeg in the Red River basin, Manitoba, Canada. The modeling framework allows for the 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. The main contribution of the reported work is the use of a system dynamics modeling and simulation approach in the development of a system performance assessment model. The assessment-modeling framework is based on flood flows, capacity of flood control structures, and failure flow levels at different locations in the basin. The results of this study (shown only to illustrate the methodology) indicate that the capacity of the existing Red River flood protection system is sufficient to accommodate future climate variability and change.

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Introduction

Changes in land use and concentration of greenhouse gases in the atmosphere are thought to be two major anthropogenic causes of climate change and variation. An increase in global temperature may affect the hydrologic cycle (Houghton et al. 1996) and influence water resources (Brent and Yu 1999). This phenomenon has been observed regionally through changes in rainfall by Karl et al. (1996) and river flow by Lettenmier et al. (1994).

Changes in temperature and precipitation under climate variation have a serious impact on the hydrologic processes related to the floods caused by snowmelt. Usual changes are observed in the shift of flood starting time and the magnitude of flood peak; therefore serious consequences may be expected in the ability of the existing large-scale water resources systems to serve their function (Klemes 1985; Lewis 1989; Burn and Simonovic 1996). The Red and Assiniboine rivers in Manitoba, Canada, are 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 the region include (1) soil moisture at freeze-up time (the previous autumn); (2) total winter precipitation; (3) rate of snowmelt; (4) spring rain amount; and (5) the timing factor (Warkentin 1999). Temperature and precipitation are the two major variables that affect the above five parameters. The annual distribution patterns of temperature and precipitation have significant influence on flood starting time, flood magnitude, and the occurrence interval of floods.

To assess the performance of the complex flood protection system under climate variability and change, taking into consideration the way continuous atmospheric variations will influence basin hydrology, requires modeling both the climatic factors (temperature and precipitation) and the river flow. Under the leadership of the Intergovernmental Panel on Climate Change (IPCC), considerable progress has been made in developing high-resolution forecasts of temperature and precipitation using general circulation models (GCMs). Use of GCM forecasts is of assistance in assessing possible impacts of climate change at 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.

A large body of knowledge allows for the sophisticated modeling of hydrologic processes on the watershed scale. Many existing models have been developed to analyze the hydrologic processes and to predict runoff. Integration of the climate change scenarios obtained by GCMs with hydrologic models that can predict river flow on the watershed scale provides sufficient information that can be utilized by water resources management models (Bicknell et al. 1997; Leavesley et al. 1983; Manley 1978; Kite et al. 1994; Ahmad and Simonovic 2000; Li and Simonovic 2002) in order to assess the impact of climate change on the performance of existing water resources management infrastructure.

This paper describes an original comprehensive methodology and regional assessment model that can analyze the performance of existing large-scale flood protection system for the city of Winnipeg under different climate change scenarios. The main objective of the research was to develop a regional dynamic hydroclimatologic assessment model (DYHAM). More specific objectives include (1) development of a hydrologic model component to simulate river flow under historical and predicted conditions, as reported in Li and Simonovic (2002); (2) identification of the magnitude and likelihood of floods under different climate change

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scenarios; (3) development of a system dynamics model for assessing the performance of flood control works; and (4) identification of the statistical indices of the Winnipeg flood protection system performance under different climate change scenarios (Simonovic 2001.

This paper addresses a need for a ‘‘tailored’’ assessment methodology (and model) through (1) description of specific characteristics of the basin and flood protection system; (2) development of a climate change scenario generator; (3) development of an original hydrologic model using system dynamics simulation; (4) development of an assessment model using reliability, resiliency, and vulnerability as the main indicators of system performance; and (5) integration of all components into the regional DYHAM. The developed assessment modeling framework is data intensive and can be easily adopted for the assessment of climate change and variability impacts in various regions, as well as for the assessment of performance of different water resources systems.

The paper is organized to present the characteristics of the Winnipeg flood protection system in the next section, followed by a description of the assessment methodology and a limited set of the assessment results to illustrate the application of DYHAM, ending with some concluding remarks.

Winnipeg City Flood Protection System

Situated in the geographic center of North America, the Red River originates in Minnesota and flows north (one of the eight rivers in the world that do so). The Red River basin covers 116,500 km^2, of which nearly 103,600 km^2 are in the United States. The basin is remarkably flat—the elevation at Wahpeton, North Dakota, is 287 m above sea level, and at Lake Winnipeg the elevation is 218 m; the basin is about 100 km across at its widest. When the conditions are right and the river floods, nothing holds it back. During major floods, the entire valley becomes the floodplain.

Assiniboine River is the main tributary of the Red River. It originates in middle northwest Saskatchewan and drains the area from the eastern part of Saskatchewan to the western part of Manitoba. The Assiniboine River flows from northwest to southeast and enters the Red River at the city of Winnipeg in Manitoba. The Assiniboine River basin covers 16,496 km^2. Topographically, the basin is gently to moderately undulating, with higher relief evident in the northeast portion, while climatologically it is continental subhumid, characterized by long, cold winters and short, warm summers.

The Red River/Assiniboine basin floods regularly. Early records show several major floods in the 1800s, the most notable being those of 1826, 1852, and 1861. In the 20th century, major floods occurred in 1950, 1966, 1979, 1996, and 1997. The Red River basin has 25 subbasins, which have different topography, soils, and drainage that result in different responses during flood conditions. One common characteristic is the overland flow during the times of heavy runoff; water overflows small streams and spreads overland, returning to those streams or other watercourses downstream. Existing monitoring and forecasting systems do not track these flows well, leading to unanticipated flooding.

In Manitoba, almost 90% of the residents of the Red River/Assiniboine basin live in urban centers. Metropolitan Winnipeg contains 670,000 people. Most of the flood management planning in Manitoba was initiated after the 1950 flood, which was the turning point in the history of flooding and flood control in Manitoba’s portion of the Red River basin. Construction of the elevated boulevards (dikes) within the city of Winnipeg and associated pumping stations was initiated in 1950. The current flood control works for the city of Winnipeg (Fig. 1) consist of the Red River Floodway, the Portage Diversion and Shellmouth Dam on the Assiniboine River, and the primary diking system within the city of Winnipeg.

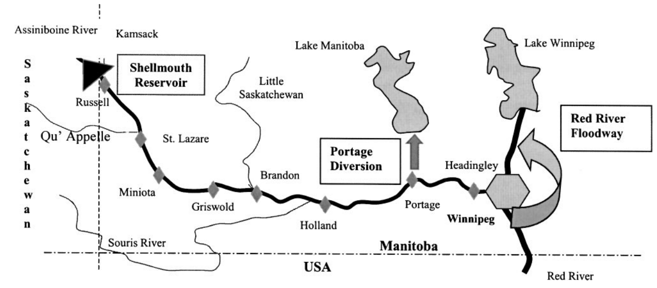

Fig. 1. Schematic presentation of Winnipeg City flood protection system

Following the 1950 flood on the Red River, the Canadian 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). 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, but uncertainty still exists about their ability to protect the city from floods under future climate change.

The KGS Group (2000) has reviewed the individual capacities of each of the major flood protection works and estimated the overall ultimate discharge capacities of the existing system (Table 1). The values are (1) flow through Winnipeg downstream of the confluence with the Assiniboine River, 2,010 m^3/s (71,000 cfs); (2) flow through the Red River Floodway, 2,067 m^3/s (73,000 cfs), associated with a maximum upstream water level of 235.91 m (774 ft); (3) maximum diverted flows of 708 m^3/s (25,000 cfs) from the Assiniboine River at the Portage Diversion; and (4) a reduction of 198 m^3/s (7,000 cfs) due to the Shellmouth Dam.

Table 1. Capacity of Winnipeg Flood Protection System [after IJC (2000); KGS (2000)]

Item	Original design flows (m^3/s)	Flows during flood of 1997 (m^3/s)	Reliable ultimate capacity (m^3/s)
Reduction in Assiniboine flood contribution due to Shellmouth Dam	198	113	198
Diverted flow at Portage diversion	708	337	708
Inflow to Winnipeg from Assiniboine River and other local watersheds	178	23	170
Red River flow upstream of the Forks	2,002	2,237	1,841
Diversion at Red River Floodway	1,699	1,897	2,067
Diking system	2,180	2,260	2,010
Natural total flow capable of being managed	4,786	4,616	4,983
Estimated probability of being exceeded in 50 year period	27%	43%	37%

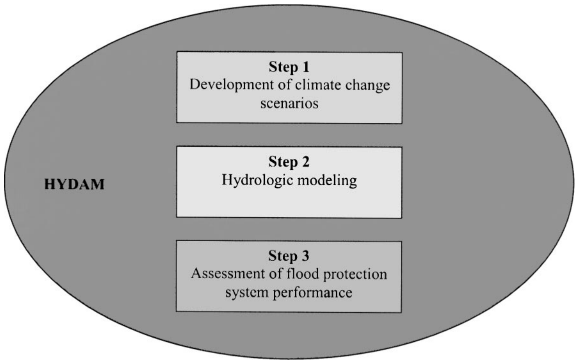

Fig. 2. Schematic presentation of assessment framework

On this basis, Winnipeg is reliably protected against a total natural flow of 4,984 m^3/s (176,000 cfs) (approximately a 1:110 year flood), which is approximately 198 m^3/s (7,000 cfs) more than the original design (Table 1). This capacity requires a water level upstream of the Red River Floodway inlet approximately 0.91 m (3 ft) above the state of nature for that flow magnitude. The capacity that would not require exceeding the state of nature water level at the Red River Floodway inlet would be approximately 4,757 m^3/s (168,000 cfs). Protection against a flow greater than 4,757 m^3/s (168,000 cfs), or even 4,984 m^3/s (176,000 cfs), is possible if all aspects of the flood-fighting campaign were to go well. There is approximately a 37% chance that this reliable capacity of the flood protection system in Winnipeg will be exceeded at least once in the next 50 years.

Assessment Methodology

Assessment of climate variability and change impacts on the performance of a large-scale flood protection system is conducted in 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 the first step, temperature and precipitation data were generated that are used as input into the second step. The hydrologic modeling task generates river flows for assessing performance of the flood protection system in the third step. A schematic presentation of the research framework is shown in Fig. 2.

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). According to Environment Canada's Climate Research Branch, Canada as a whole experienced above-average temperatures in 2000. Since comparable nationwide records began in 1948, 2000 was the 7th warmest year, at 0.9°C above normal, based on preliminary data. The warmest year was 1998 (2.5°C above normal). On a regional scale, such as the Prairies where the Red River basin is, the climate variability and change has definite impacts on areas such as crop production, forestry, the energy sector, and the 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.

Different techniques are used to predict climatic change, including the paleoclimate analog, the recent climate analog, and general circulation models (GCMs). The paleoclimate and recent climate analog techniques reconstruct past climatic events using records such as pollen deposits, tree rings, trapped gases in ice cores, and historical rainfall and runoff data. The general circulation models are based on the fundamental conservation laws of mass, momentum, and energy, which describe the apportioning and transport of heat and moisture by the atmosphere and the oceans. GCMs provide a digital-analog way to predict climatic change.

These models of the climate system have been developed and used both to gain physical insight into major features of the behavior of the climate system and to produce climate projections for a range of assumptions about emissions of carbon dioxide and other greenhouse gases and to 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. Although the GCMs use coarse discretization grids and static boundary conditions, they provide the clearest picture of potential climatic change on the global scale.

Currently, the Data Distribution Center (DDC) of the IPCC provides various GCM-related scenarios for impact assessments ⟨http://ipcc-ddc.cru.uea.ac.uk/⟩. 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 Center, Bracknell, U.K.; CGCM1 ⟨http://ipcc-ddc.cru.uea.ac.uk/dkrz/cccma_index.html⟩, which was developed at the Canadian Center for Climate Modeling and Analysis; and ECHAM4 ⟨http://ipcc-ddc.cru.uea.ac.uk/dkrz/echam4_index.html⟩, which was developed in cooperation between the Max-Planck-Institut für Meteorologie (MPI) and the Deutsches Klimarechenzentrum (DKRZ) in Hamburg, Germany. Three models are used to evaluate the reliability of the predictions and to eliminate bias associated with data simulated from a single model.

Although a large number of variables are simulated by the global circulation models (that is, soil moisture, evaporation, wind speed), this methodology focuses on two variables, temperature and precipitation, which are considered the major climatological variables affecting the hydrology/water resources sensitivity of the region under consideration.

Two general scenarios are examined for effects on precipitation and temperature. Scenario 1 (S1) assumes a 1% increase in CO_2 concentration, while Scenario 2 (S2) assumes a 1% increase in CO_2 concentration plus sulphate aerosols. As a reference, a control scenario with constant CO_2 is used. The selected models currently provide yearly and monthly temperature and precipitation data with different spatial resolutions (HadCM3—2.5 degrees of latitude by 3.75 degrees of longitude; CGCM1—3.75 by 3.75 degrees; ECHAM4—2.8 by 2.8 degrees). For the case study, the HadCM3 model provides 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 (located at approximately 51.0–52.1°N, 101.5–103.6°E). CGCM1 provides data for two grid points in the Red River basin (located at approximately 45.5–50.5°N, 94–100.5°E) and one grid point for the Assiniboine River basin (located at approximately 51.0–52.1°N, 101.5–103.6°E). Since the Assiniboine River basin (approximately at 51.0–52.1°N, 101.5–103.6°E) is located between two grid points of the ECHAM4 model, the average data from two grid points is used. In the Red River basin (located at approximately 45.5–50.5°N, 94–100.5°E), two grid points cover the upstream area, and two grid points the downstream. The av-

Table 2. Selected GCMs and Scenarios for Assessment of Impacts

Scenarios	Control (without change in CO_2)	S1 (1% increase in CO_2)	S2 (1% increase in CO_2 +sulfate aerosols)
Canadian model (CGCM1)			X
British model (HadCM3)	X	X	
German model (ECHAM4)		X	

erage of each of the two grid points is used for the upstream and downstream areas.

Unfortunately, daily temperature and precipitation are not readily available for all scenarios; those that were available with daily data for the case study area are presented in Table 2. Therefore, only limited comparative analysis is possible to assess the choice of the GCM and its impact on the system performance assessment. A simulation horizon of 100 years is used for all models starting with 2000 and ending with 2099. Daily data on temperature and precipitation are used in all simulations presented in this paper.

Hydrologic Modeling

In the region of interest, the temperature is presented as an important climate factor that influences snowpack accumulation and snowmelt as well as the soil and water physical states. The runoff and flood generation from snowmelt follow a general pattern as the temperature changes during the active snowmelt period. In the winter period, precipitation is accumulated as the snowpack due to the low temperature, and the runoff contribution mostly comes from the groundwater and the subsurface soil storage due to the frozen surface soil. As the temperature reaches an active point in the early spring, the snow starts melting. Most of the snowmelt becomes overland flow due to the small canopy storage and the frozen surface soil.

As the temperature increases, the snowmelt generates more water, which rapidly increases the streamflow and gradually leads to flood flows. In the meantime, active temperature also gradually defrosts the soil, therefore increasing the infiltration rate and the surface soil storage capacity; as a result, the streamflow starts to decline. If the heavy rain occurs during the snowmelt period, the streamflow will rise more rapidly and the peak magnitude will be larger. As the accumulated snowpack melts, the streamflow gradually returns to normal level. After the snowmelt period, main streamflow contributions will come from the groundwater and soil storage. Fluctuations in the streamflow strongly depend on the rainfall magnitude. This pattern has been clearly observed in different locations along the Assiniboine and Red rivers in Manitoba, Canada.

An original hydrologic model has been developed for the purpose of an assessment methodology that uses a system dynamics approach to explore hydrological processes in the geographic locations where the main contribution to flooding comes from the snowmelt, Li and Simonovic (2002). Temperature is identified as a critical factor that affects watershed hydrological processes. Based on the dynamic processes of the hydrologic cycle occurring in a watershed, the feedback relationships linking the watershed structure and climate factors for streamflow generation were identified prior to development of a system dynamics model. The model is used to simulate flood patterns generated by the snowmelt under temperature change in the spring.

The model structure captures a vertical water balance using five tanks representing snow, interception, surface, subsurface, and groundwater storage. Calibration and verification results show that the temperature change and the snowmelt play a key role in flood generation (Simonovic 2001; Li and Simonovic 2002). Results indicate that simulated values match observed data very well; the model is capable of capturing the essential dynamics of streamflow formation.

The original modeling contribution is provided by the use of a system dynamics simulation approach that relies on understanding complex interrelationships existing between different elements within a system (Forrester 1968; Sterman 2000). This understanding is achieved by developing a model that can simulate and quantify the behavior of the system. Simulation of the model over time is considered essential to understanding the dynamics of the system. In turn, understanding 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 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 dynamics of the hydrologic processes described above. System dynamics provides a conceptual framework useful in the assembly of nonlinear differential equations with complex feedback; it recognizes that the dynamic behavior of systems is controlled by the feedback loop structure (Richardson 1991). The positive feedback stimulates all factors in a loop to increase or decrease, and the negative feedback loop tends to keep elements in equilibrium. The system dynamics approach helps in the identification of the sources of problem behavior and understanding of the feedback structure of the system.

From the viewpoint of system dynamics, the dynamic behavior of the hydrologic system is dominated by the feedback loop structure, which controls change in the system. As external and internal conditions vary, the contribution of each feedback loop may change, and the dominance in controlling internal moisture dynamics may shift from one feedback loop to another. Hence an integrated analysis of complex feedback relationships could be helpful for a better understanding of the watershed hydrologic dynamics.

Based on the hydrologic processes in surface-subsurface layers, a basic dynamic hypothesis to generate the hydrologic dynamics is developed (Fig. 3). The basic dynamic hypothesis shows that the feedback structure of the fundamental state variables is related to the hydrologic flow processes as well as exogenous factors. The strength of each hydrological flow process is represented by a rate variable. By linking state variables to the rate variables, feedback loops can be formed to control the hydrologic behavior. When rainfall or snowmelt water enters the system, the hydrologic flow processes are regulated by those feedback loops. For example, in the complex system shown in Fig. 3, one negative feedback loop controls the canopy capacity and water interception:

$$\text{water interception} + > \text{canopy storage} - > \text{interception capacity} + > \text{water interception} \tag{1}$$

The signs in the above loop description [Eq. (1)], + and −, represent the positive or negative relationships between the first

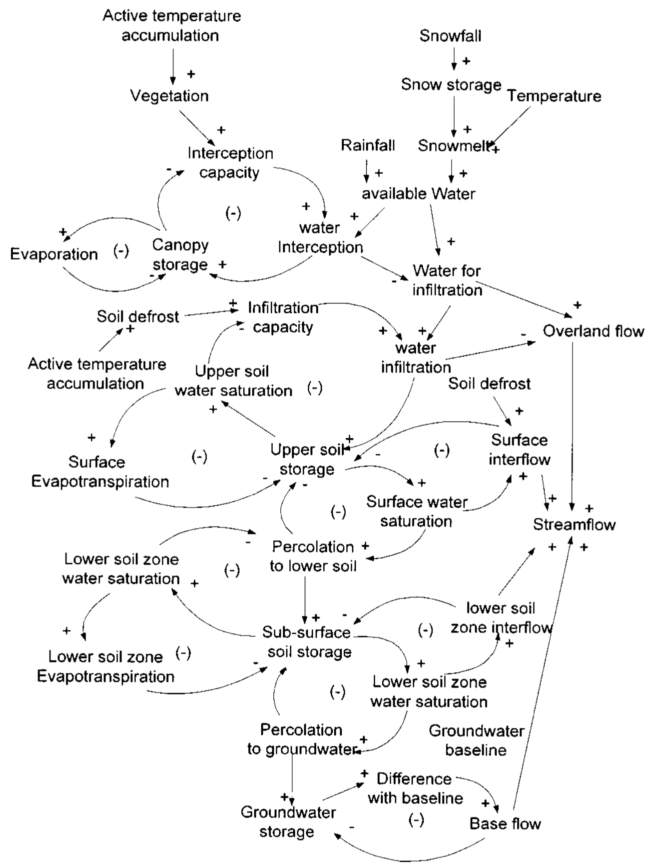

Fig. 3. Basic dynamic hypothesis of watershed dynamics

variable and the next one. The loop in Eq. (1) shows that water interception by the canopy increases water in the canopy storage, which reduces the interception capacity and finally limits the water interception rate. Interception capacity is dependent on the vegetation cover, which is subjected to active temperature accumulation during the active snowmelt period.

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, for example, any precipitation falling as snowfall is accumulated in the snow storage. A critical temperature is used to determine whether the measured or forecast precipitation is rainfall or snowfall. Snowmelt rate can be calculated by the degree-day factor (Li and Simonovic 2002). On the basis of the water balance, the snow storage change rate can be mathematically expressed as

$$\frac{dS1}{dt} = P_s c_1 - \eta T \tag{2}$$

where S1 represents the water in snow storage (cm); P_s=precipitation as snowfall (cm/day) identified by a critical temperature; c_1=snow-water equivalent coefficient (cm snow/cm precipitation); η stands for the degree-day factor for snowmelt (cm/°C/day); and T=daily mean temperature (°C).

The model was developed and implemented using the STELLA II development tool (HPS 1997). This modeling tool provides a user-friendly graphic interface and object-oriented programming approach. The model is represented by differential and difference equations that can be solved within the tool with either Euler's or the Runge-Kutta method.

The input data set for the hydrologic model use includes all calibrated parameters, temperature, 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 easily showing temporal 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.

Assessment of Flood Protection System Performance

The flood protection system for the city of Winnipeg is fairly complex (Fig. 2). The performance of this complex system is dependent on (1) the flow from the upper Assiniboine River into the Shellmouth Reservoir; (2) the outflow from the Shellmouth Reservoir; (3) the local inflow along the Assiniboine River between the Shellmouth Reservoir and the Portage Diversion; (4) the operation of the Portage Diversion; (5) the Red River flow upstream from the floodway; (6) the floodway operation; and (7) the total Red River flow in Winnipeg downstream from the Assiniboine River.

The hydrologic model described above can predict 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 Shellmouth Reservoir operating rules. The Portage Diversion and the floodway are also controlled by the operating rules. Local inflow along the Assiniboine and Red rivers can be estimated using the available data (Ahmad and Simonovic 2000). A regional system dynamics simulation model is developed at this stage to allow for the investigation of system behavior in response to the different climate change scenarios. Three statistical indices—system reliability, vulnerability, and resiliency—are employed to assess the performance of the flood protection system under the different climatic conditions. The assessment simulation model contains two major sectors: (1) the Shellmouth Reservoir operations sector, and (2) the Red River flood protection system indices sector. Both sectors are integrated within the model for seamless simulation of the flood protection system performance.

Development of the regional assessment model using the system dynamics approach is an original contribution that provides (1) an easy way to capture and represent the complexity of the regional flood protection system infrastructure and its operations; (2) the flexibility for testing the impacts of different climate change scenarios; (3) an interactive ability to check the sensitivity of each operational decision; (4) an opportunity to easily evaluate different adaptation strategies by modifying either the system infrastructure (addition of different structural or nonstructural flood protection system improvements) or the system operational rules (for example, different strategy for operating the Red River Floodway).

Effective operation and management of the Shellmouth Reservoir provides water for the needs of agriculture, industry, and ecological systems. System analysis has been found to play an important role in reservoir operation and management, and system analysis techniques have been widely applied for reservoir operation and management in the last four decades. As a promising alternative tool, system dynamics simulation is gaining popularity in water resources modeling and management. Examples include global river basin planning (Palmer et al. 1993; Fletcher 1998) and long-term water resources planning and policy analysis

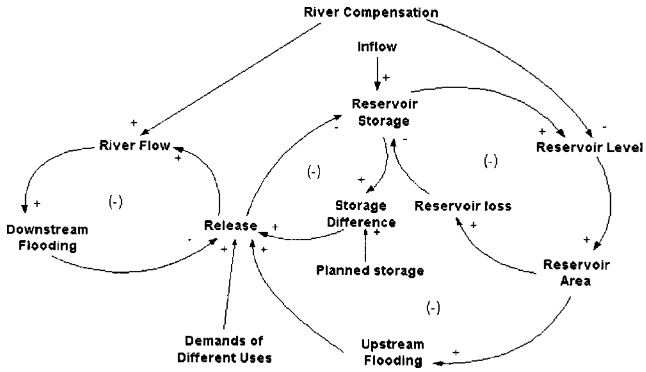

Fig. 4. Feedback causal diagram of Shellmouth Reservoir operation

(Simonovic et al. 1997; Simonovic and Fahmy 1999).

A more recent study of the reservoir operation for flood management using a system dynamics approach was conducted by Ahmad and Simonovic (2000). The assessment methodology presented in this paper draws from the work of Ahmad and Simonovic (2000) and applies system dynamics to analyze the internal system structure of the reservoir management decisions that relate the water inflow to the reservoir storage, water outflow control, reservoir operating rules, and the extent of flooding upstream and downstream from the dam. The potential to reduce floods and damage through modification of spillways and alterations of operating rules are of essential importance in identifying appropriate adaptation strategies to climate variability and change.

The simulation of reservoir performance (calculation of reservoir storage and release) depends on reservoir inflow, flooding potential upstream and downstream from the dam, and demand for water from the reservoir for different uses. The feedback causal loop diagram that describes reservoir dynamics is shown in Fig. 4. The 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. Based on the mass balance equation, the reservoir storage can be calculated using

$$\frac{dS}{dt} = Q_{\mathrm{inf}} - Q_{\mathrm{out}} - \mathrm{LOSS} \tag{3}$$

where S represents the reservoir storage; Q_{inf} stands for the inflow entering into the reservoir; Q_{out} denotes the water discharge through the conduit and the spillway; and LOSS denotes the total losses through seepage and evaporation.

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

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

The Red River section of the simulation model includes calculation of the 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. The current floodway operating rules are incorporated in the model 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.

The assessment methodology presented in this paper uses risk-based criteria for evaluation of the flood protection system performance. Hashimoto et al. (1982) formulated three criteria for evaluating the possible performance of water resource systems: reliability, resiliency, and vulnerability. 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.

Reliability is defined as the probability of a system being in a satisfactory state and is expressed as a ratio of the number of nonfailure time intervals to the total number of time intervals in the period under consideration:

$$\alpha = \frac{1}{NS} \sum_{t=1}^{NS} z_t \tag{4}$$

$$z_t = 1 \quad \forall \mathrm{x}_t \in S \tag{5}$$

$$z_t = 0 \quad \forall \mathrm{x}_t \in F \tag{6}$$

where α=reliability; z_t=state of the flood control system in the time interval t; S=satisfactory state; F=failure state; and NS= 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 the 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 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 calculated values of a certain variable (river flow or reservoir water elevation) and is calculated on a yearly basis as

$$\beta_y = \begin{cases} 0 & \text{if } V_t \leqslant V_f \\ \mathrm{Max}[V_t - V_f] & \text{else} \end{cases} \tag{7}$$

where β_y=notation for vulnerability; V_t=reference level of river flow or reservoir water elevation at time t; and V_f=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:

$$\beta_m = \frac{\sum_{f=1}^{NF} \beta_y}{NF} \tag{8}$$

$$\beta_n = \frac{\sum_{f=1}^{NF} \beta_y}{V_f \cdot NF} \tag{9}$$

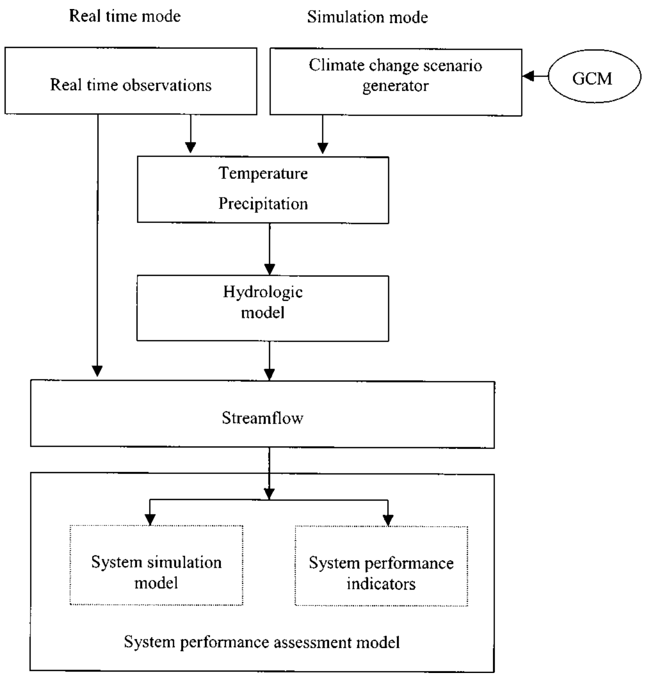

Fig. 5. Schematic diagram of DYHAM model

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

Resiliency describes a 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):

$$\gamma = \frac{1}{\left(\frac{MD}{NS}\right) FN} \tag{10}$$

where γ=resiliency indicator; MD=maximum number of consecutive time intervals of failure state in a year; NS=number of days in a year; and FN=number of failure state time intervals in a year.

Integrated Regional Dynamic Hydroclimatologic Assessment Model

The regional dynamic hydroclimatologic assessment model—DYHAM—integrates three modules: (1) a climate change scenario generator, based on different global circulation models; (2) a hydrologic model; and (3) a flood protection system performance assessment model. A schematic diagram of the DYHAM model is shown in Fig. 5.

The GCM module is based on the fundamental conservation laws of mass, momentum, and energy, which describe the apportioning and transport of heat and moisture by the atmosphere and ocean. It provides information to the climate change scenario generator in the form of daily temperature and precipitation. The output of the scenario generator represents the input into the system dynamics hydrologic model, which bridges the gap between global climate change information and regional data needed for assessment of the performance of a flood protection system and simulates streamflow and flood patterns generated by snowmelt under different temperature regimes. Streamflow generated by the hydrologic model is used as input into the system dynamics assessment model, which includes two important sectors: (1) flood protection system simulation (reservoir, diversion, and floodway); and (2) calculation of system performance indicators. DYHAM is fully implemented in the STELLA II programming environment using a system dynamics modeling approach.

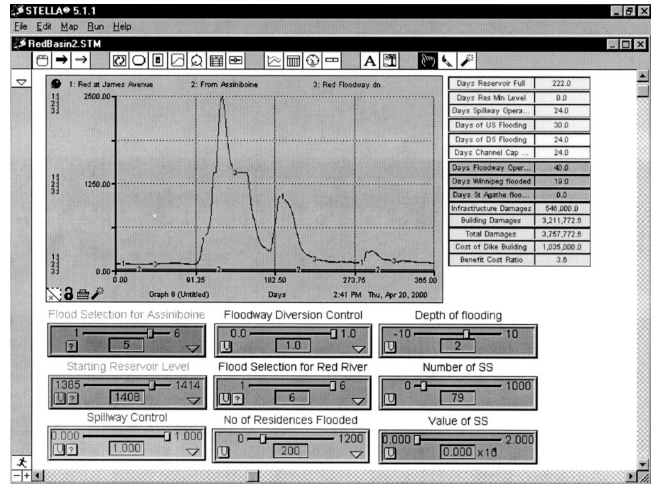

Fig. 6. System dynamics simulation model interface

DYHAM can be used in real-time and simulation mode. The 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 STELLA programming environment allows for easy use of the model in different modes.

Fig. 6 illustrates one of the DYHAM interactive interfaces developed for the analyses of the flood protection performance of the Shellmouth Reservoir (Ahmad and Simonovic 2000). The interface architecture allows an exchange of information between the model user and the model. The graphical screen (with option to look at multiple graphs under the visible screen in the figure) and table on the right-hand side provide detailed output information on the extent of flooding, engagement of infrastructure, and impacts of flooding. Adjustable "slider" buttons on the bottom of the screen are used to provide the user input to the model and set the simulation run or runs. The user can select different infrastructure options (for example, engagement of the diversion or not; introduction of controlled spillway or not; and so on) and the reservoir operational rules and then run the system for different flood scenarios provided from the combined use of the selected climate change model or models and the hydrologic model.

Illustrative Flood Protection System Assessment Results

To illustrate the assessment methodology presented in this paper, one set of results will be discussed. Detailed assessment of the Red River flood protection system is available in Simonovic (2001).

Climate change model scenarios provide the basic input information for the assessment process and the use of methodology presented in this paper. Temperature variation data generated by various GCM models provide the input for the hydrologic com-

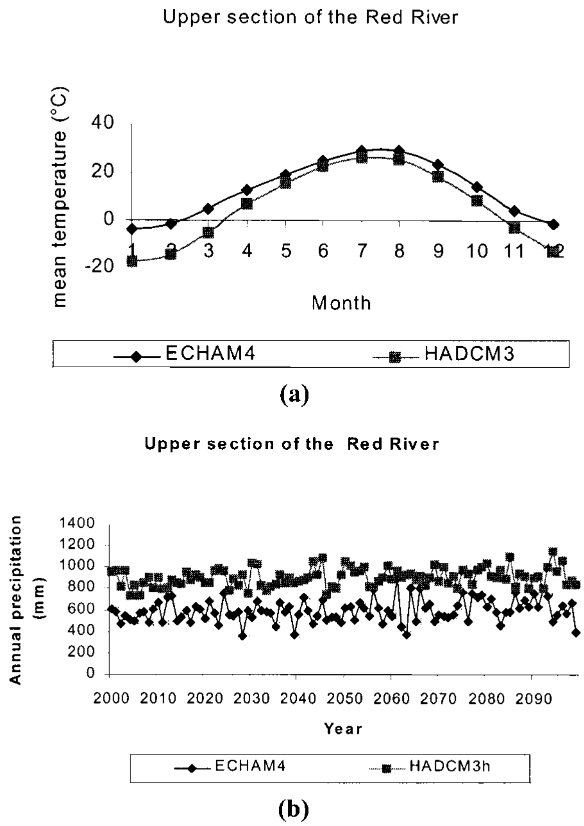

Fig. 7. Comparison of (a) average temperature and (b) annual precipitation generated by HadCM3 and ECHAM4 models for Scenario 1

ponent of the assessment model. Fig. 7 compares average monthly temperature and annual precipitation data generated for Scenario 1 (described earlier) by the application of the U.K. (HadCM3) and German (ECHAM4) models for the upper Red River basin. From this figure it is quite clear that different GCM models did provide different estimates of the main hydrologic parameters for the region under consideration.

The hydrologic model provides a flow pattern that corresponds to a particular global change scenario input (set of temperature and precipitation data). Fig. 8 illustrates the flow at Ste. Agathe

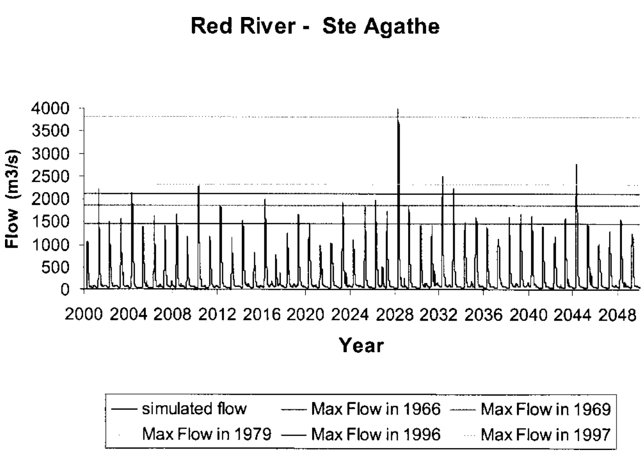

Fig. 8. Red River flow at Ste. Agathe generated by HadCM3 model for Scenario 1

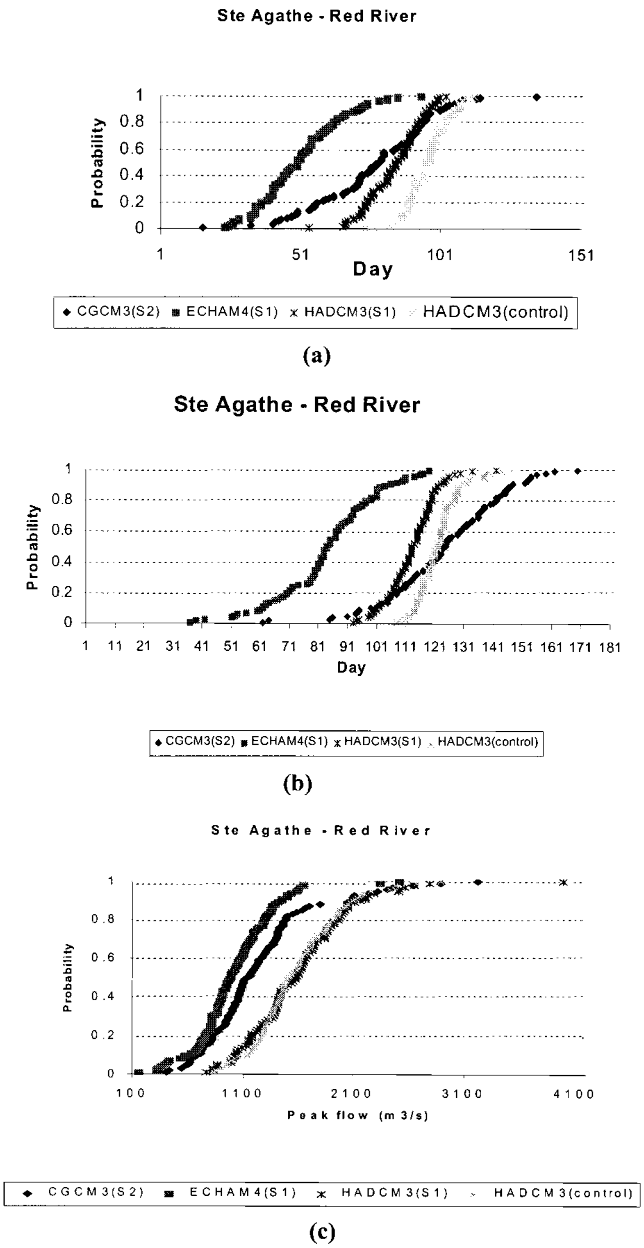

Fig. 9. Comparison of (a) flood starting time; (b) flood peak time; and (c) flood peak flow generated by different GCM models for different climate change scenarios at Ste. Agathe (Red River)

(Red River) generated for Scenario 1 of HadCM3 and compared to historical floods. The figure shows the first 50 years of simulation and indicates only one year with flood flow exceeding the 1997 flow.

Flow information generated by the hydrologic part of the assessment model is then used in detailed simulation of the flood protection system performance to assess its reliability. Simulation analysis of flood starting time [Fig. 9(a)], flood peak time [Fig. 9(b)], and flood peak flow [Fig. 9(c)] is available for different global change scenarios generated by different GCM models. Fig. 9 shows one set of results at Ste. Agathe (Red River). From this illustrative set of results it is possible to conclude that the climate variability and change may cause an increase in annual discharge and shift ahead in flood starting time and peak occurrence time in the Red River basin. The detailed study of the assessment results expands on this conclusion.

Table 3. Flood Protection System Reliability—ECHAM4 and CGCM1 Models

	ECHAM4 S1			CGCM1 S2		
River and location	Minimum	Maximum	Mean	Minimum	Maximum	Mean
Assiniboine River						
Shellmouth Reservoir	0.7972	0.9861	0.9754	0.7014	0.9836	0.9599
Channel capacity	0.8000	0.9944	0.9774	0.7479	0.9945	0.9650
Russell	0.8000	0.9917	0.9776	0.7507	0.9945	0.9653
St. Lazare	0.8000	0.9944	0.9774	0.7479	0.9945	0.9650
Miniota	0.9417	0.9806	0.9982	0.9151	0.9918	0.9938
Griswold	0.9417	0.9806	0.9982	0.9151	0.9918	0.9938
Brandon	0.9472	0.9917	0.9984	0.9178	0.9781	0.9944
Holland	0.9472	0.9889	0.9984	0.9205	0.9753	0.9944
Portage	0.9694	0.9806	0.9989	0.9205	0.9863	0.9951
Red River						
Ste. Agathe	0.8889	0.9944	0.9949	0.8795	0.9945	0.9865
Winnipeg	—	—	1.0000	—	—	1.0000

Three measures of the effectiveness of the flood protection system used in this study include reliability, vulnerability, and resiliency as defined earlier in the paper. For illustrative purposes, a presentation of the flood protection system reliability obtained from the use of Scenario 1 in ECHAM4 (German) and Scenario 2 in CGCM1 (Canadian) models is provided in Table 3. Calculation of the reliability index is done using Eqs. (4), (5), and (6). Illustrative results presented in Table 3 and confirmed in a much more detailed assessment analysis show that the flood protection system capacity for the city of Winnipeg is sufficient under low reliability criteria as established by the International Joint Commission and shown in Table 1.

Concluding Remarks

Changes in temperature and precipitation under climate variation have serious impact on the hydrologic processes related to floods that are caused by snowmelt. Usual changes are observed in the shift of flood starting time and the magnitude of flood peak. Therefore, serious consequences may be expected in the ability of existing large-scale flood protection systems to serve their function. An original methodology for assessment of impacts on the large-scale flood protection system has been developed in this study.

The main findings of this study include (1) the need for a ‘‘tailored’’ approach; and (2) use of system dynamic modeling and simulation.

The tailored approach is an exclusive way for addressing the specific characteristics of the system under consideration. The city of Winnipeg flood protection system is characterized by a number of special features, including specific topography of the two river basins. In addition, overland flooding is the main source of potential flood damages; snowmelt and spring floods define the hydrometeorological state of the system; and the existing flood protection infrastructure is driven by the Shellmouth Reservoir and Red River Floodway operating rules. The assessment methodology, which is based on the integration of different climate development scenarios, detailed modeling of hydrological processes in the region, and statistical indicators of system performance obtained through simulation, is designed to address all specific features of the system under consideration. A scenario-based approach was found to be of value in understanding potential impacts and developing adaptation strategies that may require modification of the physical system structure and/or modification of flood protection system operating rules.

Two large components of the assessment methodology use system dynamics modeling and simulation. Both the hydrologic model and the system performance assessment model benefit from the system dynamics approach. The dynamic behaviors of the hydrologic system and the flood protection system are dominated by the feedback loop structure, which controls change in the system. As external (input and boundary) and internal (system structure) conditions vary, the contribution of each feedback loop may change, and the dominance in controlling internal system dynamics may shift from one feedback loop to another. Hence, an integrated analysis of complex feedback relationships was helpful in better understanding the watershed hydrologic dynamics and dynamics of the flood protection system performance.

The main advantage of using system dynamics modeling and simulation in the assessment methodology is expected to come from the use of DYHAM in developing appropriate adaptation strategies for future flood protection system modifications and revision of system operating rules. Currently both the system structure and operating policies are under revision (IJC 2000; Simonovic and Carson 2001). Serious consideration is given to the possible capacity increase of the Red River Floodway and/or introduction of another detention structure south of the city of Winnipeg.

After the flood of 1997 the process for revision of the Red River Floodway operating rules was initiated to provide for a more equitable share of consequences between the city and its southern neighbors. Shellmouth Reservoir operation is also under investigation to assess the benefits of building the spillway gates; the reservoir is currently operated with an ungated spillway structure. Use of system dynamics and an object-oriented programming environment provides for (1) easy modification of system structure by the manipulation of system objects that will change the mathematical description of the system; and (2) easy introduction and evaluation of different operating rules, reservoir storage targets, and/or operation of floodway gates.

The main weakness of the assessment methodology is in the use of GCM scenarios for the future climate. Proper assessment of the flood protection system requires detailed (daily) data that are not always available from GCMs. Spatial resolution of these data can also be a problem for smaller watersheds. The first writer is investigating an inverse approach that will not modify the assessment methodology but will replace the input data source. Understanding of the mechanisms and processes of climatic variation and change that lead to hydrologic hazards (flood events) is expected to be improved using an inverse approach. The existing guidelines and management practices in a river basin will be analyzed with respect to critical hydrologic exposures that may lead to the failure of a flood protection system. Vulnerable subregions in a river basin will be identified together with the risk exposure; then the critical hydrologic exposures (flooding) will be transformed into corresponding critical meteorological conditions (extreme precipitation). Local weather scenarios will then be statistically linked to the large-scale features investigated within GCMs.

The proposed assessment methodology is not limited to the city of Winnipeg region or to the flood protection system analysis. The methodology can be easily adopted for application in different geographical regions (which will require modifications to the hydrologic model) and for addressing the performance of different water resources systems (which will require modifications to the system performance simulation model). Use of the proposed methodology and DYHAM in real time is another advantage of the proposed approach, as discussed earlier in the paper.

The original modeling framework (DYHAM) for assessment of climate variation and change impacts on the performance of complex flood protection system has been tested using the Red River basin as a case study. Only illustrative output results are included in this paper; they clearly show that the use of three different GCMs results in different patterns of temperature and precipitation in the Red River basin. Considerable research is still required to bring GCMs to the level of being of real value in predicting future hydrological conditions on the watershed scale.

Despite the differences between the models and the scenarios, the application of DYHAM revealed with consensus that the annual precipitation and annual streamflow volume in the Red River basin might increase under future climate change scenarios. Flood starting time and peak time might also shift earlier. The results of this study indicate that the capacity of the existing Red River flood protection system is sufficient to accommodate future climate variability and change if the low-reliability criteria shown in Table 2 are used. In the case of application of the high-reliability criteria, future increase of flood protection capacity is warranted.

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References

Ahmad, S., and Simonovic, S. P. (2000). ‘‘System dynamics of reservoir operations for flood management.’’ *J. Comput. Civ. Eng.*, 14(3), 190–198.

Bicknell, B. R., Imhoff, J. C., Kittle, J. L., Jr., Donigian, A. S., Jr., and Johanson, R. C. (1997). ‘‘Hydrologic simulation program—Fortran.’’ *User’s manual version 11, EPA/600/R-97/080*, U.S. Environmental Protection Agency, National Exposure Research Laboratory, Athens, Ga.

Brent, F., and Yu, Z. (1999). ‘‘An evaluation of two hydrologic models for climate change scenarios.’’ *J. Am. Water Resour. Assoc.*, 35(6), 1351–1363.

Burn, D. H., and Simonovic, S. P. (1996). ‘‘Sensitivity of reservoir operation performance to climatic change.’’ *Water Resour. Manage.*, 10, 463–478.

Burn, D. H., Venema, H. D., and Simonovic, S. P. (1991). ‘‘Risk-based performance criteria for real-time reservoir operation.’’ *Can. J. Civ. Eng.*, 18(1), 36–42.

Fletcher, E. J. (1998). ‘‘The use of system dynamics as a decision support tool for the management of surface water resources.’’ *Proc., 1st Int. Conf. on New Information Technology for Decision-Making in Civil Engineering*, Univ. of Quebec, Montreal, Canada, 909–920.

Forester, J. W. (1968). *Principles of systems*, 2nd Ed., Productivity Press, Mass.

Hashimoto, T., Stedinger, J. R., and Loucks, D. P. (1982). ‘‘Reliability, resiliency and vulnerability criteria for water resources systems performance evaluation.’’ *Water Resour. Res.*, 18(1), 14–20.

High Performance Systems, Inc. (HPS). (1997). *Technical documentation—STELLA*.

Houghton, J. J., Meiro Fihlo, L. G., Callander, B. A., Harris, N., Kattenberg, A., and Maskell, K. eds. (1996). *Climate change 1995: The science of climate change*, Contribution of Working Group I to *2nd Assessment Rep. of the Intergovernmental Panel on Climate Change (IPCC)*, Cambridge University Press, Port Chester, N.Y.

International Joint Commission (IJC). (2000). ‘‘Living with the red.’’ *Rep. to the Government of Canada and the United States on reducing flood impacts in the Red River Basin*, Ottawa and Washington, D.C.

Karl, T. R., Knight, R. W., Easterling, D. R., and Quayle, R. G. (1996). ‘‘Indices of climate change for the United States.’’ *Bull. Am. Meteorol. Soc.*, 77, 279–292.

Kite, G. W., Dalton, A., and Dion, K. (1994). ‘‘Simulation of streamflow in a macroscale watershed using general circulation model data.’’ *Water Resour. Res.*, 30, 1547–1559.

Klemes, V. (1985). ‘‘Sensitivity of water resources systems to climate variations.’’ *World Climate Problem Rep. WCP-98*, World Meteorological Organization.

Kontzamanis-Graumann-Smith-MacMillan Inc. (KGS Group). (2000). *Flood protection for Winnipeg. Part III: Prefeasibility study*, March, Winnipeg, Manitoba, Canada.

Leavesley, G. H., Lichty, R. W., Troutman, B. M., and Saindon, L. G. (1983). ‘‘Precipitation-runoff modeling system.’’ *User’s manual, Water-Resources Investigations Rep. 83-4238*, U.S. Geological Survey, Washington, D.C.

Lettenmaier, D. P., Wood, E. F., and Wallis, J. R. (1994). ‘‘Hydro-climatological trends in the Continental United States, 1948–1998.’’ *J. Clim.*, 7, 586–607.

Lewis, J. E. (1989). ‘‘Climate change and its effects on water resources for Canada: A review.’’ *Can. Water Resour. J.*, 14(1), 34–55.

Li, L., and Simonovic, S. P. (2002). ‘‘System dynamics model for predicting floods from snowmelt in North American prairie watersheds.’’ *Hydrolog. Process.*, 16(13), 2645–2666.

Manley, R. E. (1978). ‘‘HYSIM—A general purpose hydrologic model.’’ *Pisa Symp. in 1978*, Pergamon, Tarrytown, N.Y.

Moy, W. S., Cohon, J. L., and ReVelle, C. S. (1986). ‘‘A programming model for the analysis of the reliability, resiliency and vulnerability of a water supply reservoir.’’ *Water Resour. Res.*, 22, 489–498.

Palmer, R., Keyes, A. M., and Fisher, S. (1993). ‘‘Empowering stakeholders through simulation in water resources planning.’’ *Proc., Water Management for the ’90s*, ASCE, New York, 451–454.

Richardson, G. P. (1991). *Feedback thought in social science and systems theory*, University of Pennsylvania Press, Philadephia.

Simonovic, S. P. (2001). ‘‘Assessment of the impact of climate variability and change on the reliability, resiliency and vulnerability of complex flood protection systems.’’ *Rep. to the Natural Resources Canada*, London, Ontario. Available: ⟨http://www.engga.uwo.ca/research/iclr/simonovic/documents/CCAF_FinalReport.pdf⟩.

Simonovic, S. P., and Carson, R. W. (2001). ‘‘Flooding in the Red River basin—lessons from post flood activities.’’ *Nat. Hazards J.*, in press.

Simonovic, S. P., and Fahmy, H. (1999). ‘‘A new modeling approach for water resources policy analysis.’’ *Water Resour. Res.*, 35(1), 295–304.

Simonovic, S. P., Fahmy, H., and El-Shorbagy, A. (1997). ‘‘The use of object oriented modeling for water resources planning in Egypt.'' *Water Resour. Manage.*, 11(4), 243–261.

Simonovic, S. P., Venema, H. D., and Burn, D. H. (1992). ''Risk-based parameter selection for short-term reservoir operation.'' *J. Hydrol.*, 131, 269–291.

Sterman, J. D. (2000). *Business dynamics: Systems thinking and modeling for a complex world*, McGraw-Hill, New York.

Warkentin, A. A. (1999). *Hydrometeorologic parameter generated floods for design purposes*, Manitoba Dept. of Conservation, Manitoba, Canada.

Zhang, X., Harvey, K. D., Hogg, W. D., and Yuzyk, T. R. (2001). ''Trends in Canadian streamflows.'' *Water Resour. Res.*, 37(4), 987–998.