SYSTEM DYNAMICS MODELING OF RESERVOIR OPERATIONS FOR FLOOD MANAGEMENT

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ABSTRACT: There exists a strong need to explore simulation techniques that not only represent complex dynamic systems in a realistic way but also allow the involvement of end users in model development to increase their confidence in the modeling process. System dynamics, a feedback-based object-oriented simulation approach, is presented for modeling reservoir operations. The increased speed of model development, the trust developed in the model due to user participation, the possibility of group model development, and the effective communication of model results are main strengths of this approach. The ease of model modification in response to changes in the system and the ability to perform sensitivity analysis make this approach more attractive compared with systems analysis techniques for modeling reservoir operations. The proposed approach is applied to the Shellmouth reservoir on the Assiniboine River in Canada. Operating rules are developed for high flow/flood years to minimize flooding. Alternative operating rules are explored by changing reservoir storage allocation and reservoir outflows. Impacts on the flood management capacity of the reservoir are investigated by simulating a gated spillway in addition to an existing unregulated spillway. Sensitivity analysis is performed on the reservoir levels at the start of the flood season and the outflow from the reservoir.

INTRODUCTION

The application of systems analysis techniques for reservoir management and operations has been a major focus of research in water resources engineering during the past four decades. Numerous models have been reported in the literature for sizing storage capacity and establishing release policy, both at the project planning stage and for real-time operations. Most of the techniques that have been developed or adapted to reservoir operations are described in several textbooks, e.g., Loucks et al. (1981) and Mays and Tung (1992). Wurbs and Tibbets (1985), listing over 700 references, produced a state-of-the-art review and an annotated bibliography of systems analysis techniques applied to reservoir operations. Yeh (1985) provided an excellent review on various approaches to reservoir optimization and simulation and pointed out that, despite considerable progress, research related to reservoir systems analysis has been very slow in finding its way into practice, particularly at the level of the actual operators. He attributes this partly to the fact that operators usually have not been involved in the formulation and development of computer models; partly to the fact that most applications deal with simplified reservoir systems and are difficult to adapt to real systems; and partly to institutional constraints. Also, operators and their managers are not comfortable with the degree of abstraction necessary for efficient application of simulation techniques to very complex systems (Russell and Campbell 1996).

This literature review suggests that systems analysis has its own place in the field of reservoir management, and simulation is an essential tool for developing a quantitative basis for reservoir management decisions (Simonovic 1992). However, there is a strong need to explore simulation tools that can represent the complex systems in a realistic way and where operators can be involved in model development to increase their confidence in the modeling process. A promising alternative is the system dynamics (SD) approach for modeling reservoir operations, which is efficient and simple to use compared with traditional systems analysis techniques and does not require complex mathematical description of the system. System dynamics, a feedback-based object-oriented simulation approach, is becoming increasingly popular for modeling water resource systems. Palmer and colleagues (Palmer 1994; Palmer et al. 1993, 1995) have done extensive work in river basin planning using SD. Keyes and Palmer (1993) used SD simulation model for drought studies. Matthias and Frederick (1994) have used SD techniques to model sea-level rise in a coastal area. Fletcher (1998) has used system dynamics as a decision support tool for the management of scarce water resources. Simonovic et al. (1997) and Simonovic and Fahmy (1999) have used the SD approach for long-term water resources planning and policy analysis for the Nile River basin in Egypt.

System dynamics, a feedback-based object-oriented simulation paradigm, is presented in this paper as a powerful approach for modeling reservoir operations. The study deals with simulation of reservoir operations for flood management purposes. Operating rules have been developed for high flow years to minimize flooding. Impacts on flood management capacity of a reservoir have been explored by simulating a gated spillway in addition to an existing unregulated spillway. Alternative operating rules have been investigated by changing reservoir storage allocation, reservoir levels at the start of flooding season, and reservoir outflows.

This paper outlines a general framework for modeling reservoir operations using the SD approach. The theoretical background of the SD simulation approach is given. Then, a general modeling approach for reservoir simulation is presented by introducing model structure and complex relationships among its components. The benefits of the proposed approach are demonstrated by application to a case study of a single multipurpose reservoir. Finally, a discussion on results is presented and conclusions are drawn. Suggestions for possible model application and extension conclude the paper.

SYSTEM DYNAMICS MODELING OF RESERVOIR OPERATIONS

System dynamics has a long history as a modeling paradigm with its origin in the work of Forrester (1961), who developed the subject to provide an understanding of strategic problems in complex dynamic systems. SD models, by giving insight into feedback processes, provide system users with a better understanding of the dynamic behavior of systems. Areas of

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application of SD have always been very wide, however, with an emphasis on socioeconomic applications. In recent years there has been a tendency to model small-scale systems in greater detail with more emphasis on quantitative results (Fletcher 1998). Continuity of mass, one of the basic concepts in SD, is also an important concept for reservoir representation. Thus, reservoir simulation problems are well suited for application of SD solution techniques.

The SD tool used in this study to model reservoir operation has four basic building blocks: stock, flow, connector, and converter. Stocks (levels) are used to represent anything that accumulates; an example of stock would be water stored in a reservoir. Flows (rates) represent activities that fill and drain stocks; an example of flow includes reservoir releases or reservoir inflows. Connectors are used to establish the relationship among variables in the model. They are represented graphically by the software as arrows, and the direction of the arrow indicates the dependency relationships. They carry information from one element in a model to another element. This information can be a quantity, a constant, an algebraic relationship, or a graphical relationship. Converters transform input into output. Converters can accept input in the form of algebraic relationships, graphs, and tables. The concept of the stocks and the flows in SD is very appropriate to deal with a reservoir problem in water resources.

The SD approach is based on theory of feedback processes. A feedback system is influenced by its own past behavior. This system has a closed-loop structure that brings results from past actions of the system back to control future actions. One class of feedback system—negative feedback—seeks a goal and responds as a consequence of failing to achieve the goal, e.g., thermostat. It is the negative feedback or goal-seeking structure of the system that causes balance and stability. A second class of feedback system—positive feedback—generates growth processes where action builds a result that generates still greater action, e.g., population growth. A positive feedback system structure amplifies or adds to change and thus causes the system to diverge or move away from the goal.

A feedback loop is the basic structure within the system, and levels and rates are fundamental variables within a feedback loop. The level variables describe the condition of the system at any particular time, and rate variables tell how fast the levels are changing. The feedback loops are also known as causal loops. The diagrams representing feedback loops and their variables are known as causal loop diagrams or influence diagrams. These diagrams show how levels and rates are interconnected to produce the feedback loops and how the feedback loops interconnect to create the system. The reading of these diagrams indicates how a given system might behave because of its internal feedback loops and the effect that positive and negative feedback loops have on a system. The convention for the diagram is that arrows depicting both the direction and sign of influence indicate links between state variables. Figs. 1(a and b) are a part of causal loop diagram for a reservoir. The causal loop disgram in Fig. 1(a) indicates that the inflow has a positive influence on reservoir storage. The increase in reservoir storage causes an increase in the reservoir level, which leads to increase in area covered by the reservoir, thus causing flooding upstream of the reservoir. Increased flooding upstream of the reservoir will trigger more release from the reservoir, thus reducing the reservoir storage. Similarly, increase in releases will increase river flow, thus causing downstream flooding that will lead to a decrease in releases from the reservoir. The causal loop diagram in Fig. 1(b) indicates that storage reallocation, e.g., increasing the flood storage zone in the reservoir, will reduce flooding; however, it will also reduce the supply of water for other uses. Increasing the maximum reservoir level, e.g., putting gates on the spillway, will positively influence the availability of water for other purposes and will reduce flooding downstream of reservoir, but at the cost of increased flooding upstream of reservoir. Causal loop diagrams play an important role in describing the system behavior and the relationship between its components.

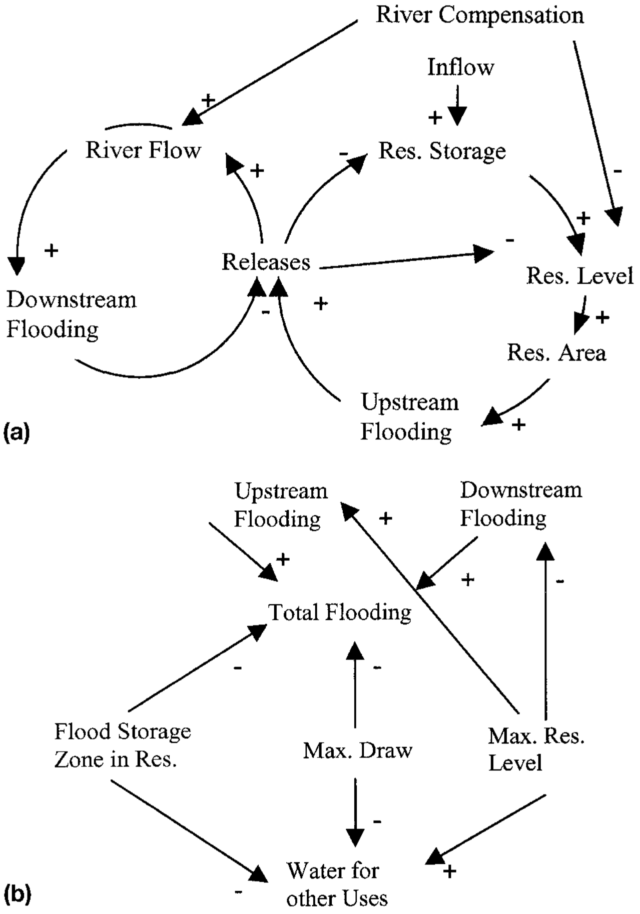


FIG. 1. Example of Causal Loop Diagram for Reservoir

The model of reservoir simulation presented in this paper, using the SD approach, has been implemented in the STELLA environment (*Tutorial* 1992). The modeling tool, which is an object-oriented simulation environment, allows the development of complex water resources models with significantly less effort than using traditional programming languages. It has a user-friendly graphical interface and supports modular program development. Using this tool, the modeler defines objects representing physical or conceptual system components and indicates the functional relationships among these objects. This mode of construction is analogous to drawing a flow chart or schematic of the system to be simulated. Building on these strengths, the general architecture of a reservoir simulation model is described in the next section.

MODEL ARCHITECTURE

This study deals with modeling reservoir operation using the SD approach. The model is developed for a single multipurpose reservoir with a focus on flood management role of the reservoir. Then, the model is used to develop a reservoir operational policy for high-flow years to minimize flooding. The model also serves as a tool for studying impacts of changing reservoir storage allocation and temporal distribution of reservoir levels and outflows. The general architecture of the model is presented in this section, and model sectors and the complex dynamic relationships among these sectors are also discussed.

The SD model of a reservoir can be constructed graphically on the screen by employing basic building blocks, i.e., stocks, flows, connectors, and converters available in the model development tool. In the reservoir model the storage is represented as a stock. Varying inflows and outflows cause changes in storage volume over time. Inflows and outflows are represented by building block "flow." Converters are provided to extend the range of calculations that can be performed on flows, and they house data and logical/mathematical functions to operate the system. Reservoir operating rules are also implemented through converters. Connectors (directed arrows) link various elements of the model, i.e., converters, flows, and stock, to indicate relationships and influence. The simulation model uses differential and difference equations to describe the complex dynamic systems. These equations are solved with Euler's method. Due to the modular nature of the simulation tool, the reservoir model is developed in sectors that are described in the next section.

Model Sectors

A general reservoir simulation model for flood management purpose can be divided into three main sectors: the reservoir, the upstream area, and the downstream area. A schematic diagram of reservoir and its three sectors is shown in Fig. 2. Details on these sectors follow.

Reservoir

This is the core sector of the reservoir model. Inflows and outflows from the reservoir are the main components of this sector. Flow from all tributaries directly contributing to the reservoir is considered as inflow to the system. Inflow data files, one for each flood year, are provided to the model as input. Total reservoir outflow consists of reservoir releases, spill, evaporation, and seepage losses. Reservoir storage can be described in terms of mass balance equation:

$$\text{Storage}(t) = \text{Storage}(t-1) + (Q_{\text{in}} - Q_{\text{out}}) \cdot dt \tag{1}$$

Storage at time step *t* is equal to the storage at a previous time step plus the difference of inflow and outflow. The solution interval (*dt*) is selected to ensure stability within the computation process.

Conduit flow and spillway modules govern the flow through the conduit and the spillway, respectively. System constraints, spillway curves, and conduit outflow capacity at different gate openings are provided to the model as part of its knowledge base. Reservoir operating rules are captured in this sector using IF-THEN-ELSE statements. A screen dump of the reservoir sector is shown in Fig. 2(b).

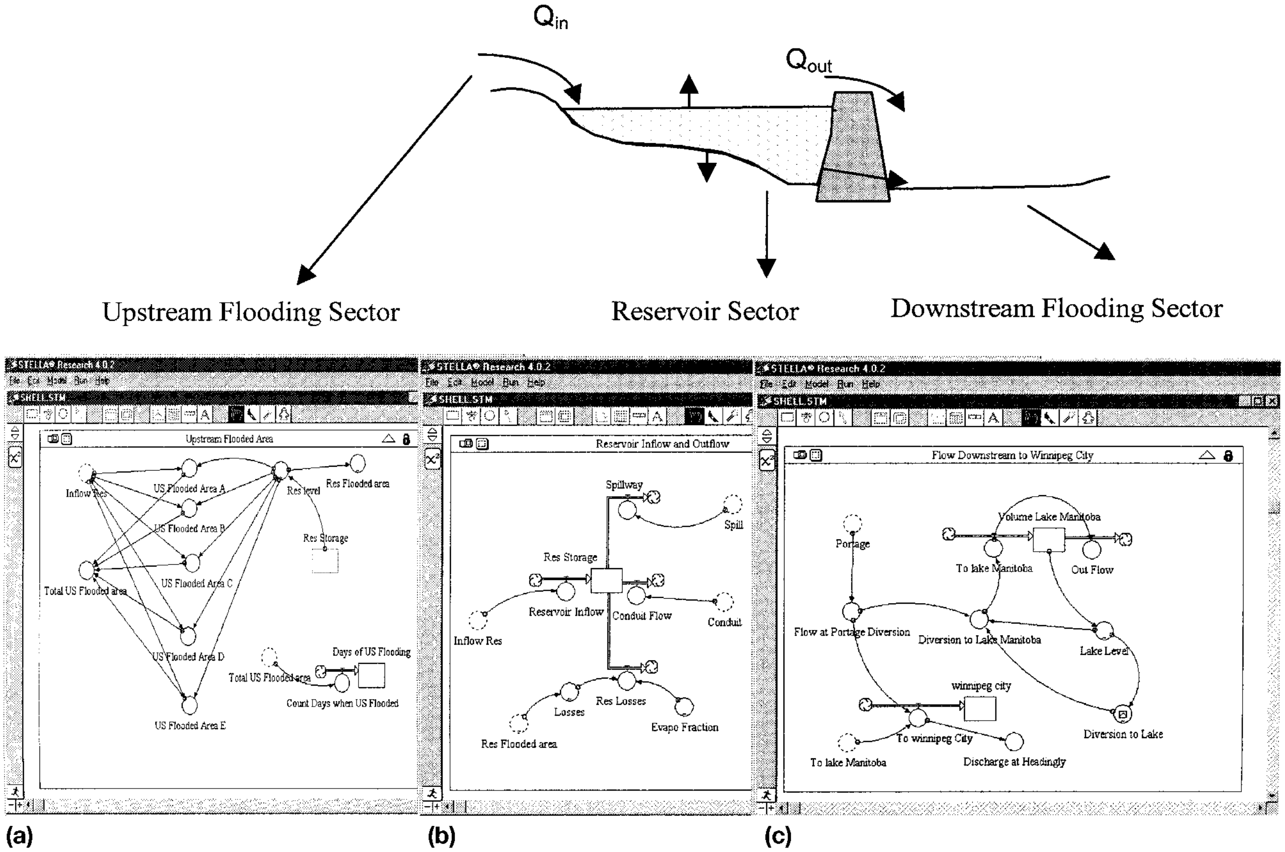
Upstream Flooding

This sector calculates the area flooded upstream of the reservoir. Upstream flooding is triggered by a combination of reservoir inflow, reservoir level, and reservoir outflow. The number of days when the upstream area is flooded is also counted in this sector. A screen dump of this sector is shown in Fig. 2(a).

Downstream Flooding

This sector calculates individual and total flooded area and duration of flooding due to the reservoir operation at selected locations between the dam and the final disposal point of the river. All sources and sinks affecting the flow in the river are introduced in this sector. A part of the downstream flooding sector is shown in Fig. 2(c).

To set up a general reservoir simulation model for flood management purpose inflows, system constraints and operating rules are required. Additional data might be required depending on specific objectives of the study. The data requirements for the model are discussed in detail in the following section.



(a) **(b)** **(c)**

FIG. 2. Schematic Diagram of Reservoir with Different Sectors

As output, the model provides information on variation of the reservoir levels, area flooded upstream and downstream of the reservoir, and duration of flooding. Once all sectors are developed and model relationships and operating rules are defined, the user can simply run the simulation and evaluate the impacts of alternate operating rules. To demonstrate the applicability of the proposed reservoir simulation approach, a case study is presented.

CASE STUDY APPLICATION

The proposed SD approach for modeling reservoir operations has been applied to the Shellmouth reservoir, located on the Assiniboine River, close to the Manitoba/Saskatchewan border in Canada. The flooding in the Assiniboine River, mainly caused by heavy spring runoff, has resulted in extensive damage to residential, agricultural, and industrial property. The Shellmouth dam and reservoir were developed primarily to protect the cities of Brandon and Winnipeg from floods on the Assiniboine River. Supplementary benefits of the project include flood control to agricultural land in the river valley. The problem of flooding upstream of the Shellmouth reservoir is caused by a combination of high water levels in the reservoir and high inflows during flood season. Releases from the reservoir that exceed the channel capacity cause flooding at several locations along the river downstream of the reservoir. Currently, there is no control structure on the spillway to regulate spill from the reservoir. Considering these aspects of flooding, the objectives of the simulation modeling study were defined as:

- Developing a reservoir operational policy for high flow years to minimize flooding.
- Exploring the impacts on the reservoir flood management capacity by installing gates on an existing unregulated spillway.
- Developing a tool for evaluating alternative operating rules by changing the reservoir storage allocation, the reservoir levels at the start of the flood season, and the reservoir outflows.

A schematic diagram of the study area is shown in Fig. 3. The Assiniboine River, on which the Shellmouth reservoir is located, flows along the towns of Russell, St. Lazare, Miniota, Griswold, Brandon, Holland, and Portage and finally joins the Red River in Winnipeg. Thus, flooding on the Assiniboine also contributes towards flooding of Winnipeg City. At Portage, a portion of the Assiniboine River discharge can be diverted to Lake Manitoba through a diversion channel of capacity 710 m^3/s. Headingly is the last station on the Assiniboine River where discharge is measured before the river joins the Red River in Winnipeg.

The Shellmouth Dam is a zoned earth-fill embankment, approximately 1,319 m long with an average height of 19.8 m. A gated concrete conduit with a maximum discharge capacity of 198.2 m^3/s on the east abutment and a concrete chute spillway on the west abutment control outflow from the dam (Water Resources Branch 1992). The reservoir is 56 km in length, 1.28 km in average width, and covers a surface area of 61 km^2 when full. The elevation of the top of the dam is 435 m above mean sea level with a dead storage elevation of 417 m. The spillway elevation is 12 m higher, at 429 m. The volume of the inactive pool below the conduit invert elevation is 12.3×10^6 m^3. The difference between volume of reservoir at active storage (370×10^6 m^3) and crest level of natural spillway (477×10^6 m^3) is the flood storage capacity of reservoir, i.e., 107×10^6 m^3. Current operating rules specify that the reservoir should be brought to 185×10^6 m^3 by March 31 to accommodate floods and a reservoir volume of 370×10^6 m^3 is a goal during the summer months. Maximum reservoir outflow is limited to 42.5 m^3/s to prevent flooding downstream, and the outflow must be greater than 0.71 m^3/s to avoid damage to fish and aquatic life in the river system (Water Resources Branch 1995).

The data sets that were used to set up the reservoir simulation model include: (1) reservoir volume curve; (2) reservoir area curve; (3) reservoir inflow (daily); (4) reservoir water levels (daily); (5) reservoir operating rules; (6) spillway rating curve; (7) conduit rating curve; (8) relationship between depth of water and area flooded at all points of interest upstream and downstream of the reservoir; (9) additional flows joining the Assiniboine at different downstream locations; and (10) evaporation and seepage losses from the reservoir.

MODELING APPROACH

The main objective of the study was to develop a reservoir operating policy for high-flow years/floods using the SD approach. The five largest flood events in the history of the reservoir, occurring in 1974, 1975, 1976, 1979, and 1995, were selected for simulation. Only inflow was considered as input

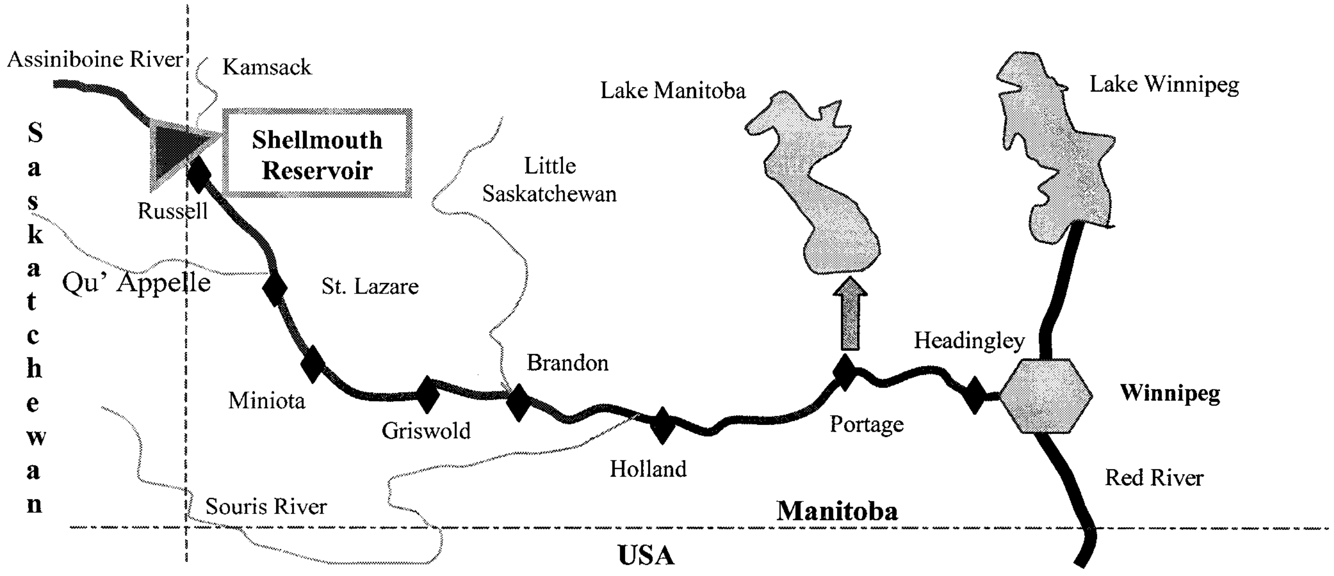


FIG. 3. Study Area

to the reservoir. Contribution of rain over the reservoir was not taken into account considering its insignificant influence on the reservoir operation during a flood. Outflow through the conduit and spills were considered as total outflow from the reservoir. The model was developed in three main sectors, i.e., the reservoir, upstream flooding, and downstream flooding, as described in general model architecture. After defining connections between model sectors and components, operating rules were incorporated in the model using logical statements of IF-THEN-ELSE structure:

$$\text{IF (Res\_level} > 429.3\text{) AND (Spillway\_Control} = 0\text{) AND (TIME} > 120\text{) AND (Reservoir\_Inflow} > \text{Unregulated\_Spillway) THEN (198)} \quad (2)$$

This statement explains that if the reservoir is full (429.3 m), unregulated spillway is selected for simulation, it is the flooding season (May), and inflow is more than outflow through the unregulated spillway, then the conduit must be operated at its maximum discharge capacity (198 m^3/s). Similarly, if for simulation, a gated spillway option is selected, the reservoir level has reached between 430.5 and 431.2 m, and it is the flooding season (late April to middle of June), then outflow should be equal to the inflow to the reservoir.

$$\text{IF (Spillway\_Control} = 1\text{) AND (Res\_level} > = 430.5\text{) AND (Res\_level} < = 431.2\text{) AND (TIME} > 110\text{) AND (TIME} < 165\text{) THEN (Reservoir\_Inflow)} \quad (3)$$

The option is provided in the model to route floods through the reservoir using natural spill or gated spill scenarios. The model uses the spillway rating curve and information on current reservoir level, inflows, and time of the year to make decision about discharges through the spillway. The conduit flow module defines the flow through the gated conduit. Based on which spillway option is active, there are two different sets of operating rules for conduit flow. Once spillway selection is made, this information is automatically passed to conduit control and appropriate conduit operating rules are fired. Current reservoir level, inflows, time of the year, and safe channel capacity downstream of the reservoir are criteria on which quantity of the releases through the conduit is based. At Portage a part of the Assiniboine River flow can be diverted to Lake Manitoba; this diversion is a function of levels in the lake and capacity of the diversion channel.

Several tests recommended by Forrester and Senge (1980) and Raymond (1985) including behavior replication test, behavior sensitivity test, and behavior prediction tests are performed to validate the model and to confirm that the model response matches the response of the system being modeled. These tests are equally valid for other simulation techniques and are independent of the problem domain.

The model development process is summarized in the schematic diagram of a model life cycle (Fig. 4). The modeling process starts with defining the purpose/goal of the system. Then, boundaries of the system to be modeled are specified. This is followed by identification of key variables in the system that affect the system the most. Then, behavior of the key variables is described, the stocks and flows are identified, and their structure is mapped in the modeling tool using basic building blocks. Quantitative information, i.e., equations and data, is included in the model structure. The model is run to test the behavior. The model is evaluated and adjustments are made. Once the model is replicating system behavior it is ready for simulation modeling.

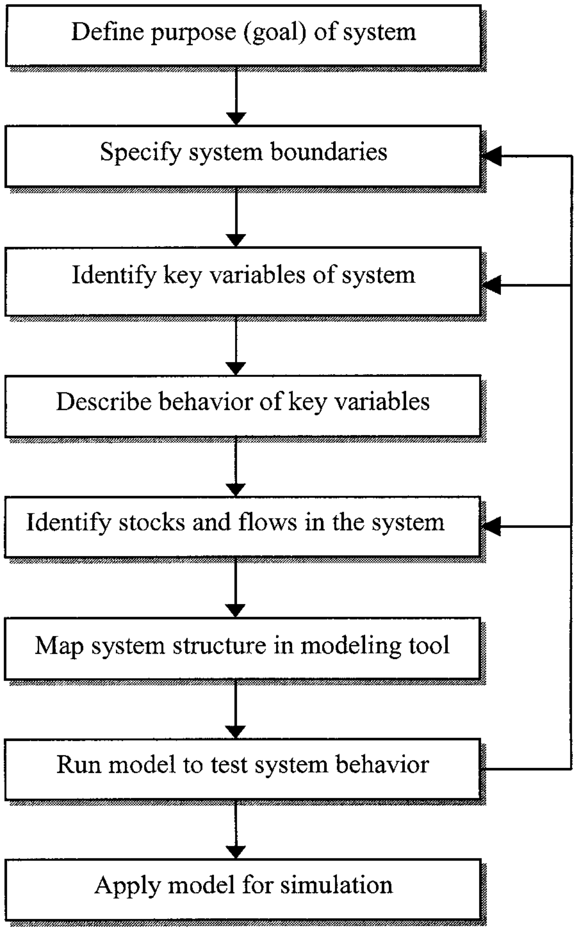
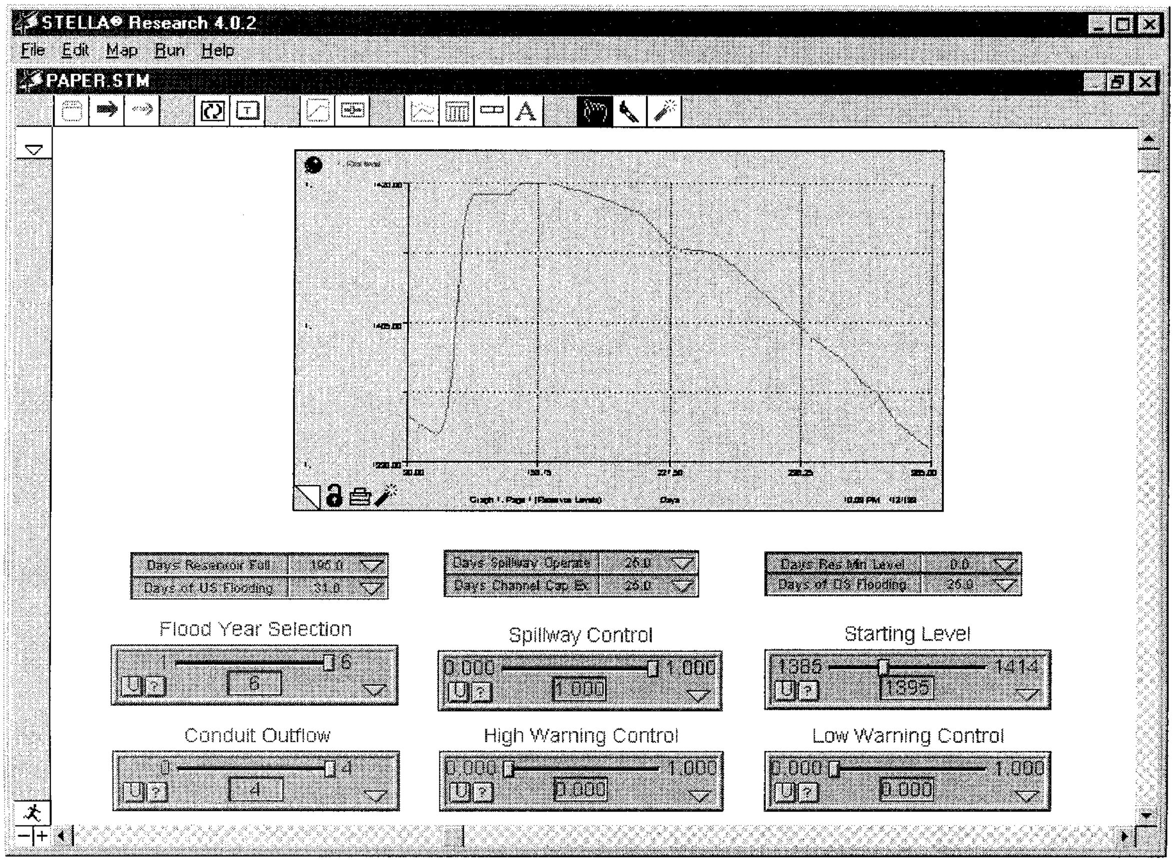


FIG. 4. System Dynamics Model Development Life Cycle

MODEL USE

The model's main control screen to run the reservoir operation simulations is shown in Fig. 5. There are five separate input data files for the five largest flood years. The user can select the flood year for simulation using a graphical tool (slider). Choices from 1 to 6 on the slider correspond to different flood years. The spillway module has a slider that provides the user with an option to choose either unregulated or gated spillway for simulation. Warnings linked to minimum and maximum reservoir levels have been provided in the model in the form of text messages and sounds. A text message ''Spillway will start operating soon'' prompts the user when the reservoir level reaches the spillway crest level. A sound warning in the model is activated when the reservoir reaches the minimum or the maximum level. While simulation is running, the operator has control over the flow through the conduit and can increase or decrease the discharges as the need arises. As output, the model provides information on variation of the reservoir levels. The model also calculates the number of days when the reservoir is full or at the minimum level and the number of days the spillway is operated. Other model output includes number of days of downstream/upstream flooding and number of days when channel capacity is exceeded due to reservoir operation. The model also calculates total and individual areas flooded at several locations along the river due to the reservoir operation.

After developing the model and ensuring that it replicated the actual system behavior, several model runs were carried out. Following each run, the reservoir levels and area flooded due to the reservoir operation were carefully studied. Then modifications of operating rules were made with a target to improve the reservoir performance for flood management. The



Days Reservoir Full 196.0
Days of US Flooding 31.0
Days Spillway Operate 26.0
Days Channel Cap Ex 26.0
Days Res Min Level 0.0
Days of DS Flooding 26.0

Flood Year Selection: 1 – 6, 6
Spillway Control: 0.000 – 1.000, 1.000
Starting Level: 1385 – 1414, 1395
Conduit Outflow: 0 – 4, 4
High Warning Control: 0.000 – 1.000, 0.000
Low Warning Control: 0.000 – 1.000, 0.000

FIG. 5. Main Control Screen of Reservoir Model

calculation of the flooded area and duration of flooding due to the reservoir operation provides information on the effectiveness of different operating policies for flood management. Simulation techniques are not capable of generating directly an optimal solution to a reservoir operation problem; however, by going through several runs of a model with alternative policies, an optimal or near optimal operating policy can be identified.

Simulations of the Shellmouth reservoir operation were made for the five largest historic floods with natural and gated spill scenarios. Model inputs were annual series of daily inflows to the reservoir during the five major flood events. Model output includes daily variation of the reservoir level, daily discharges from the reservoir, total flooded area upstream of the reservoir, discharges and flooded area at seven downstream locations, and diversion to Lake Manitoba at Portage. Discharges at Headingly were used to estimate the contribution of the Assiniboine River towards the flooding of Winnipeg City. Policy alternatives were explored by changing initial reservoir storage level, both at the start of simulation and at the start of flooding season. Trials were also made to explore the effects of changing outflow through the conduit on the variation of the reservoir level.

Models are developed to answer questions related to relatively uncertain conditions; this is especially true in water resources modeling. SD modeling provides a very convenient and powerful tool to explore how changes in one system variable impact other variables. For this study, a sensitivity analysis was performed on Time Step and Delays. Time Step, also called Delta Time (DT), is the interval of time between model calculations; thus, DT represents the smallest time interval over which a change in numerical values of any element in the model can occur. The Delay function returns a delayed value of input, using a fixed lag time of delay duration. This function is important to capture the timing of the flood peak, as flow takes five days to reach Winnipeg once released from dam. With several trials it was found that a time step of one day provides the best trade-off between speed of calculation and accuracy of results. Similarly, a variation of the delay function, used for flood routing, affects the timing and the duration of flooding at downstream locations.

RESULTS AND DISCUSSION

Daily variations of the reservoir levels for four major flood events (1974, 1975, 1976, and 1979) are shown in Fig. 6. A summary of selected results is provided in Tables 1–3. Revised operating rules with natural spill and gated spill are shown in Fig. 7 along with existing operating rules. Results show that with revised operating rules it was possible to operate the reservoir with only minor flooding upstream and downstream for four out of five major flood events. While simulating flood years 1975 and 1976, the spillway was not

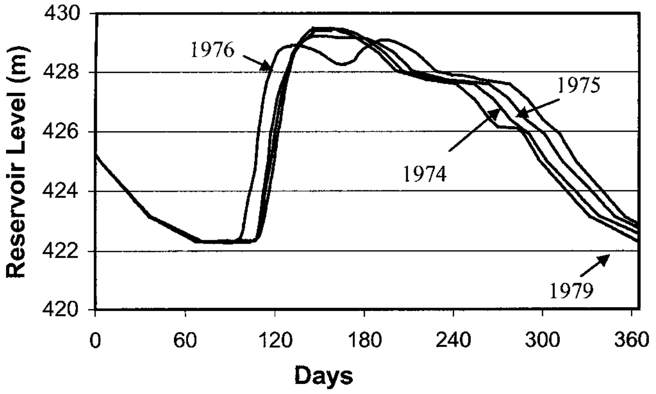


FIG. 6. Water Levels in Shellmouth Reservoir for Flood Years 1974, 1975, 1976, and 1979

TABLE 1. Flood Management with Revised Operating Rules for Selected Flood Years

Flood year (1)	Operating rules (2)	Spill (3)	Reservoir full (days) (4)	Upstream flooding (days) (5)	Down-stream flooding (days) (6)	Area flooded (ha) (7)
1974	Existing	Natural	101	4	11	630
	Revised	Natural	119	6	5	70
	Revised	Gated	125	1	0	0
1976	Existing	Natural	120	2	7	370
	Revised	Natural	158	0	0	0
	Revised	Gated	158	0	0	0
1979	Existing	Natural	106	5	19	1,067
	Revised	Natural	121	11	12	151
	Revised	Gated	129	0	0	0
1995	Existing	Natural	161	7	47	24,530
	Revised	Natural	193	5	38	21,537
	Revised	Gated	250	30	23	16,234

TABLE 2. Impacts on Flooding by Changing Reservoir Levels at Start of Year (A) and Start of Flooding Season (B) for 1976 Flood Year without Using Gated Spillway

Initial reservoir level (m) (1)	Reservoir full (days) (2)	Upstream flooding (days) (3)	Downstream flooding (days) (4)	Total area flooded (ha) (5)
A				
422.2	163	0	0	0
425.2	163	0	0	0
428.3	176	2	0	152
429.2	195	5	0	152
B				
422.2	163	0	0	0
425.2	174	12	17	4,790
428.3	195	13	26	20,160
429.2	195	13	31	21,030

TABLE 3. Impacts on Flooding by Changing Flow through Conduit

Conduit outflow [m^3/s (cfs)] (1)	Reservoir full (days) (2)	Upstream flooding (days) (3)	Downstream flooding (days) (4)	Reservoir level at end of year (m) (5)
45.3 (1,600)	157	0	0	422.64
34.0 (1,200)	164	0	0	422.79
19.8 (700)	196	10	0	424.37
11.3 (400)	247	10	0	427.33
0 (0)	250	10	0	429.25

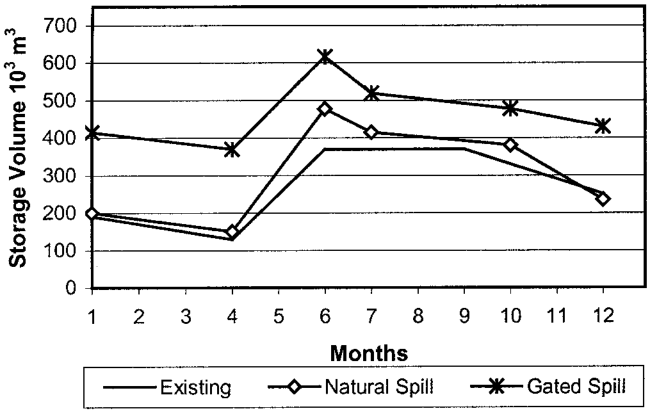


FIG. 7. Existing and Revised Rule Curves with Natural Spill and Gated Spill

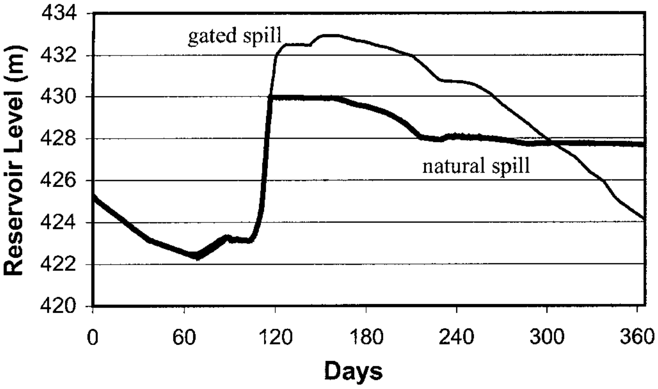


FIG. 8. Comparative Graph of Water Levels in Shellmouth Reservoir (Flood Year 1995) with Natural Spill and Gated Spill

operated and there was no flooding upstream or downstream. In flood year 1974, the spillway was operated for only five days with a maximum discharge of 9.35 m^3/s and 70 hectares were flooded. Similarly in 1979, the spillway was operated with a maximum discharge of 37.97 m^3/s and 151 hectares of land were flooded. Simulations were made again for the flood events of 1974 and 1979 with the gated spillway option and it was found that downstream flooding can easily be avoided without increasing flooding upstream of the reservoir.

The flood in 1995 has a return period of 100 years and inflows were well over three times the volume usually experienced. However, this flood event provided an opportunity to look into the advantage of having a gated spillway. With the free spill option, 166 hectares upstream and 21,371 hectares downstream were flooded for 5 and 38 days, respectively (Table 1). Peak discharge was reduced from its natural 660.92 m^3/s to 359.45 m^3/s through the reservoir operation. By routing the flood of 1995 through the reservoir with the gated spillway option, there was a reduction of about 5,000 hectares in flooded area and flood days were reduced to 23. Maximum outflow was reduced to 223.85 m^3/s, an almost 40% improvement over the unregulated spillway option. With gated spillway the maximum discharge at Headingly was 5.66 m^3/s, which is equal to the minimum required flow, as compared with 172.2 m^3/s with the free spill option. This means that Assiniboine River's contribution towards flooding of Winnipeg City was zero. Fig. 8 shows a comparative graph of the reservoir level variation with and without gates on the spillway for the 1995 flood. The reservoir levels with gated spill are higher compared with levels with free spill, as more water is stored during the flood. The reservoir with gated spill reaches a lower level at the end of simulation because discharges through the conduit, over the falling limb of the hydrograph, are higher to release water stored during the flood.

Reservoir Level at Start of Simulation

The 1976 flood year was selected to investigate how initial water levels in the reservoir, at the start of simulation, and at the start of flood season, affect the spillway operation and the reservoir levels during the flood. 1976 was selected because this year was the 2nd largest flood in terms of volume of inflow and the spillway was not operated during the simulation with the free spill option. Several simulations were carried out by considering different levels at the start of the year and at the start of flooding season. The simulations considered a range of reservoir levels between empty (422.5 m) and full (429.5) reservoir.

The effects of varying the reservoir level at the start of year are shown in Fig. 9. It can be noted that if simulation starts in January, the reservoir levels at the start of simulation do not have any serious impact on the reservoir levels during the flood and total area flooded as a result of reservoir operation (Table 2). As floods arrive typically in late April or early May, there is sufficient time to bring the reservoir to a lower level to accommodate incoming floods. Release rules are written in a way that they adjust outflow based on the information on inflow, time of the year, and the reservoir level. If the reservoir simulation starts in April, the impact of initial reservoir level on the reservoir levels during the flood is significant (Fig. 10). As the flood arrives soon after simulation starts, there is not enough time to bring the reservoir to a lower level to accommodate incoming flood. By increasing the initial reservoir level, the number of days when the reservoir is full, the number of days of upstream and downstream flooding, and flooded area increase as well (Table 2).

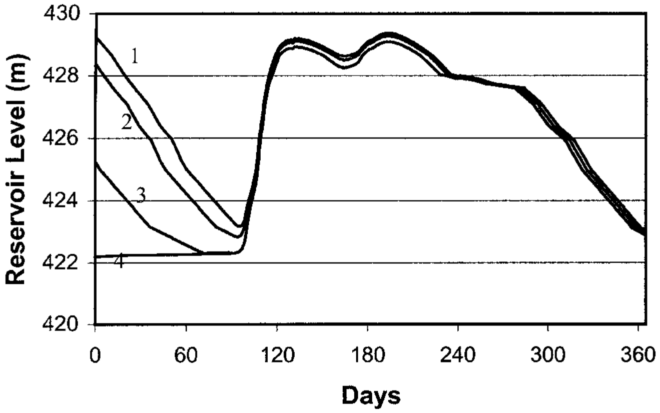


FIG. 9. Reservoir Levels by Varying Initial Reservoir Level at Start of Simulation: Curve 1 = 422.2 m; Curve 2 = 425.2 m; Curve 3 = 428.3 m; Curve 4 = 429.2 m

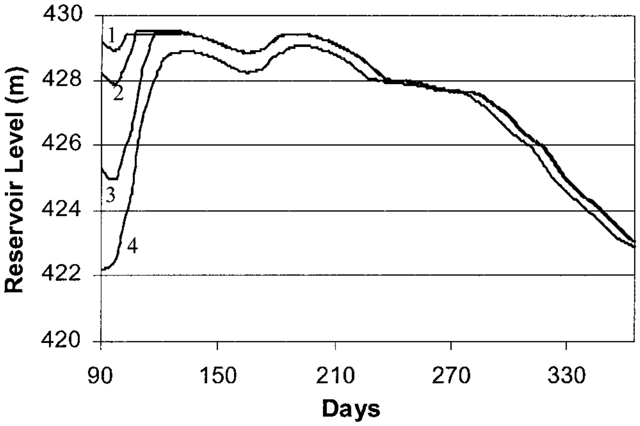


FIG. 10. Reservoir Levels by Varying Initial Reservoir Level at Day 90: Curve 1 = 422.2 m; Curve 2 = 425.2 m; Curve 3 = 428.3 m; Curve 4 = 429.2 m

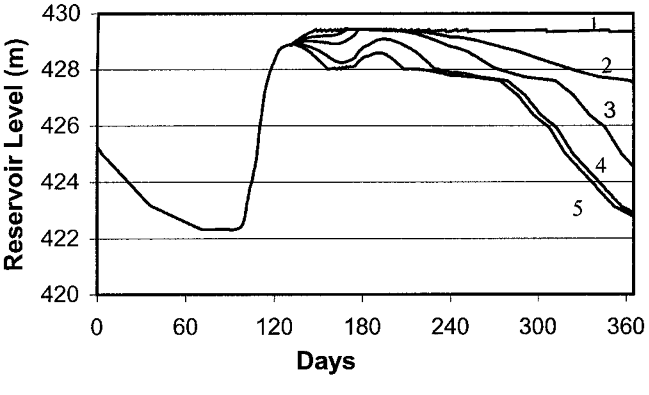


FIG. 11. Reservoir Levels by Varying Discharges through Conduit (Falling Limb of Hydrograph at Elevation 429.2–428 m): Curve 1 = 0 m^3/s; Curve 2 = 11.3 m^3/s; Curve 3 = 19.8 m^3/s; Curve 4 = 34.0 m^3/s; Curve 5 = 45.3 m^3/s

Flow through Conduit

The variation of the reservoir level, by changing outflow through the conduit for a range between no flow and maximum flow, is shown in Fig. 11. Data in Table 3 and Fig. 11 support that both reservoir levels at the end of simulation and the number of days when reservoir is full are very sensitive to outflow through the conduit.

Summary of Results

System dynamics proved to be a very time efficient, user friendly, and successful approach for modeling the reservoir operations. The simulation of the reservoir operation verified that with the revised operating rules, the capability of the Shellmouth reservoir for flood management can be improved. For four out of the five largest historic floods, the reservoir was operated without causing any significant flooding downstream or upstream. Due to revision of the operating rules, the contribution of the Assiniboine River towards the flooding of Winnipeg City is negligible (discharge at Headingly, which once reached 170 m^3/s, can be reduced to 5.66 m^3/s with the gated spillway option). Number of days when reservoir is full or at the minimum level is very sensitive to reservoir outflows, especially over the falling limb of the flood hydrograph. Reservoir levels during the flood, flooded area upstream as well as downstream, and duration of flooding are sensitive to reservoir level at the start of the flooding season.

Simulation of the Shellmouth reservoir operation, considering both gated and unregulated spillway options, suggests that installation of gates on the spillway will improve the flood management capacity of the reservoir, especially for large floods. Installation of gates may be justified, as flooding upstream due to the reservoir level rise is insignificant compared with the flood losses downstream. However a detailed study incorporating economic analysis and environmental impacts is recommended before finalizing the decision to put gates on the spillway.

CONCLUSIONS

The research reported in this paper focused on the simulation of a single multipurpose reservoir for flood management purposes using the SD approach. Operating rules were revised for high-flow/flood years to minimize flooding. Impacts on flood management capacity of the reservoir were explored by simulating a gated spillway in addition to the existing unregulated spillway. Alternative operating rules were explored by changing the reservoir storage allocation, reservoir levels at the start of flooding season, and the reservoir outflows.

The proposed SD-based simulation approach is a valuable alternative to conventional simulation techniques. The increased speed of model development, ease of model structure modification, ability to perform sensitivity analysis and effective communication of model results are the main strengths of the reservoir simulation model based on the SD approach. However, one limitation is the simplified flood routing as compared with sophisticated hydrodynamic models.

Because of its ease of construction and modification, SD simulation environments facilitate rapid prototyping and greatly reduce programming effort. Modeling effort can be directed to important tasks such as system conceptualization, data collection, gaining input from system operators, and involving stakeholders.

The Shellmouth reservoir simulation model can be finetuned easily in light of operating experience, or with the help of insight provided by an expert. The SD approach offers a way for operators to participate in the model building process, thus increasing their trust in the model. The operator's feedback provides direction for follow-up simulations and modifications in the model structure.

The entire modeling process is open, interactive, and transparent. The model is easy to expand and modify in terms of its internal structure and the amount, type, and resolution of data used. Modifications in both structure and values of parameters can be made easily as new information that can affect the model becomes available. The model can then be rerun, the results analyzed, and the model improved as necessary. Thus, the entire dynamic modeling process facilitates adaptation of a general model to a particular problem.

The architecture of the Shellmouth reservoir model is generic in nature and can be applied to other reservoirs by replacing data and operating rules for that particular reservoir. Numerous simulation scenarios, in addition to what has been demonstrated in this study, can be tested using the existing framework. As the current model provides information on extent and duration of flooding, another sector can be added to calculate damage to crops or economic losses due to lost opportunity of seeding. The model can be extended from a single multipurpose reservoir to a system of reservoirs.

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APPENDIX. REFERENCES

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 Technolo. for Decision-Making in Civ. Engrg.*, University of Quebec, Montreal, Canada, 909–920.

Forrester, J. W. (1961). *Industrial dynamics*, Productivity Press, Portland Oreg.

Forrester, J. W., and Senge, P. M. (1980). ''Tests for building confidence in system dynamics models.'' *TIMS studies in management science*, Vol. 14, A. Legasto, J. Forrester, and J. Lyneis, eds., North Holland Press, Amsterdam.

Keys, A. M., and Palmer, R. (1993). ''The role of object oriented simulation models in the drought preparedness studies.'' *Proc., 20th Ann. Nat. Conf., Water Resour. Plng. and Mgmt. Div.*, ASCE, New York, 479–482.

Loucks, D. P., Stedinger, J. R., and Haith, D. A. (1981). *Water resources systems planning and management*, Princeton Hall, Englewood Cliffs, N.J.

Matthias, R., and Frederick, P. (1994). ''Modeling spatial dynamics of sea-level rise in a coastal area.'' *Sys. Dyn. Rev.*, 10(4), 375–389.

Mays, W. L., and Tung, Y.-K. (1992). *Hydrosystems engineering and management*, McGraw-Hill, New York.

Palmer, R. (1994). ''(ACT-ACF) River basin planning study.'' ⟨http://maximus.ce.washington.edu/~actacf/⟩.

Palmer, R., Hilton, K., and Hahn, M. (1995). ''Willamette river basin reauthorization feasibility study.'' ⟨http://www.ce.washington.edu/~willamet/⟩.

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

Raymond, C. S. (1985). ''Dynamic simulation models: how valid are they?'' *Self-report methods of estimating drug use: meeting current challenges to validity*, A. B. Rouse, J. N. Kozel, and G. L. Richards, eds., National Institute on Drug Abuse, Bethesda, Md.

Russell, S. O., and Campbell, P. F. (1996). ''Reservoir operating rules with fuzzy programming.'' *J. Water Resour. Plng. and Mgmt.*, ASCE, 122(3), 165–170.

Simonovic, S. P. (1992). ''Reservoir systems analysis: closing gap between theory and practice.'' *J. Water Resour. Plng. and Mgmt.*, ASCE, 118(3), 262–280.

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. Mgmt.*, 11(4), 243–261.

Tutorial and technical documentation STELLA® II. (1992). High Performance Systems, Inc., Hanover, N.H.

Water Resources Branch. (1992). ''Shellmouth reservoir study: preliminary study of spillway control gates.'' *Internal Rep.*, Manitoba Department of Natural Resources, Winnipeg, Canada.

Water Resources Branch. (1995). ''Assiniboine river flooding & operation of Shellmouth dam.'' *Rep. Prepared for the Shellmouth Flood Review Committee*, Manitoba Department of Natural Resources, Winnipeg, Canada.

Wurbs, R. A., and Tibbets, M. N. (1985). ''State-of-the-art review and annotated bibliography of systems analysis techniques applied to reservoir operations.'' *Tech. Rep. No. 136*, Texas Water Resources Institute, College Station, Tex.

Yeh, W. W.-G. (1985). ''Reservoir management and operation models: a state-of-the-art-review.'' *Water Resour. Res.*, 21(12), 1797–1818.