Decision Support System For Flood Management In The Red River Basin

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DECISION SUPPORT SYSTEM FOR FLOOD MANAGEMENT IN THE RED RIVER BASIN

Report prepared for the

International Joint Commission
Red River Basin Task Force

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EXECUTIVE SUMMARY

This paper provides a detailed outline of the plan for the development and deployment of a *Red River Basin Decision Support System* (REDES). The system is envisaged as serving the needs of decision-makers and stakeholders in the Red River Basin. A making flood management decisions during the planning stage, flood fighting stage and post flood recovery stage, requires comprehensive support in order to properly account for all flood impacts. The objective of REDES is to enhance preparedness planning, response, and recovery with emphasis on flood prediction and monitoring, emergency response, and public involvement.

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1. INTRODUCTION

‘Flood of the century’ from 1997 in the Red River Basin suggests that there is a need for a new paradigm of flood management that I call “sustainable flood management”. It is one where local stakeholders look forward and develop the future they will live in, rather than one that just happens (Myers, 1998). This concept calls for empowerment of stakeholders, adjustment to the environment, and integrated consideration of economic, ecological and social consequences of disastrous floods. The new paradigm must go beyond simply reducing losses to building sustainable flood management strategy on the local, national and international level.

Red River flood of 1997 had a considerable impact on the residents in both countries (US and Canada). The problems encountered in the administration of floodplain management have been mounting steadily in recent years. Despite the effort and dedication of talented professionals, it is by the sheer magnitude of flooding in the basin that the future management efforts will be even larger scale (IJC, 1997; Manitoba Water Commission, 1998). The added burden of massive flooding over such a large region is made even more complex by the very nature of floodplain management: a distinct process whose principal participants are organizationally separate and geographically located across two nations. Each of the individual agencies in floodplain management has responsibilities unique to its particular function. Yet these agencies cannot and do not operate in isolation. The International Joint Commission (IJC) conducted a number of public hearings in the basin and supported a set of workshops that have identified: (a) that agencies must exchange and share information in order to accomplish their own individual objectives; (b) that the stakeholders must be involved in all stages of flood management; and (c) that considerable improvement is required in integrating data and modeling tools in order to develop more efficient flood damage reduction strategies.

The effective operation of the total floodplain management process is determined by how well the various agencies are coordinated as they perform their individual tasks and how well they communicate with other stakeholders in the basin. IJC has directed its effort at examining and making recommendations to the governments of Canada and United States that will provide improved flood preparedness, response, recovery and mitigation. In particular, the IJC has defined specific objectives for its investigations as: (a) develop and recommend a range of alternatives to prevent or reduce future flood damages in the Red River Basin; (b) improve tools and support for decision-making; and (c) facilitate integrated flood emergency management in the basin (IJC, 1997). The conceptual framework for the implementation of the results of the investigation is presented in Figure 1.

The main component of the framework presented in the Figure 1 is a decision support system for flood management in the Red River Basin (REDES). It is envisioned that REDES should be provided to stakeholders to not only estimate flood management strategies based on today's situation but that also project: (a) alternative levels of vulnerability based on future population in the basin and other factors; (b) losses in future floods based on alternative decisions made today, such as different land use and building code decisions; and (c) impacts on and changes in other aspects of sustainability like environmental quality, economic vitality, and social equity (Goslar, et al., 1986; Kunreutner and Miller, 1985).

Development of Decision Support Systems (DSS) is closely related to computers. The computer has moved out of the data processing, through the user's office into knowledge processing. Whether it takes the form of a laptop PC or a desktop multiprocessing work-station is not important. It is important that the computer is a 'silent partner' for more effective decision-making in a decision support system environment (Simonovic, 1996; 1996a). The main factor responsible for involving computers in decision-making is treatment of information as the sixth resource (besides people, machines, money, materials and management).

DSS technology is finding application in, for example, water resources management (Loucks and daCosta, 1991); operational hydrology (DeGagne et al., 1996); hydro-power generation (Allen, 1996); management of renewable resources (Bender et al., 1994); environmental management (Guariso and Werthner, 1989; USDA, 1997); and other fields. A strategy for the development and application of decision support systems for natural resources and the environment is in the process of development in the United States by the Interagency Group on Decision Support for Land, Natural Resources and Environment (IGDS). The main objectives of this effort include discussion of decision support activities currently underway in agencies, and broadening the awareness of existing and new tools (IGDS, 1998).

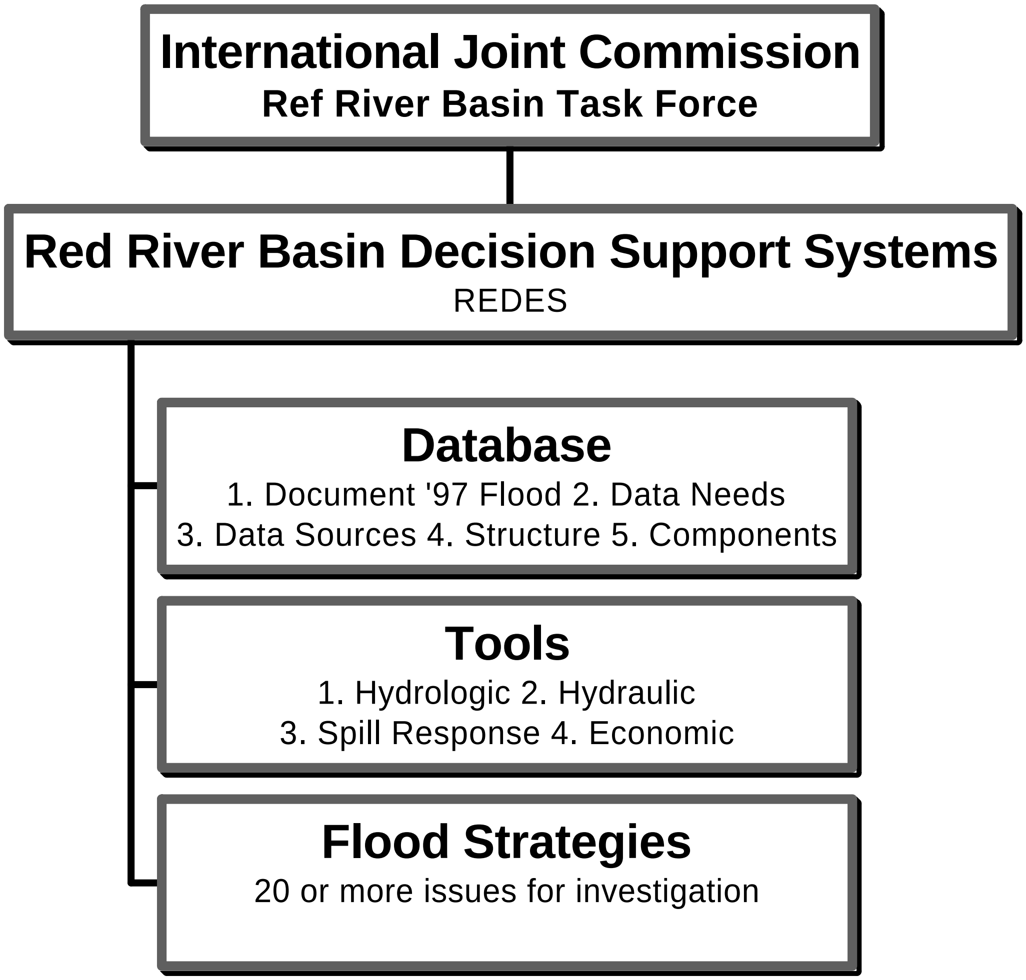


Figure 1Conceptual framework for flood management in the Red River Basin (modified after IJC, 1997)

REDES objectives and requirements are: (a) provision of support for planning different flood damage reduction alternatives; (b) evaluation of operational alternative choices during the flood fighting; and (c) support during the flood recovery period. This paper will try to answer: Who is the REDES for? What are the roles of REDES? What is the appropriate REDES architecture? What are the REDES development requirements? and How should the REDES development be staged?

Following section of the paper introduces theoretical framework for DSS development. Flood management process and some basic characteristics of flooding in the Red River Basin are presented in the next section. Detailed discussion of REDES follows. Paper ends with the set of recommendations for REDES development and implementation.

2. DECISION SUPPORT SYSTEMS

Development of Decision Support Systems (DSS) is closely related to computers. Even that a close link exists between the data processing (DP), the management information systems (MIS), and the decision support systems (DSS) a widely accepted definition of the DSS is not available. Some of the texts in the field of water resources are providing a very general definition of DSS (Loucks and daCosta, 1991) as :

computer-based tools having interactive, graphical, and modeling characteristics to address specific problems and assist individuals in their study and search for a solution to their management problems.

Others are avoiding the definition of DSS concentrating on the main purpose of such systems (Guariso and Werthner, 1989):

the support to decision-makers in solving problems that are poorly or insufficiently structured.

The problem of defining DSS is continuing. On one side, all computer applications help in decision-making process, and therefore nearly all could be called DSS. On the other hand, there are number of publications trying to set the framework within such systems will continue to be developed, used, and modified in future (Mittra, 1986; Thierauf, 1988). The latter approach will be used in this contribution trying to identify the role of DSS in sustainable flood management.

The word "system" is used in describing large number of phenomena. Aggregating nine different definitions Alexander (1974) arrived at the following definition of a system:

A system is a group of elements, either physical or nonphysical in nature, that exhibit a set of interrelationships among themselves and interact together toward one or more goals, objectives, or ends.

Applying this broad definition to a computer-based information system, the primary group of elements is data, the set of relationships is the flow of data, and the goal is to have a well-informed user capable of making efficient decisions.

In recent years there has been increasing emphasis placed on helping decision-makers make decisions from good information. The need is much greater in fields where problems are poorly structured, as is the case in flood management. As a result, the decision support system has become an essential subsystem within the framework of broader management information systems. The difference between the two, is that a management information system uses the computer for providing information to solve problems (usually recurring), and DSS position the decision-maker in the center of the decision-making process providing help in solving both, ad hoc problems as they arise and recurring problems. Within the framework of management information systems (Mittra, 1986), the DSS has four primary characteristics:

- it helps decision-makers at the upper levels;
- it is flexible and responds quickly to questions;
- it provides “what if” scenarios; and
- it considers the specific requirements of the decision-makers.

Important characteristics of DSS for sustainable flood management include accessibility, flexibility, facilitation, learning, interaction and easy to use. Since DSS have an added dimension not found in management information systems, the final *definition* will address each term in the expression decision support system.

First, DSS is primarily concerned with supporting decision-making in terms of problem identification and problem solving at all decision-making levels. The most important issue of DSS is in identifying the steps of the decision-making process or decisions that need to be made to help the decision-makers in fulfilling their organizational duties and responsibilities.

Second, a DSS provides support to the user and does not replace the individual. The emphasis is on the enhancement of a decision-making process by allowing use of quantitative models that are appropriate to the problem. In this way objective (quantitative) measurement introduced by models is combined with the subjective (qualitative) factors introduced by the user. The interaction of two is the most effective way in reaching a decision.

Third, the term system includes both, the user and the machine. The machine is a computer that, for now, operates in interactive mode through an input/output terminal. System also implies availability of quantitative models and some type of database. In the framework of this definition, these elements are more providing service to the decision-maker then directly delivering a decision.

Integrating all previous comments and characteristics, the decision support system can be defined:

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 (modified after Parker and Al-Utabi, 1986; Thierauf, 1988; and Simonovic and Savic, 1989).

This definition of DSS is based on the concept of management by perception. It relies on the decision-maker's insight and judgment at all stages of problem identification and/or problem solving. Thus, decision support systems add a new dimension to sustainable flood management.

Characteristics of decision support systems for sustainable flood management

Sustainable development principles are imposing a new set of requirements on the tools to be used in management of floods. The following discussion of DSS characteristics will address specific requirements of sustainable flood management decision-making.

*Problem identification***.** Sustainable flood management contains a number of semi-structured and non-structured problems. The management problem, which can be well formulated in an algorithmic way (a computer program), is called well structured. Decisions in this case are straightforward because alternative solutions are known. If the management problem involves lack of data or knowledge, non-quantifiable variables, and a very complex description then it is called semi- or non-structured. Structuring of the problem, in this case, must be done by the human in the man-machine system. For semi- and non-structured problems, more general man-machine solution procedures have to be used. They may include: analogy; problem redefinition; deduction; intuition; and approximation.

Because judgment and intuition are critical in examining and resolving many flood management problems, an effective DSS involves problem identification. This process includes searching the decision-making domain for future problems that need to be anticipated and solved. Future opportunities can be identified and implemented to address the long-term consequences of current decisions, defined as the second component of the sustainable flood management context.

Problem formulation (learning). Before trying to implement principles of sustainable development, water resource DSS have been used in situations in which there is a clear problem definition. DSS serve to solve such problems. However, the concept of a 'problem' as it relates to sustainable development may be expanded to include two perspectives: (i) problem as objective reality; or (ii) problem as mental construct. In the first case, a problem is viewed as unsatisfactory objective reality discovered by observations and facts. The decision-maker or expert has to define the problem. As a problem exists objectively, all participants in the decision-making process see it in the same way (even if there are different alternative solutions). Here, problem formulation is a preliminary step to DSS design. The second case presents an alternative view, considering a problem to be a subjective presentation conceived by a participant confronted with the reality perceived as unsatisfactory. Here, common threshold values have to be defined by the different participants in the decision-making process before another procedure can take place. This approach requires integration of problem formulation process into the context of a DSS. The emphasis is shifted from the analysis phase. It is important to note that problem formulation in sustainable flood management is more a social process than a technical one.

'What If' capability (adaptability). DSS environment allows a number of 'what if' questions to be asked and answered. The main benefit of DSS is that a number of decisions can be tried without having to deal with the consequences. In this way DSS can guide decision-makers through most optimistic, most pessimistic, and in-between scenarios.

Many issues related to the implementation of sustainable flood management can be examined using the 'what if' approach. A typical 'what if' approach example is question of flood protection equity. In this example there is no need to rely on a flood specialist. The ability to ask 'what if' questions, to quantify uncertainties, and to recognize the sensitivity of results to varying assumptions stimulates creative and analytical process of decision-making. The process provides a common ground for communication. Since the decision-maker can use the tool directly, higher quality decision can be made on a more timely basis.

Use of analytical models (facilitation). The integration and administration of mathematical models within the general framework can be identified as the specific feature of the concept of DSS. Since sustainable flood management is principally concerned with the future and the implications of today's decisions, modeling capability is very important to grasp and manage flood damage reduction systems. For problem identification and problem solving, decision-makers deal with analysis. This fact underlines the need for DSS modeling capabilities for:

- retrieval of data;
- execution of ad hoc analysis;
- evaluation of consequences of proposed actions; and
- proposal of decisions.

Typical models that include database management system functions as data queries and data manipulation, range from simple arithmetic functions and statistical operations to the ability to call up optimization and simulation models. The scope of a DSS is in the integration of such different facilities. The idea of DSS integrates different fields of science, and puts weight on social circumstances, which may decide or influence problem definitions and solution approaches.

User-machine interface (interaction). Whether the user is using a microcomputer or a powerful workstation is not the important issue anymore. What is important is an interactive processing mode incorporating a user-machine interface that provides answers to identified problems or 'what if' questions. The user-machine interface provides answers that decision-makers can understand, when such information is needed, under their direct control. Therefore, DSS are intended to help decision-makers throughout the process of identifying and solving their problems. The merging of the computer output with the subjective judgment of the decision-maker provides a better basis for making efficient decisions.

Computers are more than number crunchers or storage devices. With progress in the field of Artificial Intelligence (AI), computers are more capable of demonstrating their capacity to support humans in area of creative and analytical thinking. It is important to note that DSS are not general problem solvers. They are a part of a complex user-machine system with the emphasis being placed on the 'user' rather than on the 'machine'. Therefore, DSS are the possible tools to manage the complexity of sustainable flood decision-making.

Use of graphics (fast response). Closely related to the previous two characteristics is the use of color graphics and GIS. In a DSS environment, graphic display of results allow users to quickly grasp the essence of large amounts of physical data and reduce considerably the printout into a few readily understandable graphs, charts and maps. It is the way to select the important information in a user-machine interface such that the user retains control during the decision-making process.

Architecture of decision support systems

The architectural aspects of DSS are discussed to give a potential designer a conceptual tool for constructing a DSS, and to support a more practical and constructive definition of a DSS. Two main approaches representative of existing DSS are discussed with the proposed architecture to be used for the development of DSS for sustainable management of flood protection systems.

Functional approach. The approach distinguishes three components, which differ according to their functions. They are: (a) the language system; (b) the problem processing system; and (c) the knowledge system. This approach does not explicitly represent modeling or data retrieval functions. The user states a problem using the language system, and the system responds by starting the problem processing system and looking up specific information in the knowledge system.

Tool-based approach. The main components of the tool-based approach are: (a) the database; (b) the modelbase; and (c) the dialogue module. A tool-based approach is more general than a functional approach. Main components support the data retrieval, the modeling, and the model invocation functions. Tasks as problem processing or knowledge representation are not included in the modelbase or the dialogue module.

Intelligent decision support approach. This architecture is developed according to the objectives and properties of sustainable water resource decision-making. It takes advantage of combining two architectures described above. The approach has been originated in 1989 (Simonovic and Savic, 1989). Appropriate modifications have been added through different applications of the approach (Simonovic, 1993; and DeGagne et al, 1996).

The intelligent decision support concept links four basic elements of water resource decision-making: (a) engineering expertise; (b) a systems approach; (c) GIS; and (d) artificial intelligence (AI). As such, this concept becomes very similar to the integrated model-base decision support approach. The concept envisions public, technical specialists and the decision- and policy-makers as the potential users of the software system. In this environment, the computer is seen as a link between the field expert and the decision-maker, between science and policy. Therefore, the DSS is not only a tool for analysis, but an instrument for communication, training, forecasting, and experimentation. The major strength of this concept is that the products are application- and problem-oriented rather than methodology oriented. In this way, AI technology through expert systems, neural nets, fuzzy reasoning, and evolutionary programming is combined with more classical techniques of engineering analysis, data processing, and systems analysis.

3. FLOOD MANAGEMENT

Floodplains provide very good locations for urban and agricultural development. Unfortunately, the same rivers and streams that attract development periodically overflow their banks causing loss of life and property. Flood management is a broad spectrum of water resources activities aimed at reducing potential harmful impact of floods on people, environment and economy of the region. Economic analysis plays an important role in formulating plans for reducing flood damages and making operational decisions during the emergency. The main limitation of the existing flood management methodologies is the consideration of mostly economic impacts and very minor attention to environmental and social impacts of floods.

Process

Flood management process can be divided into three major stages: (a) planning; (b) flood emergency management; and (c) post flood recovery. During the *planning* stage, different alternative measures (structural and nonstructural) are analyzed and compared for possible implementation in order to reduce flood damages in the region. The analysis of alternative measures involves project formulation for each measure, understanding advantages and disadvantages of alternative project arrangements, evaluation of project positive and negative impacts and finally relative comparison of alternative measures. Flood *emergency management* includes regular appraisal of the current flood situation and daily operation of flood control works. Very important aspect of the appraisal process is identification of potential events which could affect the current flood situation (such as dike breaches, wind setup, heavy rainfall, etc.). At this stage decisions are made on urgent major capital works and flood upgrading measures for existing structures. From the appraisal of the current situation information is initiated regarding evacuation and re-population of different areas. Post *flood recovery* involves numerous hard decisions regarding return to the 'normal life'. Issues of main concern during this stage of the flood management process include evaluation of damages, rehabilitation of damaged properties and provision of flood assistance to flood victims. At this stage also, all environmental impacts are evaluated and mitigation strategies selected.

Flood damage reduction measures

Flood management has the objective to evaluate utilization of possible methods for reducing flood damages to existing buildings and other facilities and reducing flood risk to permit additional growth. Two principal types of measures are considered: (a) nonstructural measures; and (b) structural measures. Latter can be further divided into local protection measures and upstream flood protection measures (usually storage reservoirs). Nonstructural measures include: zoning (to limit the types of land uses permitted to those which may not be severely damaged by floods), protection of individual properties (waterproofing of the lower floors of existing buildings for example), flood warning system (to evacuate residents and to move valuables), and flood insurance (to recognize the risks of floods and to provide compensation when damages are not avoidable at acceptable cost). Structural measures emphasize construction of: (i) levees or walls to prevent inundation from floods below some specific design flood flow. Additional works may include drainage and pumping facilities for areas that are sealed off from precipitation runoff to the river by the levees; (ii) diversion structures to divert flow during the peak from the protected region; (iii) channel modifications to increase the hydraulic capacity or stability of the river; and (iv) one or more reservoirs upstream from the protected area to capture the volume of a designed flood and release it at non-damaging rates.

Decision-making

Canadian institutional arrangements are set for a hierarchical distributed decision-making system to combat emergencies including floods. Four levels of decision-making are present in flood management: (a) federal; (b) provincial; (c) local (city, and rural municipalities); and (d) personal (affected people). The responsibility for coordinating this process lies with the Emergency Management Organization (EMO). The magnitude of reaction (and involvement of different levels of decision-makers) is proportional to the magnitude of the event. People at the local level have the initial responsibility. If they lack the needed resources, provincial assistance, and, if need be, federal assistance, can be requested.

Red River Basin and flood of 1997(Canadian prospective)

Red River has its own characteristics (Rannie, 1980; IJC, 1997). Situated in the geographic center of North America, the Red River originates in Minnesota and flows north. It forms the boundary between North Dakota and Minnesota and enters Canada at Emerson, Manitoba (Figure 2). It continues northward to Lake Winnipeg. The Red River basin covers 116,500 km^2, exclusive of the Assiniboine River and its tributary the Souris, of which nearly 103,600 km^2 are in the United States and the remaining 13,000 km^2 are in Canada. The basin is remarkably flat. The slope of the river is on average less than 9.5 cm per kilometer. The basin is about 100 km across its widest. When the river floods, nothing holds it back. During the major floods the entire basin becomes the floodplain. The flatness of the terrain also means few natural large water storage sites are available.

The Red River Basin has a sub-humid to humid continental climate with moderately warm summers, cold winters, and rapid changes in daily weather patterns. On average the Red River basin mean monthly temperatures range from -15 to +20 degrees Celsius. Most major floods occur following heavy precipitation the previous fall, hard and deep frost prior to snowfall, substantial snowfall, sudden taws, and heavy rainfall or wet snow conditions during the spring breakup. The low absorptive capacity of the basin's clay soils is a contributing factor. Ice jams can occur occasionally, particularly on tributaries, causing backwater flooding and exacerbating main stem flood conditions.

The Red River Basin had many attractions and many disadvantages for European settlement. The soil was rich and fertile. It did not have to be cleared of many trees. But the region had one major drawback. It had an enormously high potential for serious springtime flooding (Bumsted, 1997). Recurrent floods occurred before the arrival of

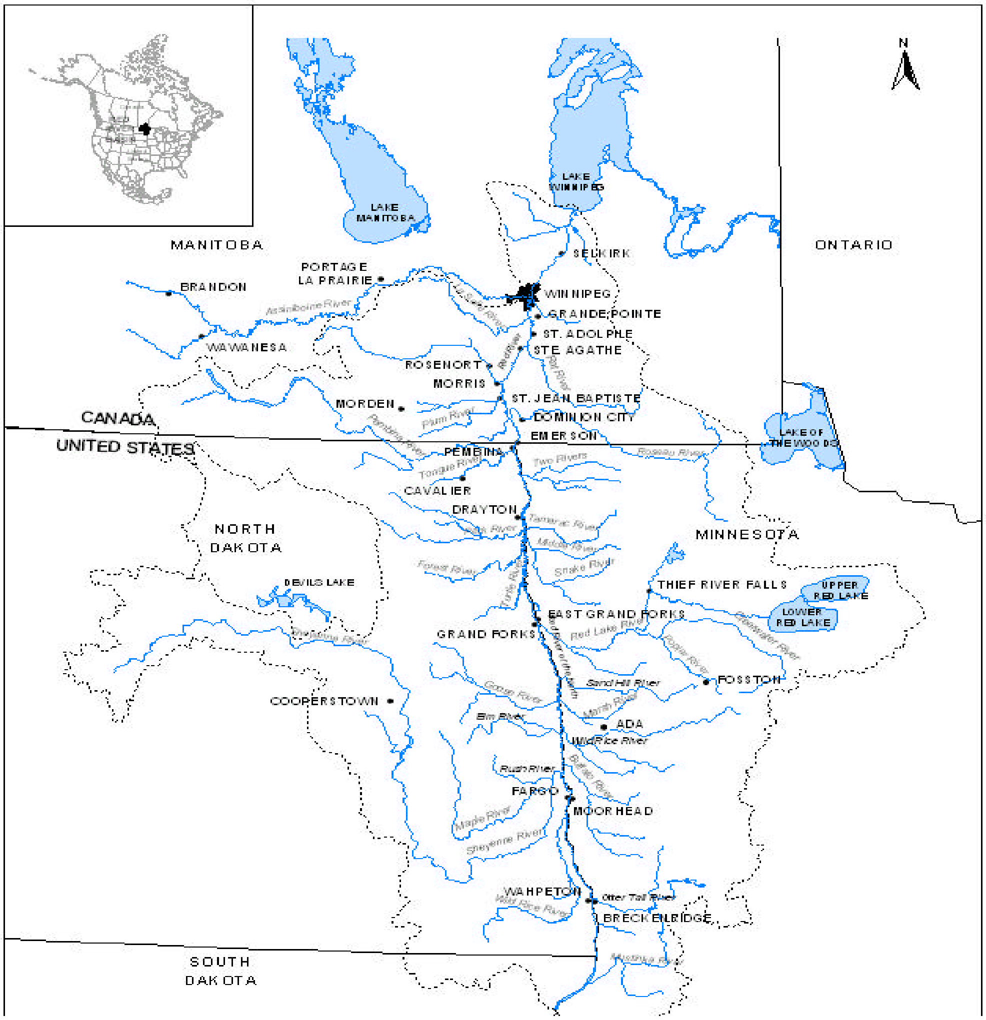


Figure 2 Red River Basin

European settlers, but aboriginal peoples did not attempt to live year-round at river's edge. Not until permanent colony settled on the banks of the Red and Assiniboine Rivers (current location of Winnipeg, population 650,000) did the flooding of the river basins become recognized as one of the natural hazards of life in the region. The earliest recorded flood in the basin was in 1826, although anecdotal evidence refers to larger floods in the late 1700s. In the period between 1862 and 1948 there were few major floods of the Red River. The only serious flooding in Winnipeg occurred in 1916. The

1826 flood remains the largest on record. All other floods were exceeded by the 1997 event (4,587 m^3/sec at Winnipeg).

Heavy precipitation occurred in major segments of the basin in the fall of 1996 (10 cm above average). The winter of 1996-1997 was unusually severe. Record or near-record snowfall throughout the basin created conditions conductive to major flooding. There was also heavy early spring precipitation. Temperatures have created less than ideal melt conditions. The Red River began to flood on March 30th. Floodwaters crested at Winnipeg on May 4th. 'Red Sea' flooded about 2,000 km^2, or about 5% of Manitoba's farmland. 8,612 soldiers from across Canada participated in 'Operation Assistance'. With 28,000 Manitobans evacuated (6,000 from Winnipeg), the damages of 1997 flood are in the hundreds of millions of dollars.

Most of the flood management planning in Canadian portion of the Red River Basin was initiated after the 1950 flood. This flood was the turning point in the history of flooding and flood control in Manitoba's portion of Red River basin. Construction of elevated boulevards (dikes) within the City of Winnipeg and associated pumping stations was initiated in 1950. The current flood control works for the Red River basin consist of the Red River Floodway, the Portage diversion and Shellmouth Dam on the Assiniboine River, the primary diking system within the City of Winnipeg, and community diking in the Red River basin (Figure 3). Following the 1950 flood on the Red River, the federal government and the Province of Manitoba set up a fact-finding commission to appraise the damages and make recommendations (Royal Commission, 1958). The commission recommended in 1958 the construction of the Red River Floodway (completed in 1966), the Portage Diversion (completed in 1970) and the Shellmouth Reservoir (completed in 1972). As a consequence of the concern over flood protection for the Red River Basin, a

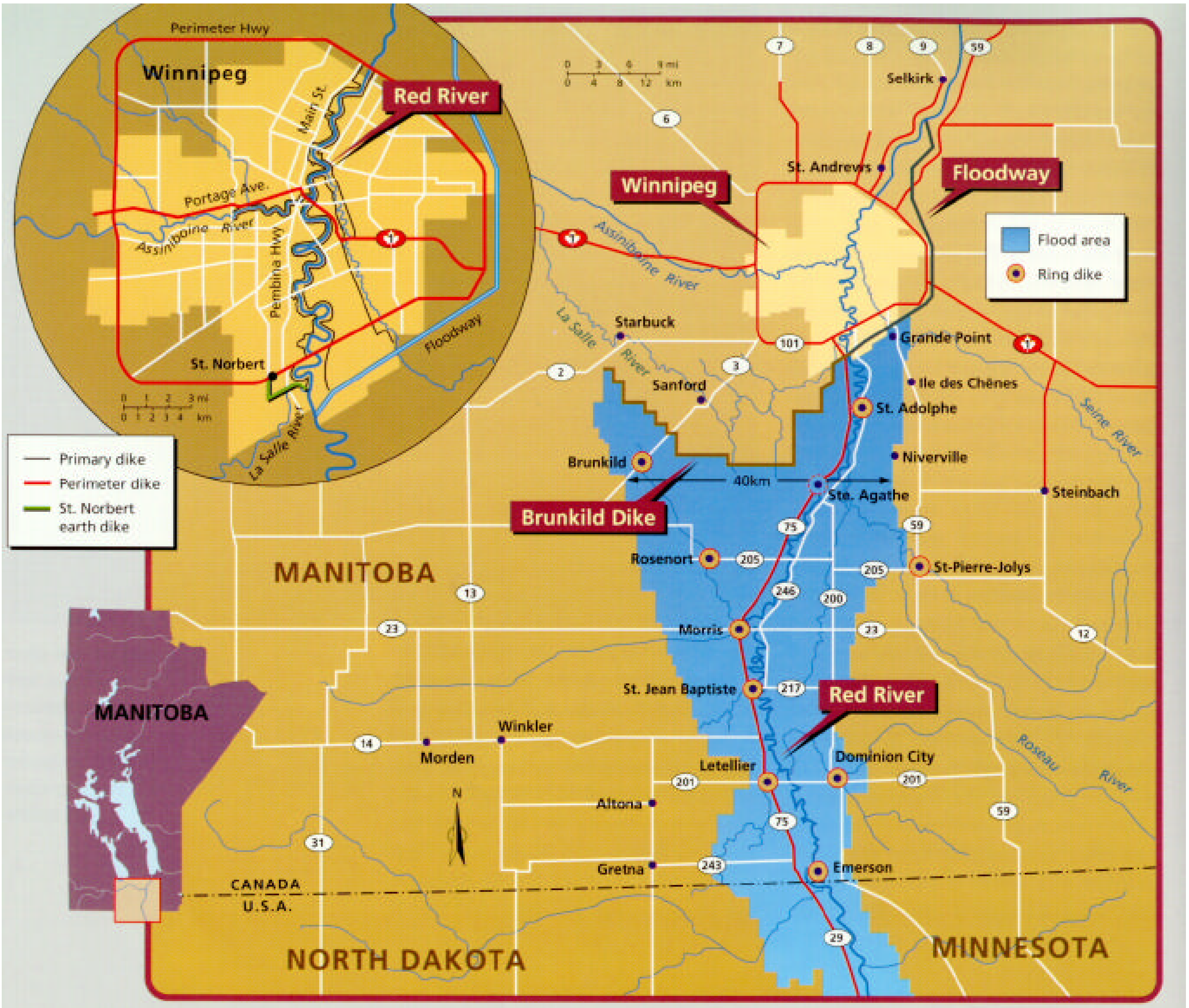


Figure 3 Current flood works in the Canadian portion of the Red River Basin

federal-provincial agreement led to the construction in early 1970s of a series of ring dikes around communities in the Basin. Moreover, financial aid programs encouraged rural inhabitants to raise their homes, as well as to create individual dikes around their properties. All the decisions regarding the capacity of current flood control works were based primarily on economic efficiency, getting the largest return for the investment.

During the spring of 1997 flood outlooks were reasonably accurate. However, the major shortcoming was the inability of existing forecasting tools to deal with the massive volumes of overland flow. In Winnipeg, the Red River Floodway performed well. The Floodway operated from April 21 to June 3. Impacts of Floodway operating policies established in 1984 on the flooding of some communities in the Basin is still under investigations (Clark et. al., 1997). Over the winter of 1996-1997 the Shellmouth Reservoir was drawn down to an all-time low in anticipation of high runoff in 1997. About 70% of the runoff above the reservoir was stored. The Portage Diversion gates were raised until May 5th , and flows downstream on the Assiniboine were maintained at nearly zero. Most of the ring dikes around Basin communities were raised and none of the towns were flooded. The town of Ste. Agathe was not protected by a ring dike and was flooded.

With few exceptions, emergency measures served the purpose for which they were intended and ultimately contributed to flood damage reduction. Flood emergency procedures in rural communities differ from cities where full-time professionals and experienced departments deal with flood matters. For example, City of Winnipeg officials understood that the central government would reimburse them for the money that they committed to flood defense (in fact no such provisions were in place at the beginning of the crisis). Rural municipalities, required by law not to run deficits, were reluctant to commit financial resources in advance of funding arrangements.

4. RED RIVER BASIN DECISION SUPPORT SYSTEM (REDES)

Floods are affecting growth and development at community and regional levels and have major impact on surrounding environment. There is a growing understanding, far from complete, of the interaction between physical processes causing floods and human activities (Smith and Ward, 1998). Public hearings and workshops organised in the basin by the Red River Basin Task Force of IJC have indicated desperate demand for public participation in decisions about the flood management, particularly at local and watershed scales. These trends are creating new demands from managers, policy makers, and the public for assistance in understanding flood related issues, developing and evaluating alternatives for flood damage reduction, and projecting the consequences of different courses of action. Consultations in the basin have also revealed many potential conflicts among social, economic and environmental values associated with flooding (Booy, 1998; North Richot Action Committee, 1997; Grant, 1997).

New computer technologies are providing access and analytical capabilities to wider audiences. The main objective in developing REDES is to provide assistance to decision-makers, including data base access, descriptive and predictive models, geographic information systems, methods to involve stakeholders in the basin, and other tools and services.

Users of REDES

Flood management in the Red River Basin involves numerous participants such as:

- governments (local, provincial and federal in Canada and local, state, and federal in the USA);
- agencies (among others Manitoba Emergency Management Organization, Manitoba Environment, Prairie Farm Rehabilitation Administration, Environment Canada, Manitoba Rural Development in Canada and U.S. Army Corps of Engineers, U.S. Geological Survey, U.S. National Weather Service, Federal Emergency Management

Agency, North Dakota State Water Commission, Minnesota Department of Natural Resources in the USA);

- private organizations (for example Red Cross, Salvation Army, and others);
- interest groups (such as Red River Water Resources Council, Red River Basin Board, North Richot Action Committee, Pembina Basin Conservation District, and others); and
- general public.

They all have different needs and responsibilities during planning, emergency management and flood recovery periods. REDES is designed to provide support for all of them. Multiple-user needs and access to REDES are accommodated through the multiple-level user interface structure to be described later. Three levels of functional support are provided within REDES to different users: information, technical and application.

Information support is the first level of support provided by REDES. It includes maps, plots, animations, video, spatial data and reports to all potential users classified as information users. Possible groups of information users include general public, private organizations and other interested stakeholders.

Technical support is the second level of support provided by REDES. It includes access to databases (archival, spatial, real-time, etc.) and modeling tools (descriptive, predictive, hydrologic, hydraulic, economic, environmental, etc.) to all technical users responsible for flood management in the basin. Most likely users of technical support will be between others engineers of Manitoba Water Resources Branch and US Army Corps of Engineers. This level of support allows for data retrieval, analysis, processing and presentation as well as hydrologic and hydraulic forecasting, modeling, simulation and optimization analyses.

Application support is the third level of support provided by REDES mostly to decision-makers and managers at different levels of governments. Application users should be able with the assistance of REDES to focus on a practical problem for initial implementation, test and fine tune various aspects of strategy and supporting infrastructure. With the application support of REDES the impacts of different measures, decisions and procedures can be tested and analyzed before moving on to full implementation.

Roles of REDES

Flood management is a decision-making process bordering between the art and science of making choices for desirable change, to solve problems and minimize negative impacts of floods. There are six major roles for REDES adopted from the general decision science literature (IGDS, 1998):

1. guiding role through the decision-making process during planning, emergency management and flood recovery;
2. assisting role in establishing the social, economic and environmental goals for managing floods in the Red River Basin;
3. supporting role in describing the problem to be solved in terms of predefined objectives, and constraints for generation of alternative actions;
4. active role in collection and integration of information that will support problem description, evaluation of consequences of actions, and learning;
5. aiding role in evaluation of alternatives using multiple and often conflicting objectives; and
6. educational role in learning from the decision process itself and from outcomes of the implemented decisions.

Different users of REDES will communicate with the system in different ways utilizing one or more of listed roles at the time. Utilization processes of different roles and their effectiveness will vary in terms of: time required for successful completion of intended application; level of consistency of linking different roles of the system; the amount of iterations performed through the process; level of involvement of stakeholders; and style and intensity with which each role is approached by different users. Highly effective use of REDES will solve the right flood management problem; clearly describe the problem, decision criteria, flood damage reduction alternatives, uncertainties, and choices to participants; use available information efficiently; evaluate a range of creative, relevant, and feasible flood management alternatives; choose alternatives consistently with criteria and information; and provide for learning to improve future flood management decisions (IGDS, 1998).

The design architecture of REDES

Flood management in the Red River Basin is a unique process due to: (a) international character of the watershed (responsibility of different agencies; differences in decision-making process; different level of dependence on government support, etc.); (b) direction of the river flow (one of eight rivers in the world flowing North); (c) physical characteristics of the watershed and land use; (d) geographical location; and (e) climate of the region. Therefore the design of the REDES is adopted for particular conditions of the Red River Basin.

DSS literature offers two main development architectures, functional and tool-based, as discussed earlier. However, development of REDES is based on an original approach identified earlier as the intelligent decision support architecture. The main power of the intelligent decision support architecture is in its ability to integrate efficiently technical knowledge of flood management, systems approach to problem formulation and solution, with the personal experience and set of graphical tools for data presentation and spatial analysis.

Schematic presentation of REDES architecture is shown in Figure 4. REDES is comprised of a web-based user interface that provides easy access to distributed virtual databases (through a shared metadata catalog), and modeling tools.

Distributed virtual database. Data about the Red River Basin exist in many forms and are not always widely available (IJC, 1997). The main intent of REDES is to ensure that all data (topographic, land use, hydrologic, hydraulic, environmental and economic) are accessible to all users in order to provide support for flood management activities. REDES will include (Figure 4) a distributed database with various agencies assuming responsibility for continuing, maintaining and updating database components. This structure requires that metadata (data regarding data) be made available.

REDES design architecture involves development of a virtual database (data catalog or library) in the form of an internet web site, in sufficient detail to provide the

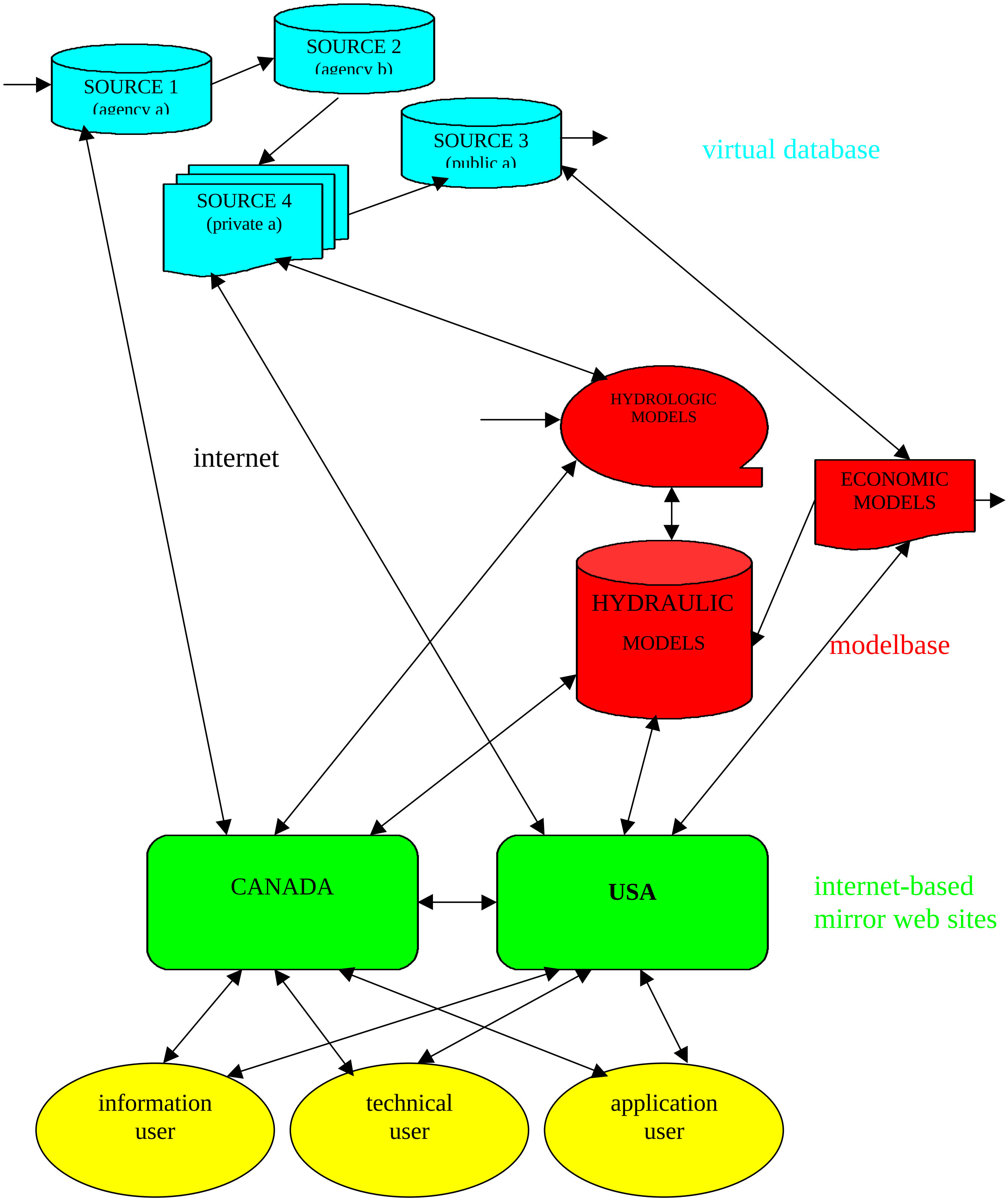


Figure 4 REDES system structure

following services: (a) quickly locate data required for flood reporting and flood fighting in the Red River Basin; (b) describe in detail the contents and limitations of the data; and (c) present the data in different formats (maps, graphs, pictures, videos, etc.). Virtual database is searchable by data type, data holder/owner, location, etc.

The Red River Basin virtual database will have no single data repository thus eliminating the requirement to provide regular updates of data to a data clearinghouse. Some data sets, however, may need to be centralized depending on the preferences of the data set providers. Metadata (a text file describing various characteristics of each data set, such as accuracy, format, etc) is critical for users of distributed databases to accurately evaluate data sets in terms of usefulness for various types of analyses. Metadata provides a method of long-term memory about data. Metadata is required as a prerequisite for any data set that becomes incorporated into the REDES.

Development of the virtual database takes into consideration the needs and capabilities of data providers, and data users, as well as seamless integration of database with other components of the REDES system. The Red River Basin virtual database will be used in three modes: (a) planning and design for flood protection; (b) real time flood emergency; and (c) flood recovery. Table 1 includes initial data components as identified by the Red River Basin Task Force of IJC.

Modelbase. Improved flood management calls for more coordinated and integrated use of descriptive and predictive modeling tools. Hydrologic, hydraulic, economic, and environmental models are required to support decision-making in the basin.

Hydrologic models combine precipitation and other inputs to forecast runoff in a river system. During the flood of 1997 on both sides of the border residents of the basin have expressed lack of confidence in the ability of responsible agencies to provide accurate forecasts because of out-dated technology, staff shortages, and inadequacy of the hydrometric network to provide essential information for flood forecasting (IJC, 1997; Manitoba Water Commission, 1998). REDES modelbase includes existing hydrologic forecasting tools and allows for the integration of new tools which are in the process of development.

TABLE 1. Initial database components

INFRASTRUCTURE ***Readily Available*** Roads - elevation and alignment Railroads - elevation and alignment Levees - elevation and alignment Wells - Active and abandoned Bridge and Culvert openings (>5ft) Utilities – Hydro, gas, water, sewage, etc. ***Not Readily Available*** Drains - dimensions and alignment Raised Pads - locations and elevations Impoundments: size, sill elev., construction date Critical Facilities Potential Spill Sources (Hazardous Material) Historic Sites **TERRAIN/ENVIRONMENTAL** ***Readily Available*** Digital Elevation Data Land Use - current and historic National Wetlands Database Soils Water Quality Threatened and Endangered Species (T&E) ***Not Readily Available*** Digital Elevation Data (detailed) Drained Basins Agricultural and other Chemical Use Critical Aquatic & Wildlife Habitat Archeological Sites **MISCELLANEOUS** ***Readily Available*** Census Data ***Not Readily Available*** Emergency plans and Organizational charts	**HYDRO-METEOROLOGICAL DATA** ***Readily Available*** High-water Marks – Flood Extent X-sections (bathymetry) Hydrometric and meteorologic sites/network Gauge locations Precipitation, snow, temperature, dew point, wind, solar radiation, etc. Stage and discharge data Elevation-Discharge Curves Discharge-Frequency curves Stage- Damage Curves ***Not Readily Available*** Head loss – Structures/roads/levee breaches Head loss – Changes since flood Ice data **GEOGRAPHIC DATA** ***Readily Available*** Political Boundaries (State, County, Province) Hydrologic Units River reach Lakes Transportation Network (roads and railway) Geodetic Control ***Not Readily Available*** Floodway/Floodplain Alignment **IMAGERY DATA** ***Readily Available*** Satellite imagery ***Not Readily Available*** Aerial Photographs

The need for hydraulic models that could be used to route forecasted flood volumes in the Red River Basin and, in particular, handle overland flow was identified early in the IJC study (IJC, 1997). The purposes of such models fall into two categories: real-time flood forecasting, and planning and design. Identified needs are: (a) real-time flood forecasting (determine flood levels and timing of peaks; determine hydrograph shape and inundation; account for overland flows; conduct backwater calculations at critical locations; incorporate infrastructure changes such as breaches and blow outs; carry out what if analyses); and (b) planning and design (post flood analyses for infrastructure evaluation and design; determine effects of flood operations; analyze structural and non-structural peak reduction proposals; conduct what-if and sensitivity analyses; define data and monitoring requirements; evaluate the aerial extent and volume of the 1826 flood).

Preliminary testing of one-dimensional unsteady flow models from Emerson to the Winnipeg Floodway inlet has shown that many requirements can be met by such modeling. It is also clear that in some regions needs for more powerful two-dimensional models exist. Wind effects, in particular, are a concern. Existing one-dimensional models and one- and two-dimensional models in the process of development (MIKE 11, MIKE 21 in Canada and UNET in USA) are the main components of the REDES modelbase.

Economic models that will help decision-makers to compare the flood-related economic factors of alternative means for flood damage reduction are also in the REDES modelbase. Their role will be in economic assessment of structural and non-structural flood damage reduction measures and investigation of potential incentives/disincentives facing individual activity in the floodplain. Examples of economic models include: expected annual flood damage (EAD) computation (U.S. Army Corps of Engineers, 1989); SID, structure inventory for damage analysis package (U.S. Army Corps of Engineers, 1989a); flood damage analysis (FDA) package (U.S. Army Corps of Engineers, 1988); and other.

Environmental models such as spill response models and habitat evaluation models will assist in evaluating the environmental consequences of flooding. REDES modelbase includes all the models currently in use in the Red River Basin.

Decision models are incorporated in the modelbase to assist the decision-makers. Sustainable flood management is built on the assumption that an acceptable compromise must be achieved between the three main sets of objectives: ecological, economic and social. Each of these three sets constitutes a larger subset of specific objectives. The quantification and evaluation of the objectives and their associated trade-offs are the main tasks of multi-objective analysis tools (Goicoechea et al., 1982). One of the possible ways for dealing with the complexity of sustainable flood management is a modified multi-objective framework. It requires definition of objectives for all stakeholders. Application of this formulation produces a set of nondominated solutions, as opposed to a single optimum followed by a subjective process to select one of the nondominated solutions, as a ‘best compromise’ solution. Uncertainty in selecting objectives for all stakeholders, as well as selecting the combination of weights may result in the selection of a ‘best compromise’ solution, which is not realistically sustainable. Some of these aspects of sustainable flood management decision-making are calling for the replacement of the ‘best compromise’ solution concept with the concept of the ‘most robust’ solution. This idea has been introduced by Simonovic (1989) and applied in sustainable context by Bender et al. (1994). It has been demonstrated that the idea of combining the sensitivity analysis of the multi-objective solution to objective values and preference (weight) structures results in the replacement of a ‘best compromise’ solution with the ‘most robust’ solution. The ‘most robust’ solution is defined as: an alternative least sensitive to changes in the objectives and preference structure.

User interface. REDES architecture is based on a single link user interface, such as a Web Page. Multiple-level interface is developed to be the door through which the overall Red River virtual database, modelbase and information sources are accessed. During the Flood of 1997 numerous Internet "Flood Information" web pages appeared that provided useful information to data consumers in the basin. However, these sites were not integrated in a way to allow access to all potential sites or sources of information. Based on the IJC public hearings in the Red River Basin and user needs assessment workshops, conducted in July 1998, there is a real need to integrate and make more readily accessible the distributed databases that currently exist and those to be developed in the future.

Three types of users will be using the same interface. Different users will be granted appropriate access through simple user identification. In this way REDES will provide for security of data sources and against inappropriate use of modeling tools. User interface is guiding user of REDES in language that is sensitive to a user’s level of technical and social understanding. Through this module users will provide the input into the trade-off analysis expressing preference sensitivity and evaluating consequences of stake holder positions. User interface provides a vehicle for common understanding and generation of direction suggestions.

As a background of user interface an additional REDES module is introduced under the name of decision process coordinator. It is developed as an expert system module for controlling decision processes and user interaction with other decision support system modules. This component of the system allows different decision options to be considered and assists the collaborative flood management decision-making process. Experience in applying economic, ecological and social analyses provide the basis for many functions of the decision process coordinator.

REDES development requirements

A conceptual framework for REDES is based on the six major roles it has to serve and the design architecture proposed earlier in this document. In this framework, analytical tools and functional applications and services support one or more of REDES roles. For example, multi-objective analysis software that allows multiple stakeholders to provide input to decision processes can aid the goal setting role of REDES; geographic information systems can display multiple types of data about the Red River Basin (topography, land use, flood extent, etc.); internet connections can help locate and access databases, documents, pictures, and videos.

REDES is a large suite of software applications that will ultimately allow for planning of flood damage reduction measures in the Red River Basin; tracking of people, missions, equipment and resources during the flood emergency management; declaration of flood disaster; post-flood recovery support; data access from, and data entry into established databases (if acceptable); access to various documentation; storage of digital photographs and videos taken on the ground; and storage of other imagery and maps. It is comprised of a web-based multilevel user interface, virtual database, and modelbase. Technical diagram of REDES system is shown in Figure 5. Technical requirements for each REDES component are presented in the following sections of the document.

Multilevel user interface. It is the entrance gate to REDES system. The design of user interface is planned in the form of the web site (mirror locations in the USA and

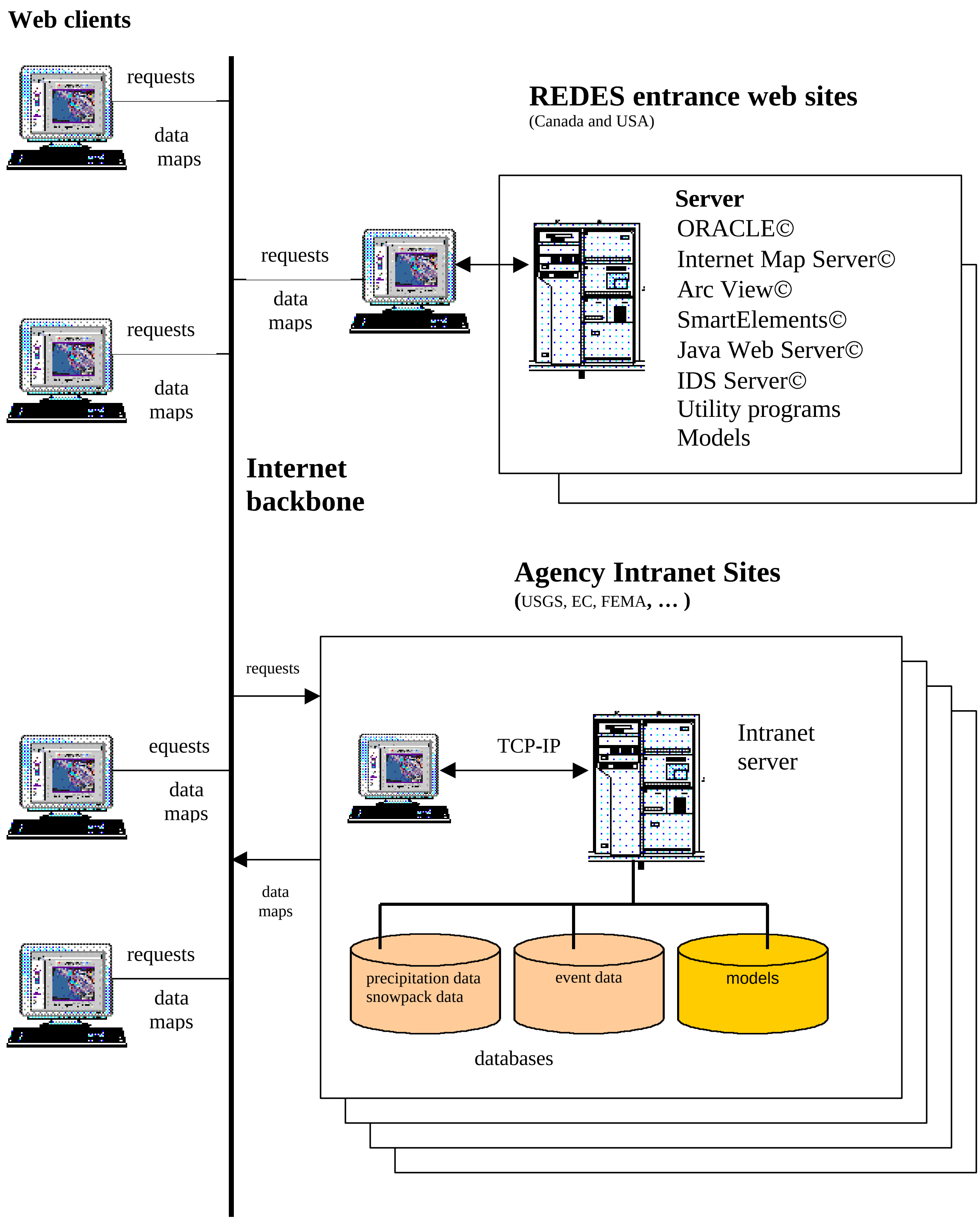
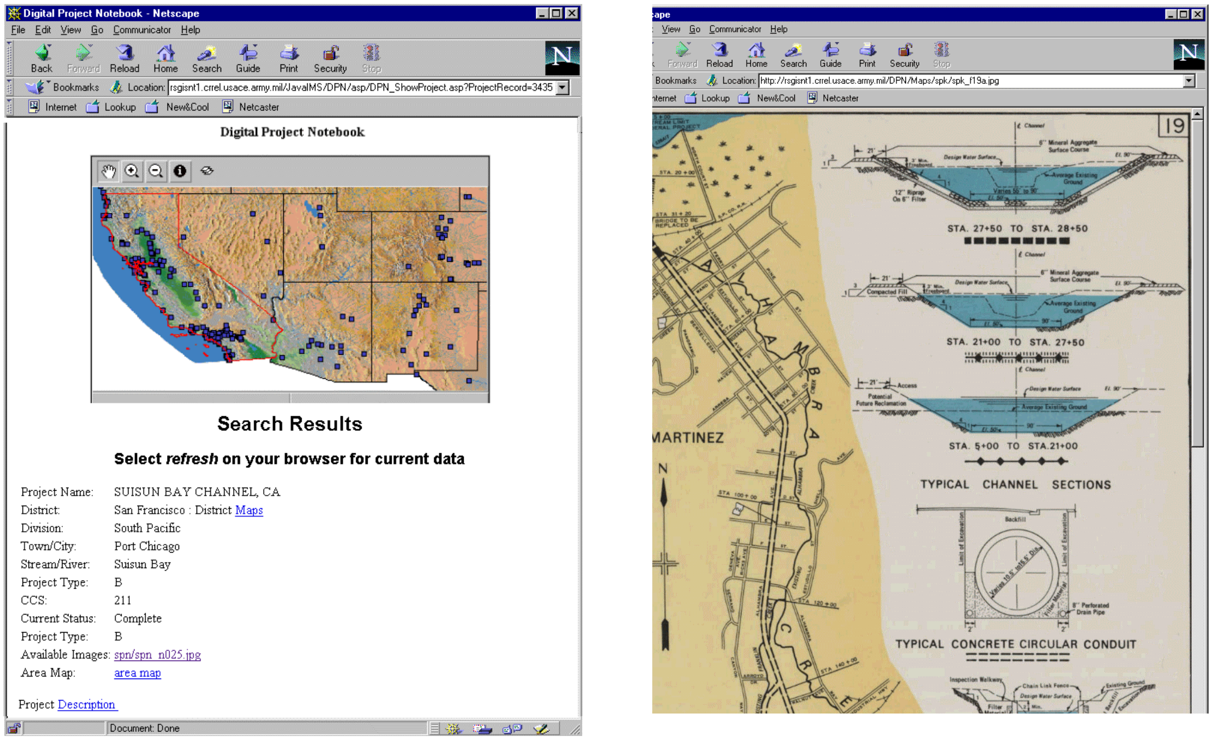


Figure 5 Technical diagram of REDES

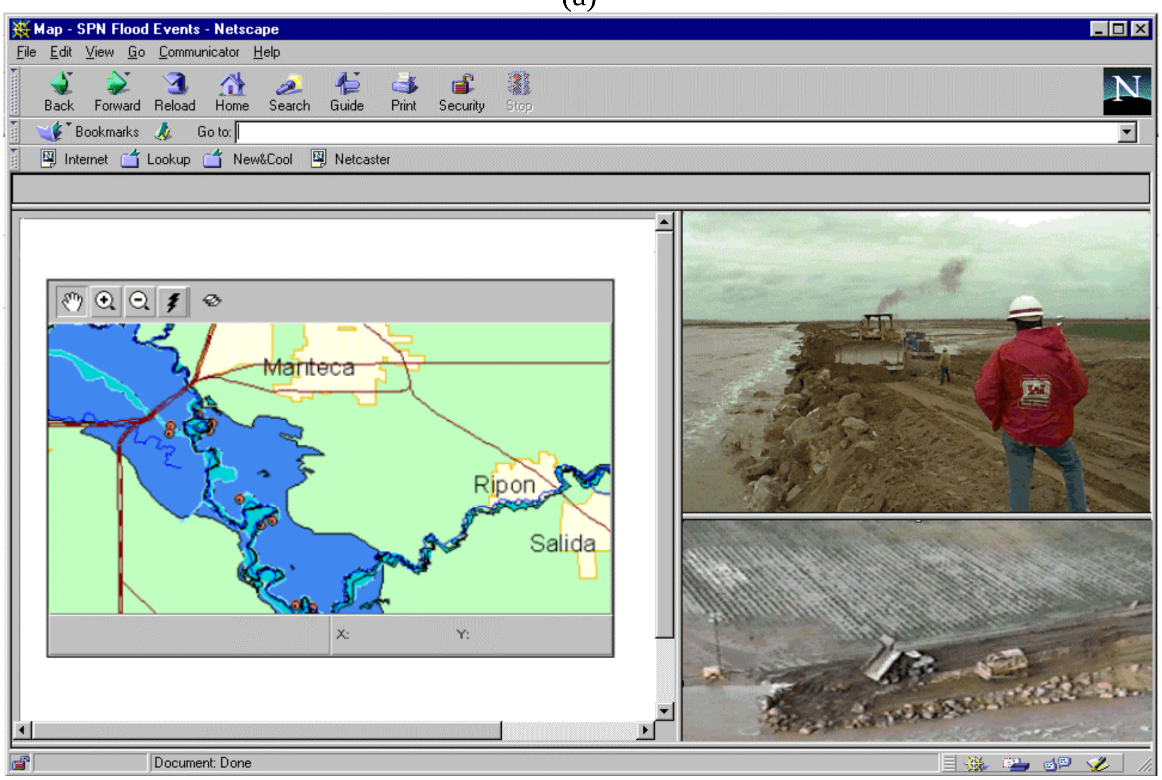
Canada) supported by numerous communication utilities written in Java, and documents presented in Hypertext Markup Language (HTML). Java utilities are providing three main functions of the user interface: (a) access to, and two-directional transfer of data residing on remote web-connected clients; (b) activation of, and access to modeling tools residing on remote web-connected clients; and (c) presentation of spatial information in the form of maps and other graphical tools.

Details of technical interface design are going to be worked out by the developer. Essential requirements are: identification of the user level and provision of appropriate support; simple intuitive design; flexible design; and easy of use. For the information user (general public for example) access to REDES will provide for example, a detail processed information on flood forecast, flooded area, maximum elevation, time of the peak, and similar. Information will be available in the form of maps, graphs, documents, digital pictures, etc. Figure 6 presents two examples of potential user interface (Fig 6a location and presentation of technical documents on structures; Fig 6b location and presentation of digital photography from the site) as designed for the US Army Corps integrated system for communication, command and control (Bruzewicz, et al., 1997). In Figure 7 simple information user interface is shown which allows selection of the water level monitoring site.

For the technical user, for example access to REDES will provide among other things, for flood protection alternative generation. Stakeholders are able to specify technical options from the problem domain and technical users will perform analyses by selecting and running appropriate models. The model analysis, in turn, describes the behavior of the alternative. For example, a technical option of building a dike at a specific location with water levels raised to a given stage, model analysis determines the cost of construction, flooded area, storage capacity, and the uncertainties of alternative



(a)



(b)

Figure 6. Examples of REDES information user interface (after Bruzewicz et al., 1997)

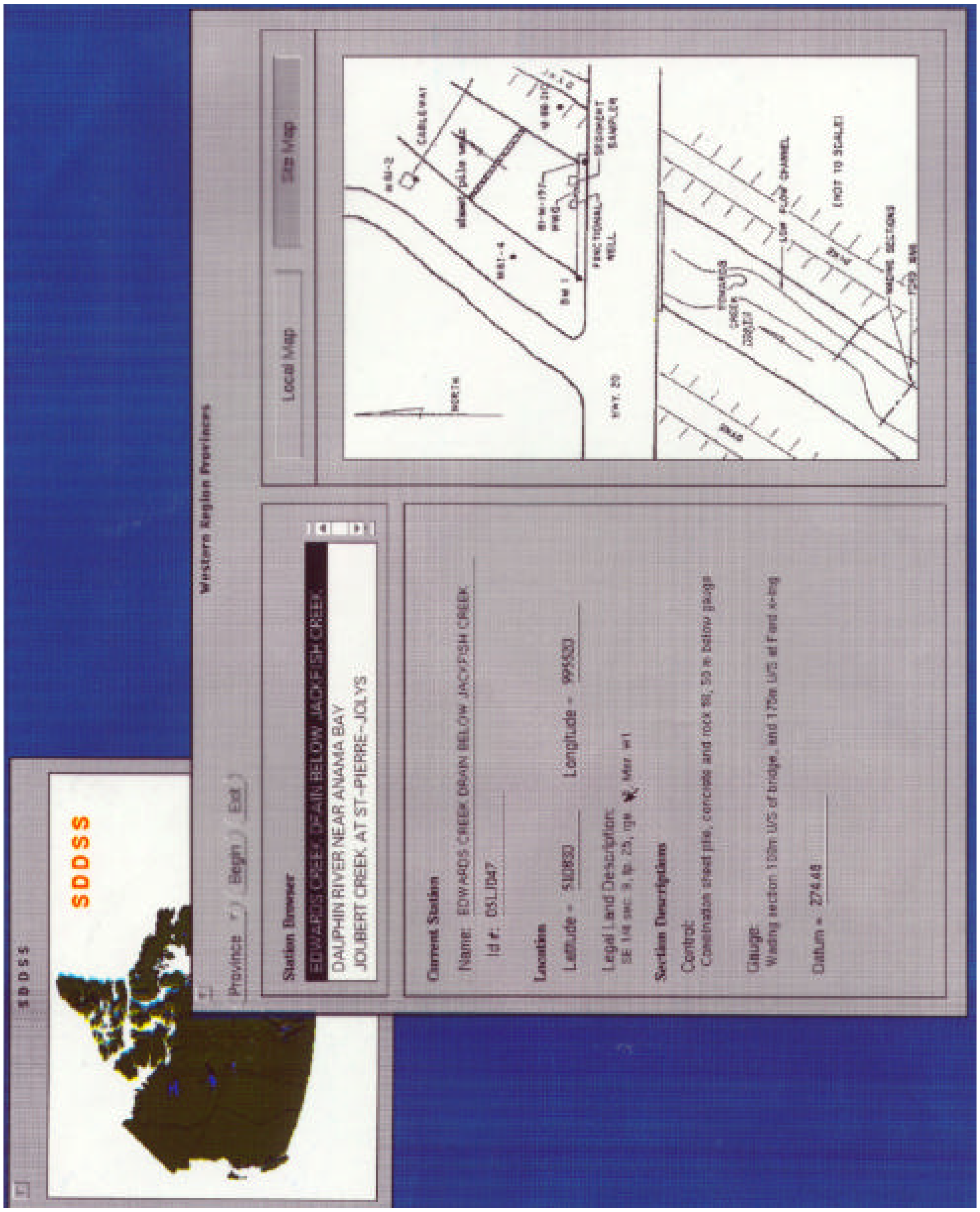
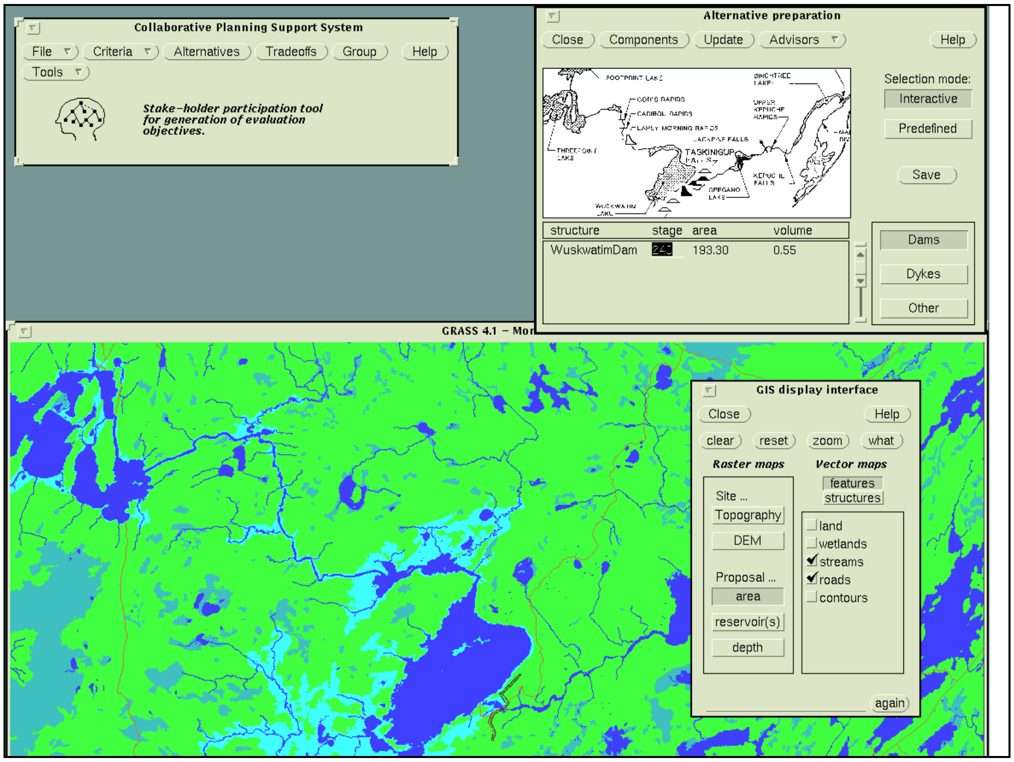
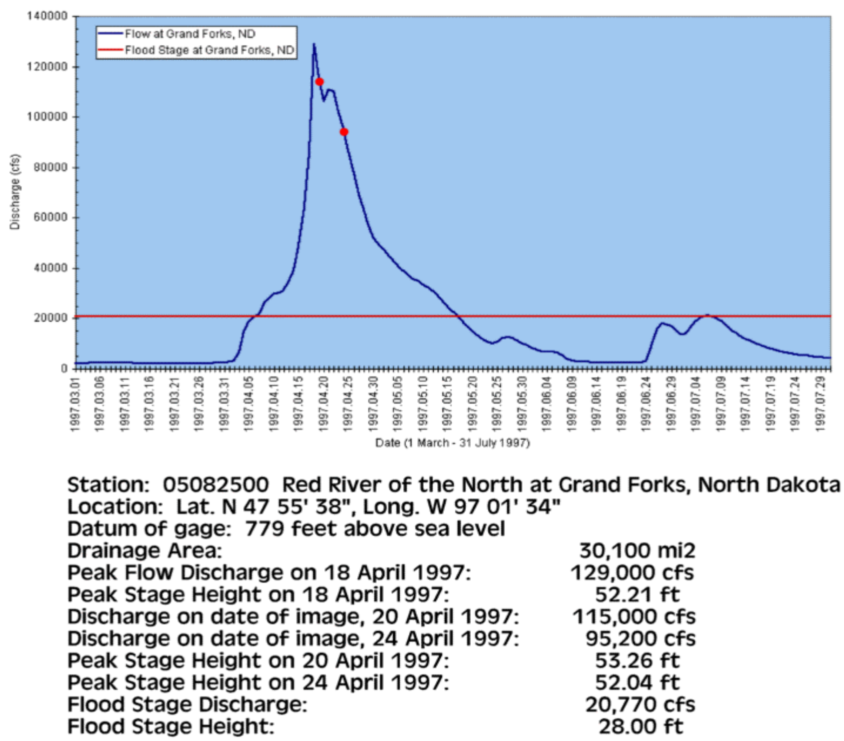


Figure 7 Example of REDES information user interface (after DeGagne et al., 1996)

behavior. Stakeholders are able to interactively adjust the system to visualize changes, designed to improve understanding of system behavior. Figure 8 presents two example computer screens: (8a) related to alternative generation (taken from Bender and Simonovic, 1998); and (8b) related to hydrologic analysis (taken from Bruzewicz, et al.,



(a)



(b)

Figure 8. Examples of REDES technical user interface (after Bender and Simonovic, 1998 and Bruzewicz et al., 1997)

1997). Example shown in Figure 9 illustrates technical user interface to be used in running multi-objective analysis.

Interface similar to one shown in the Figure 8a can be used for the support of application users too. However, decision-making support for application users may require more complex analysis of the event (processing hydrologic and hydraulic data) and integration of physical, economic, environmental and social information. Collaborative decision-making setting assumes an iterative, flexible, modeling posture. Knowledge bases are used to determine appropriate model analysis (to be performed with the assistance of technical users) given the context of the problem (the selected judgement criteria). Impacts of flooding (in the context of a particular flood management decision) and altered water regimes are addressed using modeling tools such as geographical information systems. Figure 10 illustrates a portion of the flood delineation results in the Grand Forks, ND, area (after Bruzewicz, et al., 1997).

Virtual database. Technical requirements for virtual database development are not unique, due to the fact that databases are going to be developed at different sites by different agencies. However, the development of REDES is addressing the coordination and access functions. Data standardization will be hard to achieve across numerous agencies. Therefore, technical requirements of REDES are including the development of metadata and will insure connectivity to intranet sites maintained by different agencies (Figure 5). Metadata work is aimed at:

- Identifying all potential data providers in the basin;
- Identifying all internet information providers during 1997 flood (minimum list includes Federal, Provincial, State, County, Municipality, Towns, Watershed Boards, the general public, Universities, private industry, media, commissions, Police);
- Identifying actual data providers to the Red River virtual database;
- Identifying data sets each provider can make available to the database (priorities are based on database components in Table 1 but this list is not exclusive);

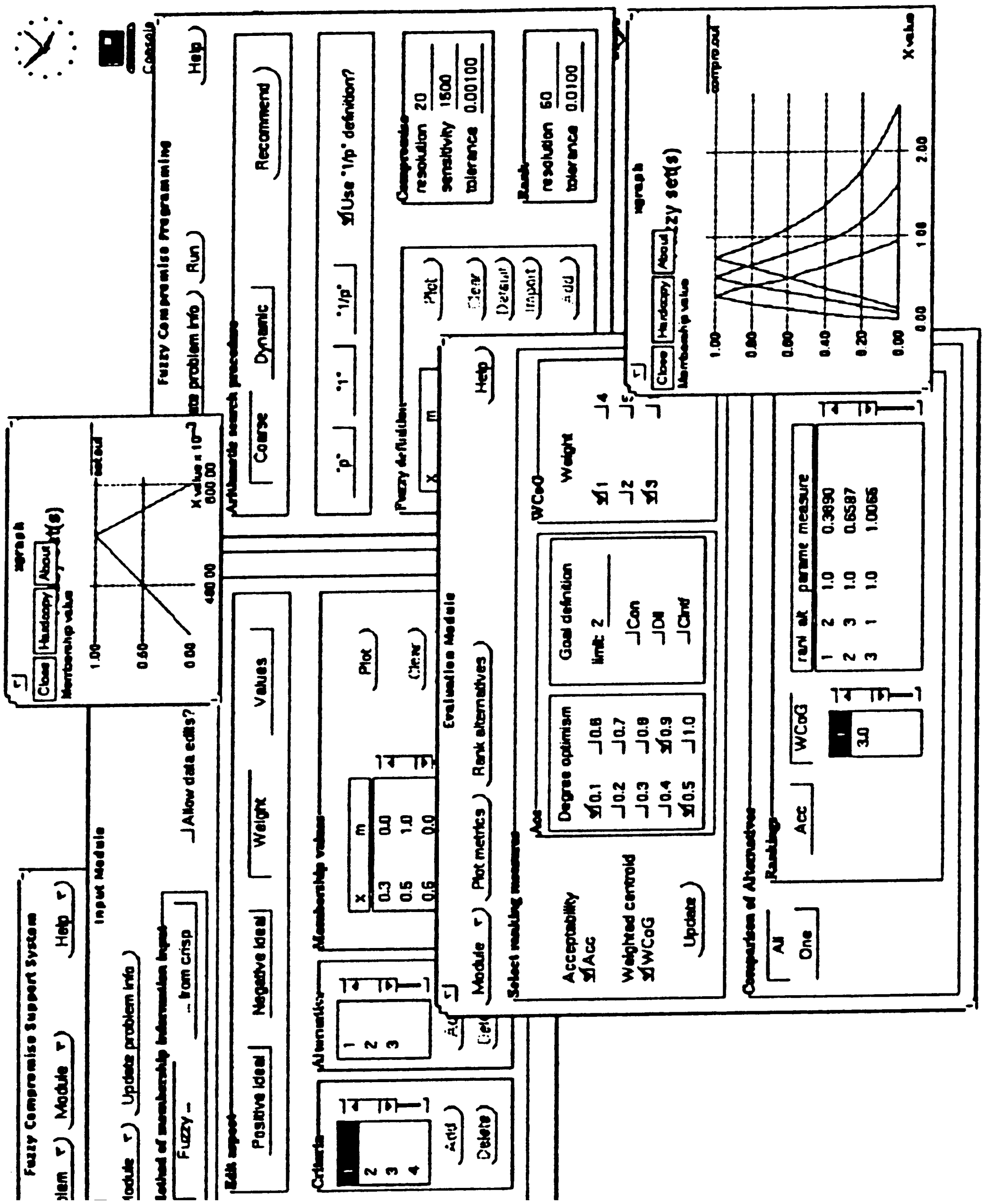


Figure 9. Example of REDES technical user interface (after Bender and Simonovic, 1998)

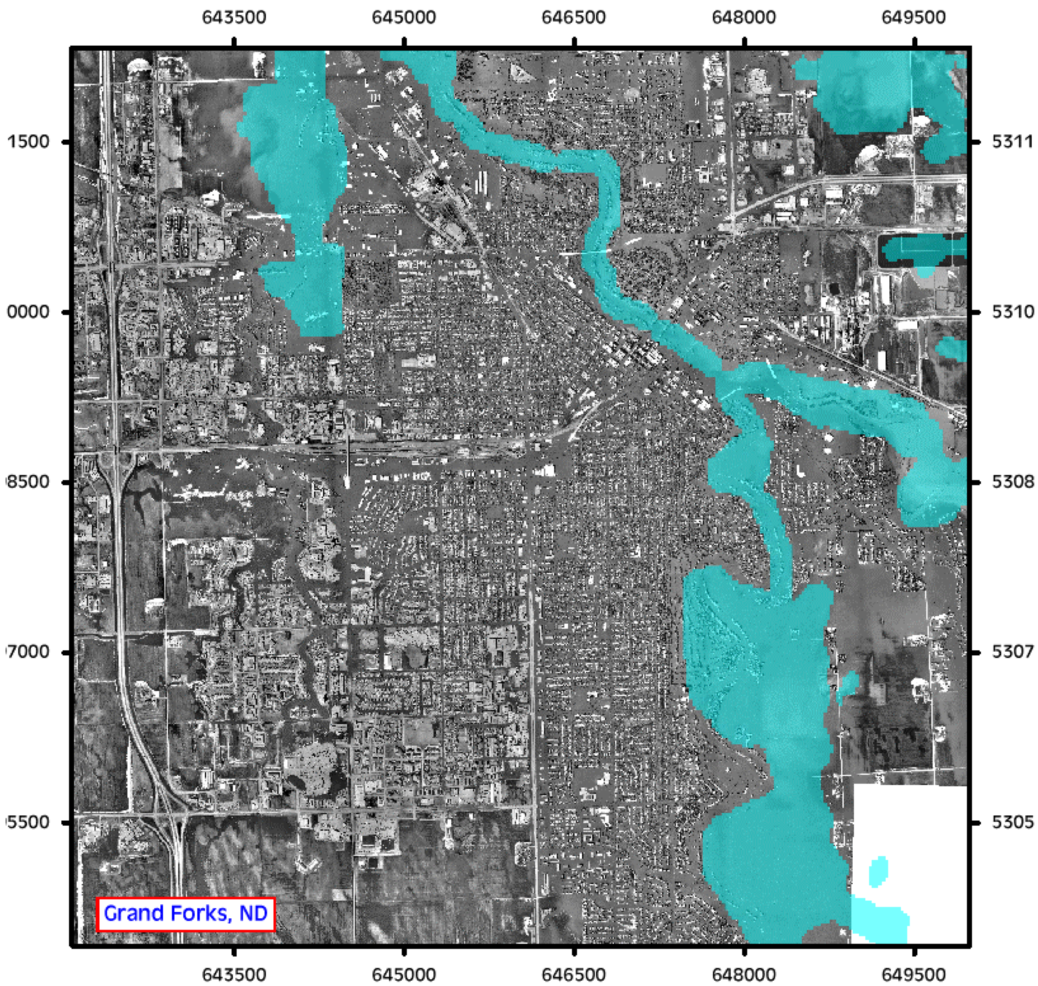


Figure 10. Example of REDES application user interface (afetr Bruzewicz et al., 1997)

- Identifying and eliminating duplications; and
- Determination of data providers capability to serve data and if necessary, identify possible partner for serving the data.

Number of data-related functions will be performed at the REDES entrance sites, as well as temporary data storage and presentation. As shown in Figure 5, Windows NT-type servers are required at each of the sites. They are equipped at list with: ORACLE© database management software; Internet Database Access Server IDS©; ArcView© GIS package; ArcView Internet Map Server©; Java Web Server©; and Neuron Data SmartElements© knowledge base development package. In addition to the above list many utility programs and some models may be stored at the entrance sites servers.

Minimum required utility tools include: Java compiler; C++ compiler; text processing tool; and graphing tool.

Modelbase. REDES modelbase is of distributed type. Models will be scattered among entrance web sites servers and intranet sites of different agencies. Each model will have its own technical requirements. REDES will provide for seamless communication between different models, between the models and databases, and between the models and presentation utilities. Most of these requirements will be addressed through the development of multi-level user interface. Particular requirements of each model will be addressed through the development of knowledge bases (expert systems) that will lead users through the processes of data preparation, results interpretation, and presentation. Successful implementation examples of similar DSS development approach are documented in Simonovic and Savic (1989), DeGagne et al. (1996) and Bender and Simonovic (1998).

5. IMPLEMENTATION PLANNING

REDES implementation is a joint effort to be coordinated by the Red River Basin Task Force of IJC with the assistance of the Global Disaster Information Network (GDIN) team (GDIN, 1997). Its implementation plan is integrating activities in progress, existent data infrastructure and models, and public needs in the Red River Basin. The professional services, equipment and software, and data and information that enable the implementation of the REDES are voluntary contributions from the organizations associated with the activities of IJC in the Red River Basin. Organizations and agencies actively engaged in the development, implementation, and operation of the REDES include among others the following:

- International Joint Commission
- University of Manitoba
- Manitoba Department of Natural Resources
  - Water Resources Branch
- Manitoba Environment
- Manitoba Remote Sensing
- Manitoba Department of Highways
- Manitoba Emergency Management Organization
- Environment Canada
- Agriculture Canada
  - Prairie Farm Rehabilitation Administration
- Department of Western Economic Diversification
- National Oceanic & Atmospheric Administration
  - National Weather Service, Office of Hydrology
- US Department of Defense,
  - ASD C3I (GDIN)
  - US Army Corps of Engineers:
    - St. Paul District
    - Headquarters

- US Geological Survey
  - EROS Data Center
- North Dakota State Water Commission
- Minnesota Department of Natural Resources
  - Division of Waters
- Federal Emergency Management Organization
- North Dakota State University.

IJC Red River Basin Task Force is conducting a number of studies that will generate the REDES components: (a) hydraulic models for Red River (MIKE 11© in Manitoba and UNET in USA); (b) detailed digital elevation model for Pembina area; (c) metadata development for Canadian part of the Red River Basin; (d) 1997 flood mapping; and (e) stage-damage curves for the Red River Basin. Development of many other tasks will follow in the next fiscal year.

In consonance with the GDIN mission, the US Department of Defense has agreed to apply a number of program resources to support timely REDES activation. These include the following assets: (a) report on user needs assessment; (b) provision of ENGLink Interactive applications for user interface development; and (c) support of experts to develop web-based content and site structure.

REDES implementation is planned in two phases: (1) prototype development; and (2) development of operational system. The emphasis of the first phase is on the support for information and application users, and the second phase on the support for technical users. A preliminary schedule is presented in the Table 2. It depicts the principal activities leading to successful demonstration (end of phase 1) and operational implementation of the complete REDES systems (end of phase 2).

Table 2. Preliminary schedule for REDES development

Task	xii	i	ii	iii	iv	v	vi	vii	viii	ix	x	xi	xii	i	ii	iii	iv	v	vi	vii
Different																				
User needs assessment																				
DEM development																				
Metada																				
Virtual database																				
Hydraulic modeling																				
Phase 1 - REDES																				
Prototype functional requirements																				
Interface development																				
Integration of database																				
Integration of existing models																				
Entrance web sites development																				
Prototype demonstrations																				
Phase 2 - REDES																				
REDES functional requirements																				
Integration of agency Intranet sites																				
Integration of models																				
Operational testing																				
Operational cutover																				

6. CONCLUSIONS

The initial impetus for developing REDES is in the expressed needs of the Red River Basin residents for improvement in the flood management and a major change in the decision-making process. REDES is envisioned as a tool for analyzing alternative mitigation and recovery strategies. We propose this development effort as a way of making flood management process in the Red River Basin more transparent and efficient in reducing future economic, environmental and social flood damages.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

Alexander, M.J., *Information systems analysis*. SRA, Chicago, USA, 1974.

Allen, R.B., Decision Support, *Civil Engineering,* ASCE, July, 53-55, 1996.

Bender, M.J., G.V. Johnson, and S.P. Simonovic, Sustainable Management of Renewable Resources: A Comparison of Alternative Decision Approaches, *International Journal of Sustainable Development and World Ecology*, Vol. 1, No. 2, 77-88, 1994.

Bender, M.J., and S.P. Simonovic, A Prototype Collaborative Planning Support System for Hydroelectric Development, *Journal for Information Technology Management*, in press, 1998.

Booy, C., Red River Flood Control at Winnipeg, *Presentation to the International Joint Commission*, St. Adolphe, Manitoba, pp.11, 1998.

Bruzewicz, A.J., D.M., Pokrzywka, and C. Devine, Remote Sensing, GIS, and the Intranet in the US rmy Corps of Engineers: ENGLink Interactive for Emergency Management, *Internal report*, Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, 1997.

Bumsted, J.M., *Floods of the Centuries: A History of Flood Disasters in the Red River Basin 1776-1997.* Great Plains Publications, Winnipeg, Canada, pp. 144, 1997.

Clark, R.H., C.D., Howard, and J.N., MacKenzie, *Report on the 1997 Red River Floodway Operations.* North Ritchot Restoration Committee, pp.23, 1997.

DeGagne,M.P.J., G. G. Douglas, H.R. Hudson, and S.P. Simonovic, A decision support system for the analysis and use of stage-discharge rating curves, *Journal of Hydrology*, Vol.184, No.3-4, 225-241, 1996.

Global Disaster Information Network, *Harnessing Information and Technology for Disaster Management*, Disaster Information Task Force Report, November 1997.

Goicoechea, A., Hansen, D.R., and Duckstein, L., *Multiobjective Decision Analysis with Engineering and Business Applications*, John Wiley and Sons, New York, USA, 1982.

Goslar, M.D., G.I. Green, and T.H. Hughes, Decision Support Systems: An Emprical Assessment for Decision-making, *Decision Sciences*, Vol.17, 79-91, 1986.

Grant, K., The Social Dimensions of the Flood of the Century, *Report on a strategic research workshop*, University of Manitoba, Winnipeg, pp.17, 1997.

Guariso, G., and H. Werthner, *Environmental Decision Support Systems*. Ellis Horwood Limited Publishers, Chichester, UK, 1989.

International Joint Commission (IJC), Red River Flooding: Short-Term Measures, *Interim report of the International Red River Basin Task Force*, Ottawa, Washington, December 1997.

Interagency Group on Decision Support for Land, Natural Resources and the Environment (IGDS), A Strategy for the Development and Application of Decision Support Systems for Natural Resources and the Environment, *Report for consideration by Federal Agencies*, IGDS, 1998.

Kuereuther, H., and L.Miller, Intearctive Computer Modeling for Policy Analysis: The Flood Hazard Problem, *Water Resources Research*, Vol.21, No.2, 105-113, 1985.

Manitoba Water Commission, An Independent Review of Actions Taken During the 1997 Red River Flood, *A Report to the Minister of Natural Resources,* Winnipeg, Manitoba, June 1998.

Mittra, S.S., *Decision support systems: Tools and techniques*. John Wiley & Sons, New York, USA, 1986.

Myers, M.F., Building safer communities: Lessons from the US, *Presentation at the Canada's National Mitigation Policy Workshop,* Winnipeg, Canada, October 1998.

North Richot Action Committee, *Presentation to the International Joint Commission*, Ste. Agathe, Manitoba, Canada, pp.12, 1997.

Loucks, D.P., and J.R. daCosta, (editors), *Decision support systems: Water Resources Planning*. Springer-Verlag, Berlin, Germany, 1991.

Parker, B.J., and G.A. Al-Utabi, Decision support systems: The reality that seems to be hard to accept? *OMEGA International Journal of Management Science*, (14), 2, 1986.

Rannie, W.F., The Red River Flood Control System and Recent Flood Events. *Water Resources Bulletin*, Vol. 114, No. 6, 613-645, 1980.

Simonovic, S.P., and D.A. Savic, Intelligent Decision Support and Reservoir Management and Operations, *ASCE Journal of Computing in Civil Engineering*, Vol.3, No.4, 367-385, 1989.

Simonovic, S.P., Application of Water Resources Systems Concept to the Formulation of a Water Master Plan, *Water International*,Vol.14, No.1, 37-51, 1989.

Simonovic, S.P., Flood control management by integrating GIS with expert systems: Winnipeg City case study, in *Application of Geographic Information Systems in Hydrology and Water Resources* (ed. by H.P.Nachtnebel and K.Kovar), IAHS Publ. no.211, 61-72, 1993.

Simonovic, S.P., Decision Support Systems For Sustainable Management Of Water Resources 1. General Principles, *Water International*, Vol.21, No.4, 223-232, 1996.

Simonovic, S.P., Decision Support Systems For Sustainable Management Of Water Resources 2. Case Studies, *Water International*, Vol.21, No.4, 233-244, 1996a.

Smith, K., and R. Ward, *Floods: Physical Processes and Human Impacts*, John Wiley and Sons, New York, 1998.

Thierauf, R.J., *User-Oriented Decision Support Systems*, Prentice Hall, Englewood Cliffs, New Jersey, 1988.

USDA (United States Department of Agriculture), Decision Support Systems for Ecosystem Management: An Evaluation of Existing Systems, *General Technical Report RM-GTR-296*, Rocky Mountain Research Station, Fort Collins, Colorado, US, 1997.

U.S. Army Corps of Engineers, FDA: Flood Damage Analysis Package, *User's Manual*, CPD-59, Hydrologic Engineering Center, Davis, California, 1988.

U.S. Army Corps of Engineers, SID: Structure Inventory for Damage Analysis, *User's Manual*, CPD-41, Hydrologic Engineering Center, Davis, California, 1989a.

U.S. Army Corps of Engineers, EAD: Expected Annual Flood Damage Computation, *User's Manual*, Hydrologic Engineering Center, Davis, California, 1989.