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An Intelligent Decision Support System for Management of Floods

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Abstract. Integrating human knowledge with modeling tools, an intelligent decision support system (DSS) is developed to assist decision makers during different phases of flood management. The DSS is developed as a virtual planning tool and can address both engineering and non-engineering issues related to flood management. Different models (hydrodynamic, forecasting, and economic) that are part of the DSS share data and communicate with each other by providing feedback. The DSS is able to assist in: selecting suitable flood damage reduction options (using an expert system approach); forecasting floods (using artificial neural networks approach); modeling the operation of flood control structures; and describing the impacts (area flooded and damage) of floods in time and space. The proposed DSS is implemented for the Red River Basin in Manitoba, Canada. The results from the test application of DSS for 1997 flood in the Red River Basin are very promising. The DSS is able to predict the peak flows with 2% error and reveals that with revised operating rules the contribution of Assiniboine River to the flooding of Winnipeg city can be significantly reduced. The decision support environment allows a number of "what-if" type questions to be asked and answered, thus, multiple decisions can be tried without having to deal with the real life consequences.

Key words: artificial neural networks, decision support system, flood forecasting, flood management, reservoir operation, Red River, system dynamics

Introduction

Floodplains provide advantageous locations for urban and agricultural development. Unfortunately, the same rivers that attract development periodically overflow their banks causing loss of life and property damage. A variety of structural and non-structural measures can be implemented to reduce flood damages. However, complete control of floods is seldom economically feasible. Flood management is aimed at reducing potentially harmful impacts of floods on people, the environment and the economy of the region.

The flood management process can be divided into three phases: (a) pre-flood planning; (b) flood emergency management; and (c) post-flood recovery. During the first phase, called *pre-flood planning*, different flood management options (structural and non-structural) are analyzed and compared for possible implementation to reduce flood damages in the river basin. Hydrodynamic modeling and economic analysis tools play an important role in this phase. Future population and economic activity projections are also important in analyzing the long-term impacts of decisions made during this phase of the flood management.

The second phase of flood management, called *flood emergency management*, involves the forecasting of floods and a regular updating of forecasts. A frequent assessment of the current flood situation and the operation of flood control structures are important during this phase. At this stage, urgent decisions are made to protect communities and capital works. This may involve upgrading flood protection works such as strengthening and extending dikes. From an appraisal of the current situation, decisions on evacuation of different areas are also made.

The third phase, called *post-flood recovery,* involves decisions regarding the return to normal life activity from a period of flooding. During this phase, impacts are evaluated and mitigation strategies are implemented. Some issues of main concern during this phase of the flood management include: the provision of assistance to flood victims; an evaluation of flood damages; and the rehabilitation of damaged properties.

Flood management is a complex process, requiring the simultaneous consideration of the hydrologic, hydraulic, geotechnical, environmental, economic and behavioral aspects (Simonovic and Ahmad, 2005). It requires a basin-wide planning perspective, as flood control in one area may exacerbate the flooding conditions of another area. A large database and several analytical tools are required to describe the flooding and its' impacts. The use of decision support systems (DSS) based on state-of-the art modeling tools, is becoming increasingly popular in dealing with the complexity of issues involved in flood management. Advances in remote sensing, geographic information systems (GIS), artificial intelligence, policy analysis, simulation modeling, and risk analysis have made it possible to develop and implement easy -to- use and interactive decision support systems for flood management (Ahmad and Simonovic, 2004).

Simonovic (1999b) defined a DSS: "*A decision support system allows decision-makers to combine personal judgment with computer output, in a user-machine interface, to produce meaningful information for support in a decision-making process. Such systems are capable of assisting in solution of all problems (structured, semi-structured, and unstructured) using all information available on request. They use quantitative models and database elements for problem solving. They are an integral part of the decision-maker's approach to problem identification and solution*". The purpose of DSS is not to replace humans but to support decision makers in making informed choices. In the end, the time and the steps necessary to find a satisfactory solution to a problem are essentially shortened. A detailed discussion of the structure and components of DSS can be found in Thierauf (1988) and Mallach (1994).

Considerable work on decision support systems has been reported in the literature for a variety of engineering tasks, ranging from design to planning, management, and operations. Examples of several decision support systems with environmental applications can be found in Guariso and Werthner (1989). DSS have been developed for estuarine water-quality management (Câmara, 1990), impact analysis of catchment policies (Davis *et al.*, 1991), reservoir management and operations (Simonovic, 1992), regional water-resources planning (McKinney *et al.*, 1993), stream flow forecasting (Bender and Simonovic, 1994), drought monitoring (Chang *et al.*, 1996), drought management (Palmer and Tull, 1987; Palmer and Holmes, 1988), and river management (Ford and Killen, 1995). Keyes and Palmer (1993) developed a DSS for the prioritization of discharges. In a series of two papers, Simonovic (1996a,b) discussed the structure of DSS for the sustainable management of water resources. Simonovic (1999a) presented a framework for a decision support system for flood management. Bender and Simonovic (2000) used the systems approach for collaborative decision support in water resources planning. Ahmad and Simonovic (2001a) developed a DSS to evaluate economic losses and area flooded due to operation of flood control structures. This work differs at two levels from all previous attempts. First, in a single model it provides decision support for different phases of flood management, from flood forecasting to impact estimation. Second, it addresses both engineering and non-engineering issues in an integrated manner.

A comprehensive decision support system that covers all phases of the flood management process is developed and described in this paper. The system is called DEcision Support for Management Of Floods (DESMOF). The paper begins with an introduction to the flood management process. The next section is devoted to the details of the DESMOF and its' functionality. Three major functions of the system, i.e., selection of flood damage reduction options, flood forecasting, and operation of flood control structures are described. A case study of the Red River in Manitoba, Canada is presented to demonstrate the applicability of the DESMOF. The paper concludes with the discussion of the functions of DESMOF.

Decision Support System for Management of Floods

The DESMOF is developed to meet the specific needs of the Red River basin in Manitoba, Canada. The data used by the DESMOF is case study specific, but the framework is generic and can be used for flood management in other areas.

The architecture of the DESMOF, with its components and their interconnectivity is presented in Figure 1. The four components of DESMOF are: (i) Graphical user interface; (ii) knowledgebase; (iii) modelbase; and (iv) database. The main strength of the architecture is its ability to integrate the knowledge of the problem domain with the database, modelbase, and graphical tools to provide assistance in decision making.

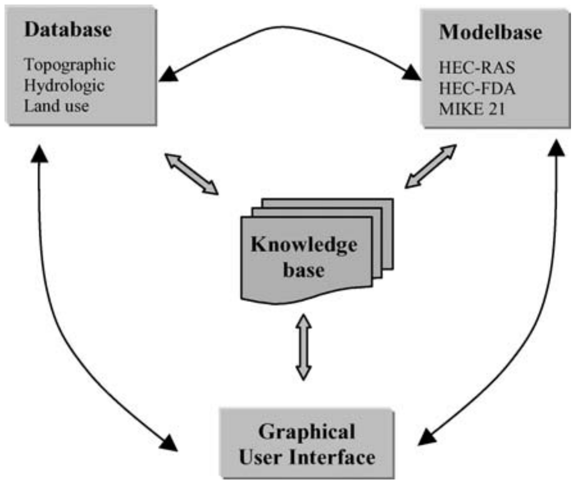


Figure 1. Architecture of decision support system for management of floods.

(i) *Graphical user interface (GUI)*: GUI of DESMOF is developed using Visual Basic. It helps in problem formulation, data input, and presentation of results, using graphics, data visualization tools and GIS. GUI can directly communicate with database, modelbase and knowledgebase.

(ii) *Knowledgebase*: The human expertise and heuristic knowledge are a valuable resource when coupled with modeling tools to make decisions for flood management. Human expertise and heuristic knowledge related to the selection of flood damage reduction option are captured using expert systems approach and coded in the knowledgebase of the DESMOF. The knowledgebase draws inferences from the data presented through GUI, consults modelsbase, and assists flood manager in selecting a suitable flood damage reduction option for a given location.

(iii) *Modelbase*: The modelbase of DESMOF consists of a set of tools for flood forecasting, hydrodynamic modeling, economic analysis, and policy analysis. Both, one-dimensional (HEC-RAS) and two-dimensional (MIKE 21) hydrodynamic modeling tools are available to simulate the runoff process. HEC-FDA is available for flood damage analysis. System dynamics modeling environment (Stella) is available for operation of flood control structures, and analysis of impacts. The modeling tools in the modelbase communicate with the user through GUI to formulate problem, obtain required data from database, and provide results to knowledgebase or directly to the user.

(iv) *Database*: The database of DESMOF holds all required data for flood management. The data sets include: topographic data (river setup, cross sections, floodplains); hydrologic data (precipitation, discharge); reservoir data (area curves, volume curves, operating rules); and infrastructure data (damage curves, land use). GIS (ArcView) processes and provides topographic data related to river and floodplains as input to the hydrodynamic models and economic analysis model in the modelbase.

The DESMOF consists of three modules: (a) selection of flood damage reduction options; (b) flood forecasting; and (c) operation of flood control structures. Hydrodynamic models and economic analysis model provide support to the three main modules. The DESMOF is developed to address the specific characteristics of flooding in the Red River basin. The Red River basin specific characteristics include: frequent flooding (need for flood damage reduction options); river passing through a major city (need for flood forecasting); presence of flood control structures such as reservoir, floodway, and dikes (need for operation of flood control structures); and flat topography (requires 2-D hydrodynamic modeling). Different modules of DESMOF can be activated from the opening screen. A graphical user interface behind the opening screen allows for the interaction between the system and the user. In an interactive environment, using GUI, the user enters information about different aspects of the river system and the area to be protected from floods. Results are communicated to the user through GUI. Built-in help facility and menu-driven commands make it an easy-to-use system. An explanation capability is available to inform the user of why a particular question was asked or why a certain recommendation was made. In the following section, the three modules of DESMOF are individually described in more detail in terms of background, method, and link with other modules.

Selection of Flood Damage Reduction Options Module

BACKGROUND

The function of this module is to assist in selecting a suitable flood damage reduction option for a given area. The knowledge base of the module is developed by capturing the process used by expert engineers for selection of a suitable flood damage reduction option. An expert system approach is used to integrate information available in the knowledge base with analytical tools for selection of a flood damage reduction option.

Typically, the selection process of a suitable flood damage reduction option for a given area starts with the review of available information and data related to the river system, and the area to be protected from floods. Based on preliminary information, the feasibility of different available flood management options (e.g., dike, reservoir, diversion) is evaluated. Feasibility studies for engineering projects depend on the understanding of the various components of the problem, a broad knowledge of techniques yielding possible solutions, and the constraints related to these solutions. An experienced professional with knowledge of the flood management domain using available data/information may discard some flood damage reduction options without going into detailed analysis. For example, a reservoir is not a practical option when floodplains are very flat and a storage location is not available. In a similar process, different flood management options are analyzed one by one based on the heuristic knowledge. Finally, one or more potential flood management options are selected for detailed analysis. The detailed analysis covers hydraulic and economic evaluation of the selected options, leading to the final selection of an appropriate flood damage reduction option. The entire process is captured in the knowledge base of this module (Ahmad and Simonovic, 2001b).

METHOD

The approach makes use of an expert system shell M 4 (Cimflex Teknowledge Corporation, 1991) for knowledge coding and inferencing, and employs modeling tools for river analysis (HEC-RAS, U.S. Army Corps of Engineers 1998a) and flood damage analysis (HEC-FDA, U.S. Army Corps of Engineers 1998b). The knowledge specific to the flood management domain is collected through a series of interviews with experts. The acquired expert knowledge is coded using M 4, which provides a rule-based programming language environment.

HEC-RAS is used for hydraulic analysis. The data required to set-up the model include: schematic presentation of the river reach; cross section data; distance between cross sections; coordinates for the left and the right bank; Manning's n values for floodplains and the main channel; and contraction and expansion coefficients. The computational procedure is based on the solution of a one-dimensional energy equation. The model can analyze flood management plans involving flow diversion, channel modification, (dredging) and dikes. The model calculates water surface profiles (elevations) from given geometry, discharge data, and boundary conditions. First, surface water profiles for "without project" conditions are generated. Then, introducing different flood management options into the model, e.g., diversion, dredging, and dikes, the modified surface water profiles are generated.

HEC-FDA is used for the estimation of benefits (reduction of damages) derived from the implementation of selected flood damage reduction options. As the first step in calculating flood damages, potential flood management plans are identified. A plan consists of one or more flood damage reduction options. A plan starts with the base year of implementation, and exists over the design life of the project. The "without project" condition is always the first plan against which all subsequent plans are compared. The water surface profiles are imported from HEC-RAS. In HEC-FDA, water surface profile data must consist of eight flood events (0.50, 0.20, 0.10, 0.04, 0.02, 0.01, 0.004, and 0.002 exceedance probability flood events). For calculation of flood damages, general depth-damage functions are provided. The computation of damages is based on the residual damage associated with a specific exceedance probability event. The expected annual damage for each year in the analysis period is computed, discounted back to present value, and annualized to get the equivalent value over the analysis period (project life). HEC-FDA calculates the reduced annual damages (benefits from implementing a flood management option) by comparing "with project" and "without project" plans.

A user can start the consultation process from the user interface. Through an interactive process, the program asks the user a series of questions related to hydraulic, hydrological, topographic, geotechnical, and environmental aspects of the river system, and the area to be protected from floods. Expected responses vary from simple yes/no answers to multiple-choice selection or entering values. The flood management options considered by the DESMOF are: (i) dikes; (ii) diversion (floodway); (ii) retention basin (controlled flooding); (iv) reservoir; (v) dredging (increasing the hydraulic capacity of a channel); and (vi) relocation of town. Once all information required to make a preliminary selection is compiled through interaction with the user, the system consults the model's knowledge base to recommend a single, or combination of flood management options to protect the area under consideration from flooding. Following the initial recommendation of flood management options, a detailed hydraulic and flood damage analysis of the recommended option is performed. With information on reduced damages (benefits) from HEC-FDA, and physical details (dimensions, capacity) of the flood control structures from HEC-RAS, a user consults the DESMOF again. Now, DESMOF performs a benefit-cost analysis and makes a final recommendation for the flood management option to be implemented to reduce flood damages.

LINK WITH OTHER MODULES

The selection of a flood damage reduction module makes use of information from the hydrodynamic model and the economic analysis model, and it provides information to the operation of flood control structures module.

Flood Forecasting Module

BACKGROUND

The function of this module is to forecast floods. A good forecast of floods not only provides vital information for the management of floods, but also reduces loss of life and property. The artificial neural networks (ANN) approach is used to forecast floods from a selected set of hydrometrological parameters.

ANN application in water resources started in the early 1990's. A review of state-of-the-art ANN applications in hydrology can be found in the ASCE Task Committee (2000) report. Attempts have been made to forecast runoff hydrographs using different input parameters. Smith and Eli (1995) used a back-propagation ANN to predict the peak discharge, and the time of peak resulting from a single rainfall event. They used a synthetic watershed to generate runoff from stochastically generated rainfall patterns. Carriere *et al.* (1996) used ANN with a recurrent back-propagation algorithm to generate a runoff hydrograph using rainfall intensity, duration, catchment slope, and catchment cover. Muttiah *et al.* (1997) used information on the drainage basin, elevation, average slope, and average annual precipitation to predict two-year peak discharge from a watershed. The ANN approach presented here uses multi-layer feed-forward ANN architecture with back percolation algorithm (Ahmad and Simonovic, 2005) to predict a complete runoff hydrograph.

METHOD

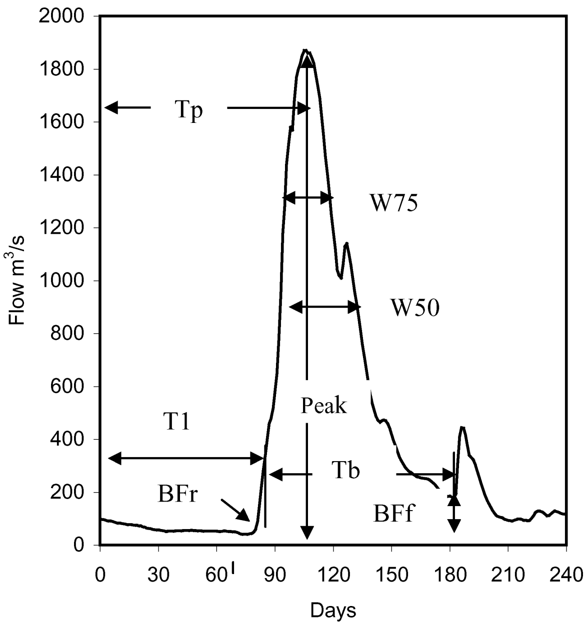
The ANN model is developed to address the specific characteristics of the Red River basin in Canada. Five hydro-metrological parameters that are used as input to the ANN model to forecast a runoff hydrograph are identified. These parameters are defined as follows (Warkentin, 1999): (1) Antecedent Precipitation Index – the index of soil moisture at freeze-up the previous autumn, based on weighted basin precipitation from May to October; (2) Melt Index – the rate of snowmelt, expressed in mean deg-days/day measured in degree F; (3) Winter Precipitation – the total basin precipitation from November 1st of previous year to the start of active snowmelt during the flood year, measured in inches; (4) Spring Precipitation – the total basin precipitation from the start of active snowmelt to the start of the spring crest; and (5) Timing Factor – an index of the south-north time phasing of the runoff based on the percentage of tributary peaks experienced on the date of the mainstream peak. This is basically a percentage of the worst possible south-north progression of melt and rain.

Eight runoff-hydrograph characteristics, that ANN model is trained to produce as output, are identified. This output is used to develop (forecast) a runoff hydrograph. These hydrograph characteristics are: (1) peak flow; (2) time of peak; (3, 4) base flow at the rising and recession sides of the hydrograph; (5, 6) timing of the rising and recession sides of the hydrograph; and (7, 8) width of the hydrograph at 75 and 50% of the peak. The definition of eight output parameters and their method of extraction from observed runoff hydrograph are shown in Figure 2. To provide a training data set for ANN model, these parameters are extracted from hydrographs of observed floods.

An ANN model is developed by relating input parameters to flood hydrograph characteristics. The model consists of two networks with five input and four output parameters in each network. Each network has one hidden layer with four nodes. After comparing the observed flood hydrograph to that generated with ANN model, adjustments in the controlling parameters of the ANN i.e., number of nodes and weights are made. Once model training is complete, it is used to predict the runoff-hydrograph using the input data that is never seen by the network (forecasting data set).

LINK WITH OTHER MODULES

The flood forecasting module provides information to the operation of flood control structures module.



Peak :Peak value of hydrograph (m^3/s)
Tp :Time to peak (days)
T1 :Time when rising side of hydrograph starts (days)
Tb :Total time between rising and recession sides of hydrograph (days)
BFr : Base flow at T1 (m^3/s)
BFf : Base flow at time T1+Tb (m^3/s)
W50: Width of hydrograph at 50 % of peak (days)
W75: Width of hydrograph at 75 % of peak (days)

Figure 2. Hydrograph characteristics for the artificial neural network model.

Operation of Flood Control Structures Module

BACKGROUND

The function of this module is to simulate the operation of the flood control structure i.e., reservoir. The module serves as a tool for studying impacts of changing reservoir storage allocation, and temporal distribution of reservoir levels and outflows. Stella (HPS, 2001) based on the system dynamics modeling approach is used to develop this module. The development of module requires data specific to the reservoir to be modeled. In this work data from the Shellmouth reservoir, Manitoba is used.

METHOD

The data sets that are used to set up the module 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 water level and area flooded upstream and downstream of the reservoir; and (9) evaporation and seepage losses from the reservoir.

Reservoir operating rules are captured using IF-THEN-ELSE statements. For example, Equation (1) for the Shellmouth reservoir states that if the reservoir is full (reservoir level 429.3 m), unregulated spillway is selected for simulation, it is the flooding season (after April), 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) (Ahmad and Simonovic, 2000).

$$\begin{aligned}&\text{IF (Res\_level} > 429.3\text{) AND (Spillway\_Control} = 0\text{) AND (TIME} > 120\text{)}\\&\quad\text{AND (Reservoir\_Inflow} > \text{Unregulated\_Spillway) THEN (198)}\end{aligned} \tag{1}$$

The option is provided in the model to route floods through the reservoir using natural spill or gated spill scenarios. Current reservoir level, inflows, time of the year, safe channel capacity downstream of the reservoir, and flooded area are criterions on which the quantity of the releases through the reservoir is based. As output, the model provides information on the variation of the reservoir levels, area flooded upstream and downstream of the reservoir, and duration of flooding.

LINK WITH OTHER MODULES

The operation of the flood control structures module receives information from selection of the flood damage reduction module and the flood forecasting module. It makes use of information from the economic analysis model, and provides information on area flooded and duration of flooding.

Red River Case Study

The Red River basin in Manitoba, Canada is used as a study area to demonstrate the applicability of the decision support system for management of flood. Approximately 1.25 million people live in the Red River basin in the United States and Canada. The Red River valley is a highly productive agricultural area serving local, regional, and international food needs. The Red River originates in the north-central United States and flows north. It forms the boundary between North Dakota and Minnesota and enters Canada at Emerson, Manitoba. It continues northward to Lake Winnipeg. From its origin to its outlet in Lake Winnipeg, the river is 563 km long. The Red River basin covers 116,500 km^2 of which nearly 103,500 km^2 are within the USA, and the remaining 13,000 km^2 are in Canada (IJC, 1997). In the city of Winnipeg, a major tributary, the Assiniboine River, joins the Red River from the west. The Canadian portion of the Red River basin is shown in Figure 3. The Red

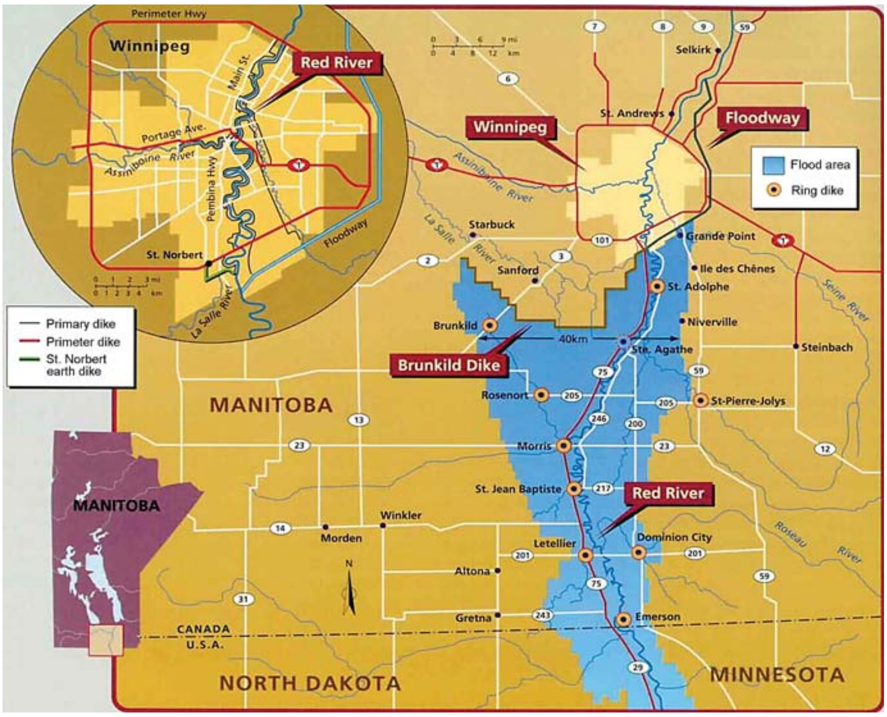


Figure 3. Canadian portion of the Red River basin (after Winnipeg Free Press).

River basin has a sub-humid to humid climate with moderately warm summers, cold winters, and rapid changes in daily weather patterns (Royal Commission, 1958). The basin is remarkably flat, and the entire valley becomes a floodplain during major flood events.

The flood control structures in the Red River basin include the Red River Floodway, the Portage Diversion, the Shellmouth Reservoir (completed in 1972) and the system of dikes along the rivers. A schematic diagram of flood control structures in the Canadian portion of the Red River basin is shown in Figure 4. The Portage Diversion was constructed in 1970 to divert the water in the Assiniboine River to Lake Manitoba through a diversion channel of capacity 710 m^3/s. The Red River floodway was constructed in 1966 to reduce flooding in the city of Winnipeg by diverting water from the Red River.

Flooding on the Assiniboine River contributes to flooding of Winnipeg city. 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. The Shellmouth Dam is 1319 m long and 19.8 m high, zoned earth-fill embankment. A gated concrete conduit (discharge capacity of 198.2 m^3/s) and a concrete chute spillway control

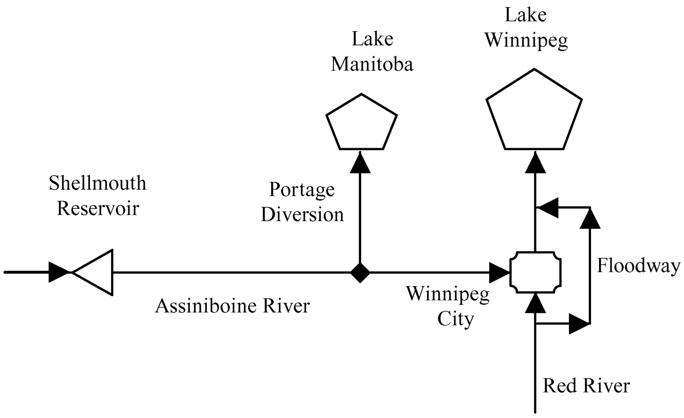


Figure 4. Schematic diagram of the flood control structures in the Red River basin.

outflow from the dam. The reservoir covers a surface area of 61 km^2 when full. The elevation of 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 difference between volume of reservoir at active storage (370×10^6 m^3) and crest level of natural spillway (477×10^6 m^3) is flood storage capacity of reservoir, i.e., 107×10^6 m^3. Maximum reservoir outflow is limited to 42.5 m^3/s to prevent downstream flooding and the outflow must be greater than 0.71 m^3/s to avoid damage to fish and aquatic life in the river system.

Model Application and Results

SELECTION OF FLOOD DAMAGE REDUCTION OPTION

The DESMOF was consulted to identify a suitable flood damage reduction option for the town of St. Agathe near Winnipeg. The user starts the process in an interactive mode by providing information on the river system, and area to be protected from floods (Figure 5). The module evaluates different options and provides a preliminary recommendation to further analyze the options of building a dike or a diversion channel. The two recommended options are analyzed using HEC-RAS and HEC-FDA. The analysis through HEC-RAS generates the modified surface water profiles due to the implementation of the selected flood management option, and also provides dimensions of the structure for reducing flood damages. The flood frequency estimates reported by the Royal Commission (1958) are used as the basis for water surface profile calculations. Analysis through HEC-RAS reveals that building a diversion channel will not reduce flood damages significantly. The area is flat and there is not enough slope difference to accommodate the diverted water back into the river without causing serious backwater effect. Once the technical feasibility of the selected flood management option is evaluated, the DESMOF activates HEC-FDA. Flood Damage Analysis with HEC-FDA provides the reduced

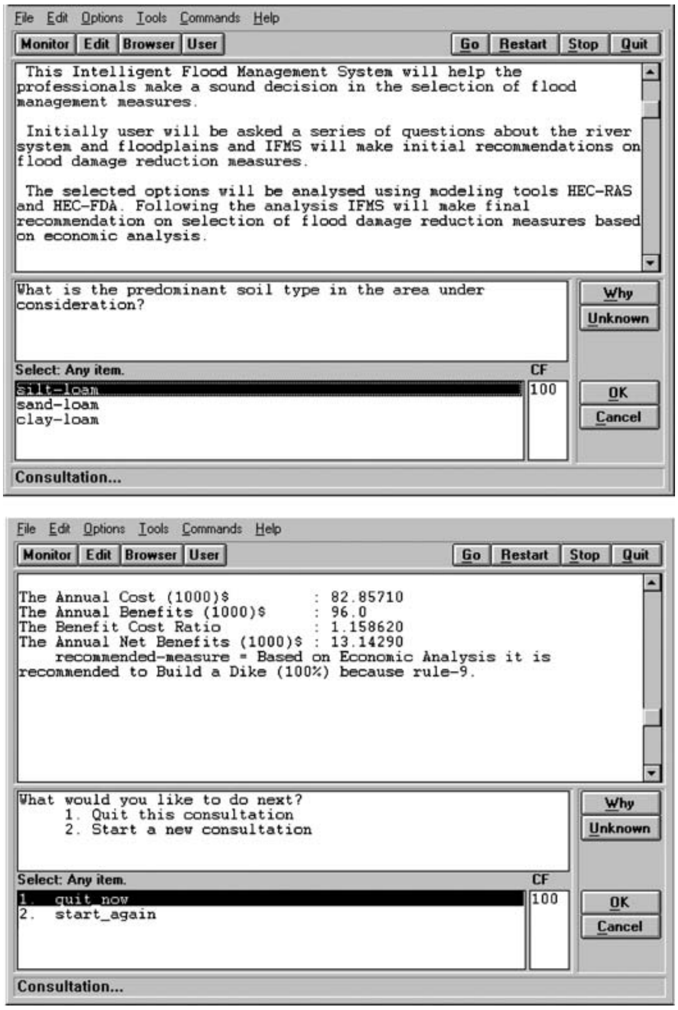


Figure 5. Control screen of the module for selection of flood damage reduction options.

damage (benefit) resulting from the implementation of a selected flood management plan. The damage curves developed by KGS (2000) are used for damage calculations. For calculation of cost, the dimension of structures come from HEC-RAS (e.g., length and height of dike) and the user provides unit cost estimates (e.g., cost per cubic meter of dike). Following the hydraulic and flood damage analysis, DESMOF continues the consultation, and performs the benefit-cost analysis (for 50 years with discount rate of 4.5%) to make a final recommendation. The benefits and costs for each year in the analysis period are computed, discounted back to present value, and annualized to get the equivalent value over the period of analysis (project life). Based on the benefit-cost ratio and net annual benefits, DESMOF makes a

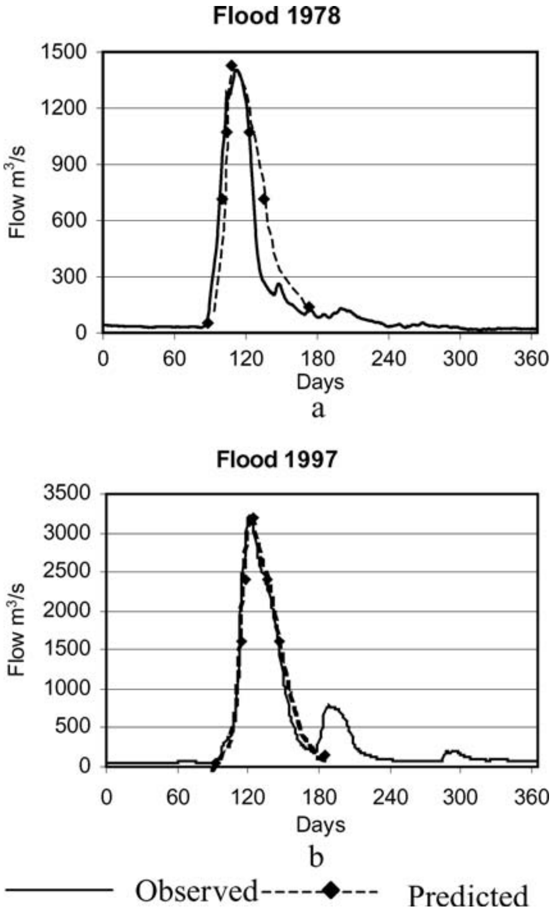


Figure 6. Comparison of the observed and the predicted flood hydrographs.

final recommendation of building a *dike* to reduce flood damages in the given area (Figure 5). Once the selection of a suitable flood damage reduction option is made, flood-forecasting module of DESMOF is activated.

FLOOD FORECASTING

Flood forecasts are made for the town of Ste. Agathe on the Red River near Winnipeg. To forecast floods, the user provides input parameters for the ANN model. As output, ANN model generates a complete flood hydrograph. The comparison of observed and predicted hydrographs for 1978 and 1997 floods is shown in Figures 6a and b. The flood in 1997 was the largest flood on the Red River in the past hundred years. Percentage error of individual hydrograph parameters is given in Table I. The network produced an excellent prediction of peak flows with an error of -1 to $+2\%$. Network performance is very good in estimating the time

Table I. Error in observed and predicted hydrograph parameters for selected floods

	1978			1997		
	Obs.	Pred.	% Er	Obs.	Pred.	% Er
Peak	1,400	1,429	2.1	3,230	3,207	−0.7
Tpeak	112	108	−3.6	121	125	3.3
T1	85	88	3.5	92	92	0.0
Tb	84	85	1.2	82	93	13.4
W50	29	35	20.7	32	32	0.0
W75	24	19	−20.8	19	19	0.0

of peak; the error is in the range of −3 to +3%. Over all, the network captured the timing of the start of the rising side of the hydrograph quite well; the error is 3%. The% error in estimating the time of base (time between the rising and recession side of the hydrograph) is in the range of 1 to 13%. The error in estimating the width of hydrograph at 50 and 75% of the peak is in the range of −20 to +20%.

The model performance in predicting the peak flow and time of peak is very good; this suggests that these hydrograph characteristics can be well estimated using the current input parameters. However, the inability of the forecasted hydrograph to properly match the shape of the recession side of the observed hydrograph may be due to the lumped nature of input parameters used.

OPERATION OF FLOOD CONTROL STRUCTURE

This module is used to simulate the operation of flood control structures i.e. Shellmouth reservoir and Portage diversion located on the Asssinboine River. The module's control screen is shown in Figure 7. There are six separate input data files; five for the largest flood years in the history of the reservoir (1974–1976, 1979, and 1995) and sixth for the flood event generated by the flood forecasting module. The user can select the flood year for simulation using a graphical tool (slider). The spillway module has a slider that provides the user with an option to choose either natural (unregulated) or gated spillway for simulation. Warnings linked to minimum and maximum reservoir levels have been provided in the form of text messages and sound alarms. While the simulation is running, the operator has control over the flow through the conduit, and can increase or decrease the discharge as the need arises.

Simulations of the Shellmouth reservoir operation are made with natural and gated spill scenarios. Module inputs are daily inflows to the reservoir for a selected flood year. Module output includes daily variations of the reservoir level, daily discharges from the reservoir, total flooded areas upstream of the reservoir, discharges and flooded areas downstream, and diversion to Lake Manitoba at Portage. The module calculates the number of days when the reservoir is full, or at the minimum

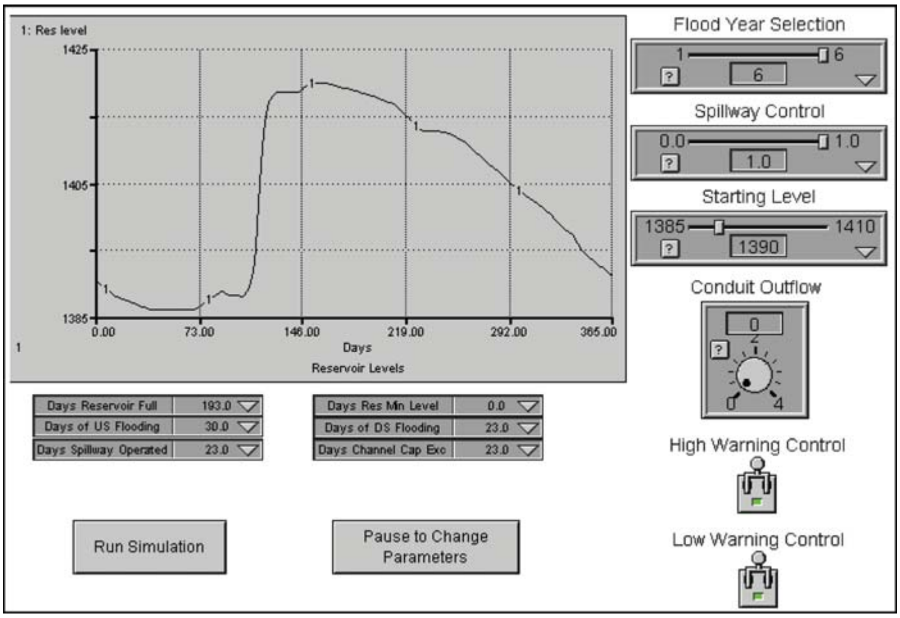


Figure 7. Control screen of the module for operation of flood control structures.

level, and the number of days the spillway is operated. Other output includes the number of days of downstream/upstream flooding, and number of days when channel capacity is exceeded due to reservoir operation. Discharges at Headingly are used to estimate the contribution of the Assiniboine River to flooding of the Winnipeg City. Policy alternatives are explored by changing initial reservoir storage level, both at the start of simulation and at the start of flood season. Simulations are also made to explore the effects of changing outflow through the conduit on the reservoir level.

Results of reservoir operation for floods of 1979 and 1995 are summarized in Table II. These results show that with revised operating rules, it is possible to

Table II. Flood management with revised operating rules for selected flood years

Flood year	Operating rules	spill	Reservoir full (days)	Upstream flooding (days)	Downstream flooding (days)	Area flooded (hec.)
1979	Existing	Natural	106	5	19	1,100
	Revised	Natural	121	11	12	200
	Revised	Gated	129	0	0	0
1995	Existing	Natural	161	7	47	24,600
	Revised	Natural	193	5	38	21,600
	Revised	Gated	250	30	23	16,300

operate the reservoir with only minor flooding upstream and downstream for major flood events. In 1979, the 1,100 hectars of downstream area was flooded for 19 days. With revised operating rules, the flooded area was reduced to 200 hectares. Simulations were made again with the gated spillway option, and it is found that downstream flooding can easily be avoided without increasing flooding upstream of the reservoir. The 1995 flood in the Assiniboine River has a return period of 100 years and inflows are 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 and revised operating rules, 200 hectares upstream and 21,600 hectares downstream are flooded for 5 and 38 days, respectively (Table II). By routing the flood of 1995 through the reservoir with the gated spillway option, there was a reduction of 5,300 hectares in flooded area downstream of reservoir, and flooding duration was reduced to 23 days. The maximum discharge at Headingly was also reduced to 6 m^3/s, which is equal to the minimum required flow, as compared with 175 m^3/s with the free spill option. This means that Assiniboine River's contribution to flooding of the Winnipeg City is reduced to zero.

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. The number of days when the reservoir is full or at the minimum level is very sensitive to reservoir outflows. Reservoir levels during the flood, flooded areas upstream as well as downstream, and duration of flooding are sensitive to reservoir level at the start of the flooding season. Simulation suggests that installation of gates on the spillway will improve the flood management capacity of the reservoir, especially for large floods.

Conclusions

An intelligent decision support system is developed, to be used in planning mode, for the management of floods. To demonstrate the applicability of the proposed approach, the Red River basin in Canada is used as a case study. The selection of a suitable flood damage reduction option is made using the knowledgebase. Flood forecasts are made using artificial neural networks approach. Operation of flood control structure, Shellmouth reservoir, is simulated using a system dynamics model. DESMOF is a comprehensive DSS capable of handling different phases of flood management. Decision makers, by using DESMOF, can:

- Select a suitable flood damage reduction option for a given area
- Forecast floods based on hydrometeorological parameters
- Estimate impacts of different operating policies for flood control structures, and
- Evaluate different flood management options not only based on existing data, but also on future population and development scenarios in the basin.

While creating DESMOF, development of a shared database used by all models, and establishing two way communication links among different models related to different phases of flood management, were challenging task.

In many cases, responsibility for identifying and constructing flood control structures, flood forecasting, and operation of flood control structures are carried out by separate organizations with limited interaction. The DESMOF highlights the need for coordination among different agencies involved in flood management.

The DESMOF can capture, in knowledge base, valuable human expertise in flood management. It may be valuable as a training tool for entry-level flood managers, and may augment the experienced professionals as an interactive problem-solving and advisory system. The DESMOF environment allows a number of 'what-if' questions to be asked and answered. The main benefit is that multiple decisions can be tried without having to deal with the real-life consequences. In this way, DESMOF can guide decision-makers through the most optimistic, pessimistic, and in-between scenarios. DESMOF through simulation can provide a *virtual planning* experience for flood managers and decision-makers to further investigate the flood management process.

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References

Ahmad, S. and Simonovic, S. P., 2000, 'Modeling reservoir operations using system dynamics', *ASCE Journal of Computing in Civil Engineering* **14**(3), 190–198.

Ahmad, S. and Simonovic, S. P., 2001a, 'A decision support tool for evaluation of impacts of flood management policies', *Journal of Hydrological Science and Technology* **17**(1–4), 11–22.

Ahmad, S. and Simonovic, S. P., 2001b, 'Integration of heuristic knowledge with analytical tools for selection of flood control measures', *Canadian Journal of Civil Engineering* **28**(2), 208–221.

Ahmad, S. and Simonovic, S. P., 2004, 'Spatial system dynamics: A new approach for simulation of water resources systemsE', *ASC Journal of Computing in Civil Engineering* **18**(4), 331–340.

Ahmad, S. and Simonovic, S. P., 2005, 'An artificial neural network model for generating hydrograph from hydro-meteorological parameters', *Journal of Hydrology* (in press).

ASCE Task Committee: 2000, 'Artificial neural networks in hydrology II: Hydrologic applications', *Journal of Hydrologic Engineering* **5**(2), 124–137.

Bender, M. J. and Simonovic, S. P., 1994, 'Decision-support system for long-range stream flow forecasting', *ASCE Journal of Computing in Civil Engineering* **8**(1), 20–34.

Bender, M. J. and Simonovic, S. P., 2000, 'A systems approach for collaborative decision support in water resources planning', *International Journal of Technology Management* **19**(3/4/5), 546–557.

Câmara, A. S., 1990, 'Decision Support System for estuarine water-quality management', *ASCE Journal of Water Resources Planning and Management* **116**(3), 417–432.

Carriere, P., Mohaghegh, S., and Gaskari, R., 1996, 'Performance of a virtual runoff hydrograph system', *ASCE Journal of Water Resources Planning and Management ASCE* **122**(6), 421–427.

Chang, T. J., Kleopa, X. A., and Teoh, C. B., 1996, 'Development of an expert system for daily drought monitoring', *ASCE Journal of Computing in Civil Engineering* **10**(1), 20–24.

Cimflex Teknowledge Corporation: 1991, *M.4 User Guide*, California, USA.

Davis, J. R., Nanninga, P. M., Biggins, J., and Laut, P., 1991, 'Prototype decision support system for analyzing impact of catchment policies', *ASCE Journal of Water Resources Planning and Management* **117**(4), 399–414.

Dynes, R. R. and Tierney K. J. (eds.) 1994, *Disasters, Collective Behavior, and Social Organization*, University of Delaware Press, Newark.

Fischer, H. W., 1998, *Response to Disaster : Fact Versus Fiction & Its Perpetuation: The Sociology of Disaster*, University Press of America, Lanham, MD.

Ford, D. T. and Killen, J. R., 1995, 'PC-Based decision-support system for Trinity river, Texas', *ASCE Journal of Water Resources Planning and Management* **121**(5), 375–381.

Guariso, G. and Werthner, H., 1989, *Environmental Decision Support Systems*, Ellis Horwood Ltd., England.

HPS Inc., 2001, *Tutorial and Technical Documentation STELLA? II*, Hanover, NH.

IJC, 1997, International Joint Commission, Red River flooding: Short-term measures. *Interim Report of the International Red River Basin Task Force*, Ottawa, Washington.

Keyes, A. M. and Palmer, R. N., 1993, 'Development of a decision support system for the prioritization of multimedia dischargers', *Journal of Environmental Management* 601–612.

KGS, 2000, 'Red River basin stage-damage curves update and preparation of flood damage maps, *Report submitted to Int. Joint Commission*, Ottawa, Washington DC.

Mallach, E. G., 1994, *Understanding Decision Support Systems and Expert Systems*, Richard D. Irwin, Inc., USA.

McKinney, D. C., Maidment, D. R. and Tanriverdi, M., 1993, 'Expert geographic information system for Texas water planning', *ASCE Journal of Water Resources Planning and Management* **119**(2), 170–183.

Muttiah, R. S., Srinivasan, R., and Allen, P. M., 1997, 'Prediction of two-year peak stream discharges using neural networks', *Journnral of American Water Resources Assoc.* **33**(3), 625–630.

Palmer, R. N. and Tull, R. M., 1987, 'Expert system for drought management planning', *ASCE Journal of Computing in Civil Engineering* **1**(4), 284–297.

Palmer, R. N. and Holmes, K. J., 1988, 'Operational guidance during droughts: An expert system approach', *ASCE Journal of Water Resources Planning and Management* **114**(6), 647–666.

Royal Commission: 1958, '*Report on Flood Cost Benefit*, Winnipeg, Manitoba.

Simonovic, S. P., 1992, 'Reservoir systems analysis: Closing gap between theory and practice', *ASCE Journal of Water Resources Planning and Management* **118**(3), 262–280.

Simonovic, S. P., 1996a, 'Decision support systems for sustainable management of water resources. 1. General Principles', *Water International* **21**(4), 223–232.

Simonovic, S. P., 1996b, 'Decision support systems for sustainable management of water resources. 2. Case Studies, *Water International* **21**(4), 233–244.

Simonovic, S. P., 1999a, 'Decision support system for flood management in the Red River Basin', *Canadian Water Resources Journal* **24**(3), 203–223.

Simonovic, S. P., 1999b, 'Decision support system for flood management in the Red River Basin, *Report to the Int. Joint Commission Red River Basin Task Force*, Ottawa, Washington D.C.

Simonovic, S. P. and Ahmad, S., 2005, 'Computer-based model for flood evacuation emergency planning', *Natural Hazards* **34**(1), 25–51.

Smith, J. and Eli, R. N. 1995, 'Neural-network models of rainfall-runoff process', *ASCE Journal of Water Resources Planning and Management* **121**(6), 499–508.

Thierauf, R. J., 1988, *User Oriented Decision Support Systems*, Prentice-Hall, Inc, Englewoods Cliffs, NJ.

U.S. Army Corps of Engineers: 1998a, *HEC-RAS: River Analysis System, Reference Manual*, CPD-69, Hydrologic Engineering Center, Davis, CA.

U.S. Army Corps of Engineers: 1998b, *HEC-FDA: Flood Damage Reduction Analysis, User's Manual,* CPD-72, Hydrologic Engineering Center, Davis, CA.

Warkentin, A. A., 1999, 'Red river at Winnipeg: Hydro-meteorological parameter generated floods for design purposes', *Proceedings of the Canadian Water Resources Association Winnipeg Conference: Red River Flooding – Decreasing Our Risks*; Winnipeg, MB. 32 pp.