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 conducted workshops that concluded: (a) that agencies must exchange and share information in order to accomplish their 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 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 efforts to examine and make 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; (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.

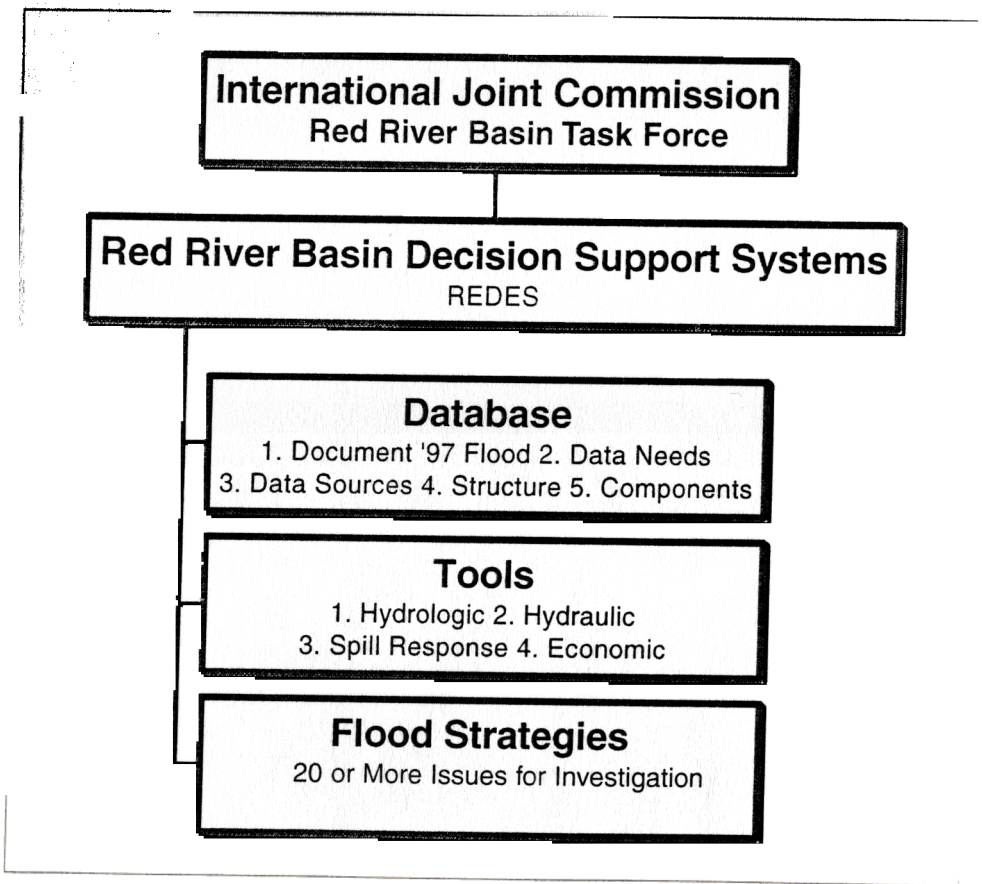

Figure 1: Conceptual Framework for Flood Management in the Red River Basin (modified after IJC, 1997)

DECISION SUPPORT SYSTEM FOR FLOOD MANAGEMENT IN THE RED RIVER BASIN

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Written comments on this paper will be accepted until March 2000

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Abstract
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. Making flood management decisions during the planning, flood-fighting and post-flood recovery stages 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.

Résumé
L'auteur de cette étude présente le détail du plan d'élaboration et d'installation du système de soutien des décisions pour le bassin de la rivière Rouge (REDES). En principe, le système répondra aux besoins des décideurs et des intervenants du bassin. Pour prendre des décisions touchant la gestion des inondations pendant les étapes de planification, de lutte contre l'inondation et de reprise des activités après l'inondation, il faut un mécanisme complet de soutien qui permet de tenir compte de tous les effets de l'inondation. L'objet de REDES est d'améliorer la planification d'intervention en cas d'urgence, la réaction et la reprise des activités. Pour ce faire, le système examine en profondeur les prévisions relatives aux inondations et la surveillance connexe, les plans en cas d'urgence et la participation du public.

Introduction

The *Flood of the Century* in the Red River Basin in 1997 suggested a need for a new paradigm of sustainable flood management in which local stakeholders look forward to 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.

The 1997 Red River flood took a heavy toll on the economy of both the United States and Canada. The problems of floodplain management had been mounting steadily in recent years. Despite the effort and dedication of talented professionals, the sheer magnitude of flooding in the basin means that the future management efforts will be at a larger scale (IJC, 1997; Manitoba Water Commission, 1998). Floodplain management is made more complex when the principal participants are organizationally separate and geographically located within two nations. Each agency in floodplain management

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Characteristics of Decision Support Systems for Sustainable Flood Management

Sustainable development principles impose a new set of requirements on the tools used in flood management (Simonovic, 1996; 1996a).

- *Problem identification.* Sustainable flood management contains a number of semi-structured and non-structured problems (characterized by lack of data or knowledge, non-quantifiable variables, and a very complex description). In this case, structuring the problem must be done by the human in the man-machine system using analogy, problem redefinition, deduction, intuition and approximation.
- *Problem formulation (learning).* DSS support in problem formulation focuses on two definitions of a problem. In the first case, a problem is viewed as an unsatisfactory reality discovered by observations and facts, and the decision-maker 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. In the second case the problem is considered to be a subjective presentation conceived by a participant confronted with unsatisfactory reality. Here, common threshold values have to be defined by the different participants in the decision-making process before the next procedure can take place. This approach requires the integration of problem formulation into the context of a DSS. The emphasis is shifted from the analysis phase. Problem formulation in sustainable flood management is more a social than a technical process.
- *'What if' capability (adaptability).* Many issues related to the implementation of sustainable flood management can be examined using the 'what if' approach, an example of which is the question of flood protection equity, with no need to rely on a flood specialist. Asking 'what if' questions to quantify uncertainties and to recognize the sensitivity of results to varying assumptions, stimulates the creative and analytical process of decision-making. The process provides a common ground for communication.
- *Use of analytical models (facilitation).* Since sustainable flood management is principally concerned with the future and the implications of today's decisions, a modeling capability is very important in managing flood damage reduction systems. This fact underlines the need for DSS modeling capabilities for the retrieval of data, execution of ad hoc analysis, evaluation of consequences of proposed actions and the proposal of decisions. DSS integrates different fields of science, and puts weight on social circumstances, which may influence problem definitions and solution approaches.
- *User-machine interface (interaction).* DSS incorporates 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, and indicates when such information is needed. Therefore, DSS is intended to help decision-makers throughout the process of identifying and solving problems. The merging of the computer output with the subjective judgment of the decision-maker provides a better basis for making efficient decisions.
- *Use of graphics (fast response).* Closely related to the previous two characteristics is the use of color graphics and GIS. In DSS, the graphic display of results allows users to obtain the essence of large amounts of physical data through readily understandable graphs, charts and maps, and to select the important information in a user-machine interface in which the user retains control during the decision-making process.

The main component of the framework presented in 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 not only to estimate flood management strategies based on today's situation, but also to project: (a) alternative levels of vulnerability based on future population and other factors in the basin; (b) losses from 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 such as environmental quality, economic vitality, and social equity.

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

DSS technology can be applied in 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) and environmental management (Guariso and Werthner, 1989; USDA, 1997). A strategy for the development and application of decision support systems for natural resources and the environment is being developed in the United States by the Interagency Group on Decision Support for Land, Natural Resources and Environment (IGDS). It includes a discussion of decision support activities currently underway in varies agencies, as well as existing and new tools (IGDS, 1998).

REDES objectives are: (a) planning different flood damage reduction alternatives; (b) evaluating alternative operational choices during the flood fighting; and (c) planning support during the flood recovery period. This paper will try to answer: who is REDES for? what are the roles of REDES? what is the appropriate REDES architecture? and what are the requirements for REDES development?

Decision Support Systems

Some texts in the field of water resources provide a very general definition of DSS: "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" (Loucks and daCosta, 1991).

Others avoid defining DSS, concentrating on the main purpose of such systems (Guariso and Werthner, 1989). All computer applications help in the decision-making process, and therefore nearly all could be called DSS. However, methods for setting the framework within such systems will continue to be developed, used, and modified in future (Mittra, 1986; Thierauf, 1988). The following definition is recommended in the context of water resources decision-making: *A DSS allows decision-makers to combine personal judgment with computer output in a user-machine interface, to produce meaningful information for the decision-making process. Such systems can assist in the solution of all problems (structured, semi-structured and unstructured) using all available information. They use quantitative models and database elements. 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; 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.

dinating 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 necessary, federal assistance can be requested.

Red River Basin 1997 Flood (Canadian perspective)

The Red River has its own characteristics (Rannie, 1980; IJC, 1997; Burnsted, 1997). Situated in the geographic center of North America, it originates in Minnesota and flows north. 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 13,000 km^2 in Canada). The basin is remarkably flat. During a major flood the entire basin becomes the floodplain. Most major floods occur following heavy precipitation the previous fall, hard and deep frost prior to snowfall, substantial snowfall, sudden thaws, and heavy rainfall or wet snow conditions during the spring breakup.

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 Red River floods. 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 (100 mm 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 created less than ideal melt conditions. The Red River began to flood on March 30. Floodwaters crested at Winnipeg on May 4. The so-called 'Red Sea' flooded about 2,000 km^2, 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 the 1997 flood totalled hundreds of millions of dollars.

Most of the flood management planning in the 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 the basin. Following the 1950 flood, 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 in the basin, a federal-provincial agreement led to the construction in the 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 current flood control works were based primarily on economic efficiency, getting the largest return for the investment.

During the spring of 1997, flood forecasts were reasonably accurate. However, the major shortcoming was the inability to deal with the massive volumes of overland flow. In Winnipeg, the Red River Floodway performed well, operating 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). During 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 5, and flows downstream on the Assiniboine were maintained at nearly zero. Most of the ring dikes around

Flood Management

Floodplains are 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 the potential harmful impact of floods on the people, environment and economy of the region. Economic analysis plays an important role in formulating plans for reducing flood damage and making operational decisions during an emergency. The main limitation of existing flood management methodologies is the stress on economic impacts and the minor attention to environmental and social impacts (Simonovic, 1998).

Process

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

Flood Damage Reduction Measures

Flood management evaluates the possible methods for reducing flood damage to existing buildings and other facilities, and reducing flood risk to permit additional growth. Nonstructural and structural measures are considered. The latter can be divided into local protection measures and upstream flood protection measures (usually storage reservoirs). Nonstructural measures include zoning (to limit the 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), flood warning system (to evacuate residents and move valuables), and flood insurance (to recognize the risks of floods and to provide acceptable compensation when damages are not avoidable). Structural measures emphasize the construction of levees or walls to prevent inundation from floods below some specific design flood flow. Additional works may include drainage and pumping facilities for areas sealed off from precipitation runoff to the river by levees; diversion structures to divert flow from the protected region during the peak channel modifications to increase the hydraulic capacity or stability of the river; and one or more reservoirs upstream from the protected area to capture the flood volume and release it at non-damaging rates.

Decision-making (Canadian perspective)

Canadian institutional arrangements include a hierarchical decision-making system to combat emergencies including floods. Four levels of decision-making are present in flood management: federal, provincial, local (city and rural municipalities) and personal (affected people). The responsibility for coor-

Application support will be provided by REDES to decision-makers and managers at different levels of governments. With the assistance of REDES, users may focus on a practical problem for initial implementation, test and fine tune aspects of strategy and infrastructure. With REDES the impacts of different measures, decisions and procedures can be tested and analyzed before moving to full implementation.

Roles of REDES

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

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

Users of REDES will communicate with the system in different ways. The utilization processes and their effectiveness will vary in terms of the time required for successful completion of intended application, the level of consistency of linking different roles of the system, the amount of iterations performed through the process, the level of involvement of stakeholders, and the style and intensity with which each role is approached by different users. The effective use of REDES will indicate 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 and provide information 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 will be adapted to the particular conditions of the Red River Basin.

DSS literature offers two main development architectures, functional and tool-based, (Simonovic, 1996). However, the development of REDES is based on an original approach identified as the intelligent decision support architecture, whose main advantage is its ability to integrate technical knowledge of flood management and a systems approach to problem formulation and solution with the personal experience and set of graphical tools for data presentation and spatial analysis.

A schematic presentation of REDES architecture is shown in Figure 2. REDES will be 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

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. The flood of 1997 severely taxed the flood management capabilities of the region and demonstrated the need for improvements to current procedures in order to minimize the impacts of future similar or larger flood events.

Red River Basin Decision Support System (REDES)

There is a far-from-complete understanding 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 IJC Red River Basin Task Force indicated demand for public participation in decisions about 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 database 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 both Canada and USA);
- agencies in Canada (Manitoba Emergency Management Organization, Manitoba Environment, Prairie Farm Rehabilitation Administration, Environment Canada, Manitoba Rural Development); agencies in USA (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);
- private organizations (Red Cross, Salvation Army, etc.);
- interest groups (Red River Water Resources Council, Red River Basin Board, North Richot Action Committee, Pembina Basin Conservation District, etc.);
- general public.

All have different needs and responsibilities during the planning, emergency management and flood recovery periods and REDES will be designed to provide support for all. Multiple-user needs and access to REDES will be accommodated through the multiple-level user interface structure (described later). Information, technical and application support will be provided within REDES to different users.

Information support includes maps, plots, animations, video, spatial data and reports to all potential users. Possible groups of information users include the general public, private organizations and other interested stakeholders.

Technical support 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 the engineers of Manitoba Water Resources Branch and the 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.

data; and present the data in different formats (maps, graphs, pictures, videos, etc.). Virtual database is searchable by data type, data holder/owner, location, etc.

The 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 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 evaluate data sets in terms of usefulness for various analyses. Metadata provides a method of long-term memory about data. Metadata is required as a prerequisite for any data set that will be incorporated into the REDES.

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

Modelbase. Improved flood management requires 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 1997 flood, residents on both sides of the border expressed lack of confidence in the ability of 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 will include existing hydrologic forecasting tools and allow for the integration of new tools in the process of development.

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, the need for more powerful two-dimensional models exists. 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) will be the main components of REDES modelbase.

Economic models that will help decision-makers to compare the flood-related economic factors of alternative means for flood damage reduction will also be 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

ensure that all data (topographic, land use, hydrologic, hydraulic, environmental and economic) are accessible to all users to provide support for flood management activities. REDES will include (Figure 2) 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 (PhaseFour, 1999).

Proposed 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 quickly locate data required for flood reporting and flood fighting in the basin; describe in detail the contents and limitations of the

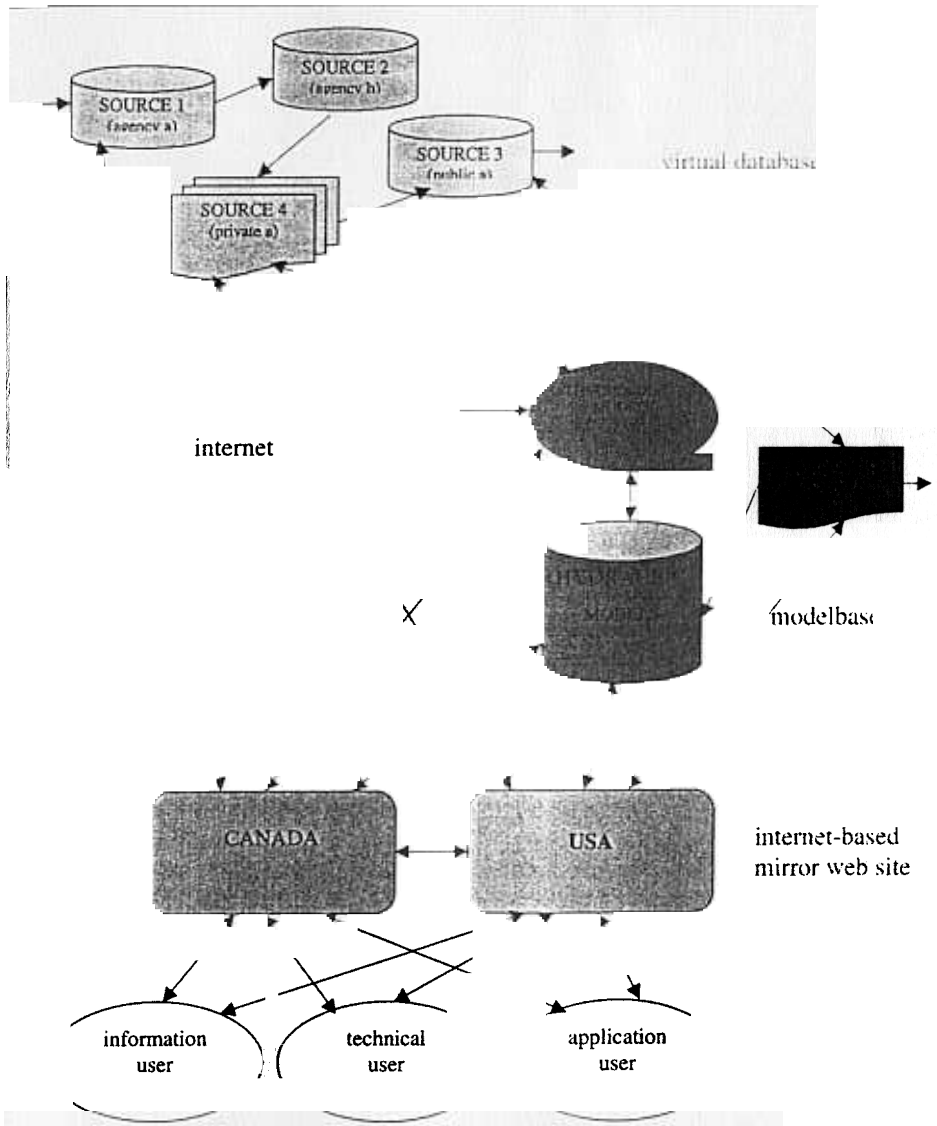


Figure 2: REDES System Structure

multi-objective framework, which requires the 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 aspects of sustainable flood management decision-making require the replacement of the 'best compromise' solution concept with the concept of the 'most robust' solution. This idea was introduced by Simonovic (1989) and applied in sustainable hydropower generation context by Bender *et al.* (1994). 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 will be the door through which the overall Red River virtual database, modelbase and information sources could be accessed. During the 1997 flood numerous Internet 'Flood Information' web pages appeared that provided useful information to data consumers. 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 and user needs assessment workshops in July 1998, it appears that there is a real need to integrate and make accessible the current databases 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 inappropriate use of modeling tools. User interface will guide users 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 stakeholder positions. User interface provides a vehicle for common understanding and the generation of direction suggestions.

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

REDES Development Requirements

A conceptual framework for REDES is based on its six major roles, 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 will be a large suite of software applications that will ultimately allow for the planning of flood damage reduction measures; 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 will be comprised of a web-based

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 and 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

Corps of Engineers, 1989a); and the flood damage analysis (FDA) package (U.S. Army Corps of Engineers, 1988).

Environmental models such as spill response models and habitat evaluation models will assist in evaluating the environmental consequences of flooding. The REDES modelbase will include all the models currently in use in the basin.

Decision models will be incorporated in the modelbase to assist the decision-makers. Sustainable flood management assumes that an acceptable compromise must be achieved among the three main objectives: ecological, economic and social. Each of these constitutes a 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 way to deal with the complexity of sustainable flood management is a modified

requirements are the identification of the user level and provision of appropriate support, simple intuitive design, flexible design and ease of use. For the information user such as the general public, access to REDES will provide processed information forecast, flooded area, maximum elevation, time of peak, etc. Information will be available in the form of maps, graphs, ıts, digital pictures, etc. Figure 4a

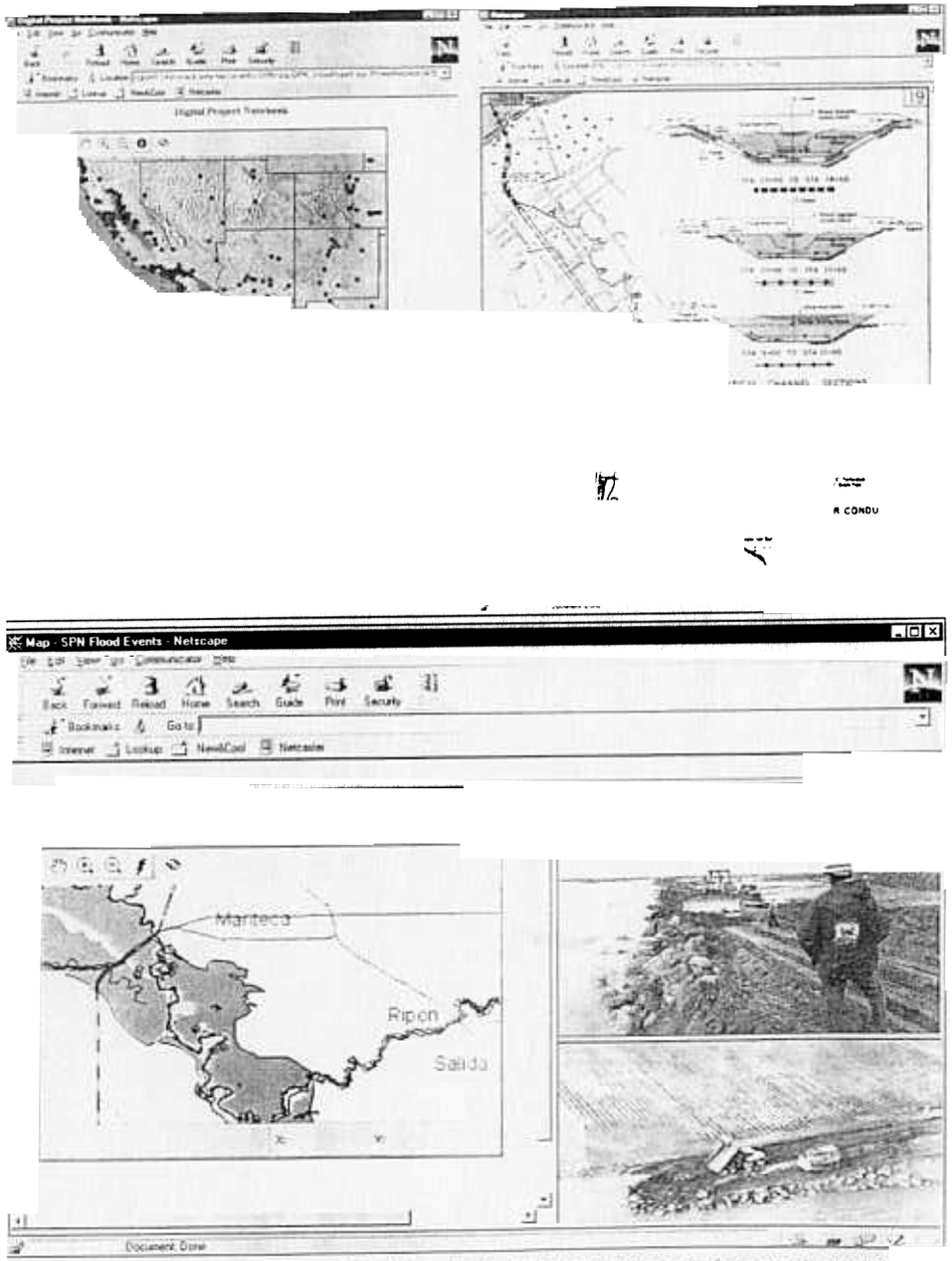
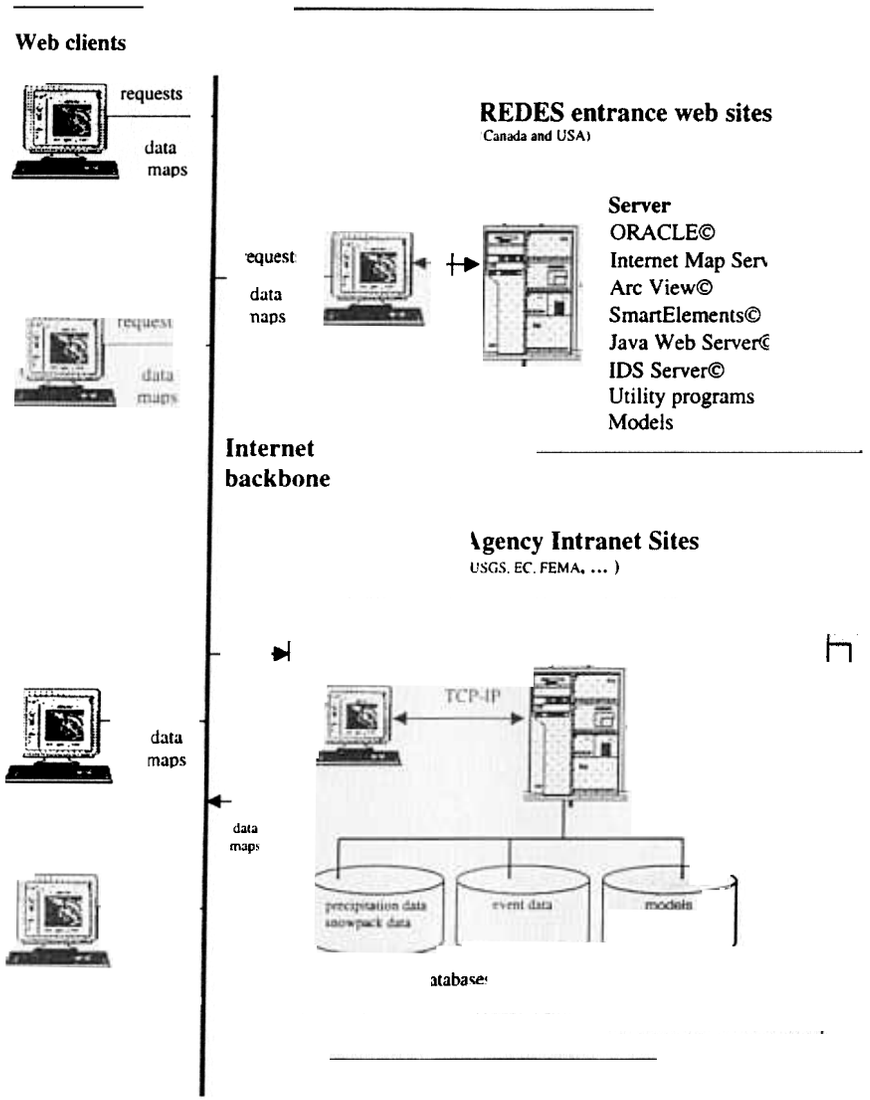


Figure 4: Examples of Information User Interface (after Bruzewicz, *et al.*, 1997)

multilevel user interface, virtual database, and modelbase. A technical diagram of the REDES system is shown in Figure 3.

Multilevel user interface. It will be the entrance gate to the REDES system. The design of user interface is planned in the form of the web site (mirror locations in the USA and Canada) supported by numerous communication utilities written in Java, and documents presented in Hypertext Markup Language (HTML). Java utilities provide three main functions of the user interface: access to and two-directional transfer of data residing on remote web-connected clients; activation of and access to modeling tools residing on remote web-connected clients; and presentation of spatial information in the form of maps and other graphical tools.

Details of technical interface design will be worked out by the developer. Essential



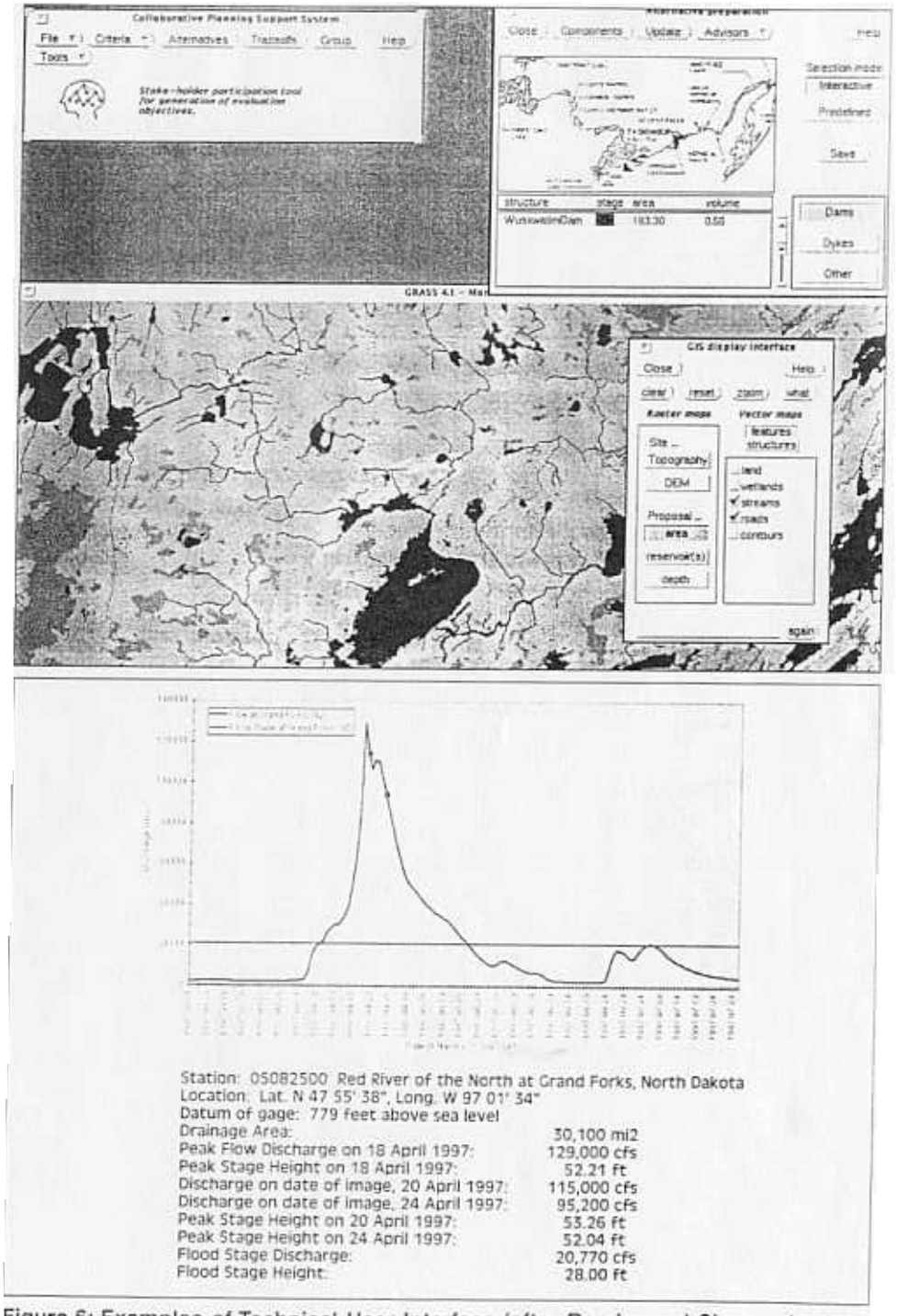


Figure 6: Examples of Technical User Interface (after Bender and Simonovic, 1999 and Bruzewicz, *et al.*, 1997)

presents the location and presentation of technical documents on structures. Figure 4b gives the 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 5 the information user interface is shown which allows selection of the water level monitoring site.

For the technical user, access to REDES will provide flood protection alternative generation among other things. 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, for the technical option of building a dike at a specific location with water levels raised to a given stage, the model analysis determines the cost of construction, flooded area, storage capacity, and the uncertainties of alternative behavior. Stakeholders are able to adjust the system to visualize changes to improve understanding of system behavior. Figure 6a is a sample computer screen related to alternative generation (Bender and Simonovic, 1999); and Figure 6b is related to hydrologic analysis (Bruzewicz *et al.*, 1997). Figure 7 illustrates the technical user interface to be used in running multi-objective analysis.

An interface similar to one shown in Figure 6a can be used for the support of application users. 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

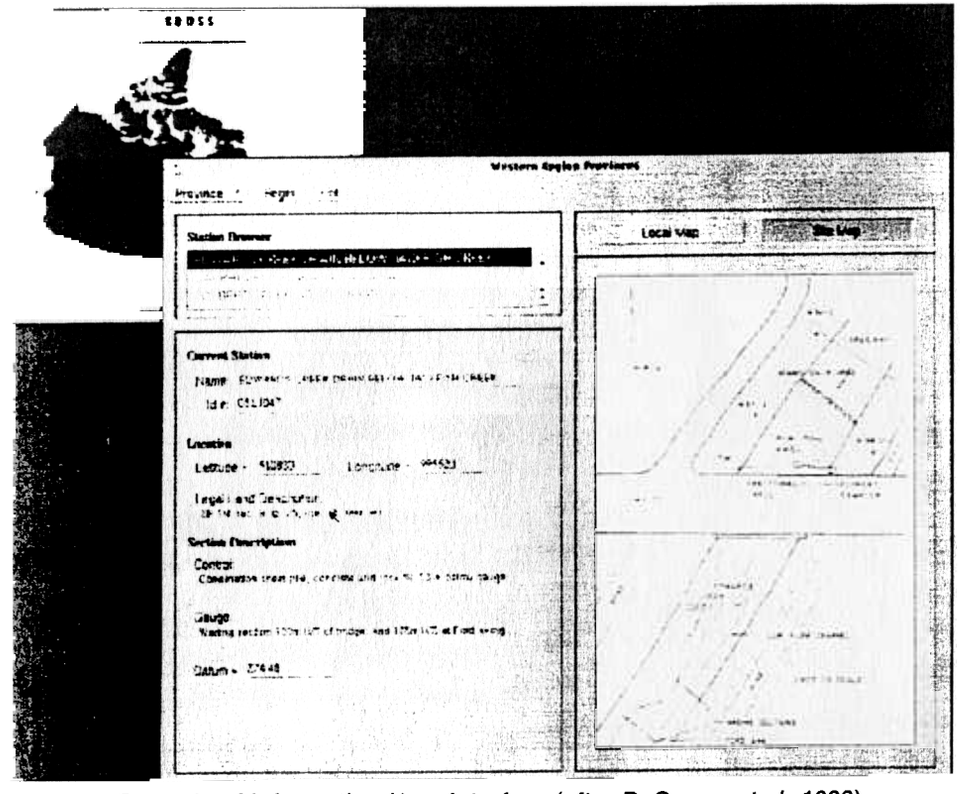


Figure 5: Example of Information User Interface (after DeGagne *et al.*, 1996)

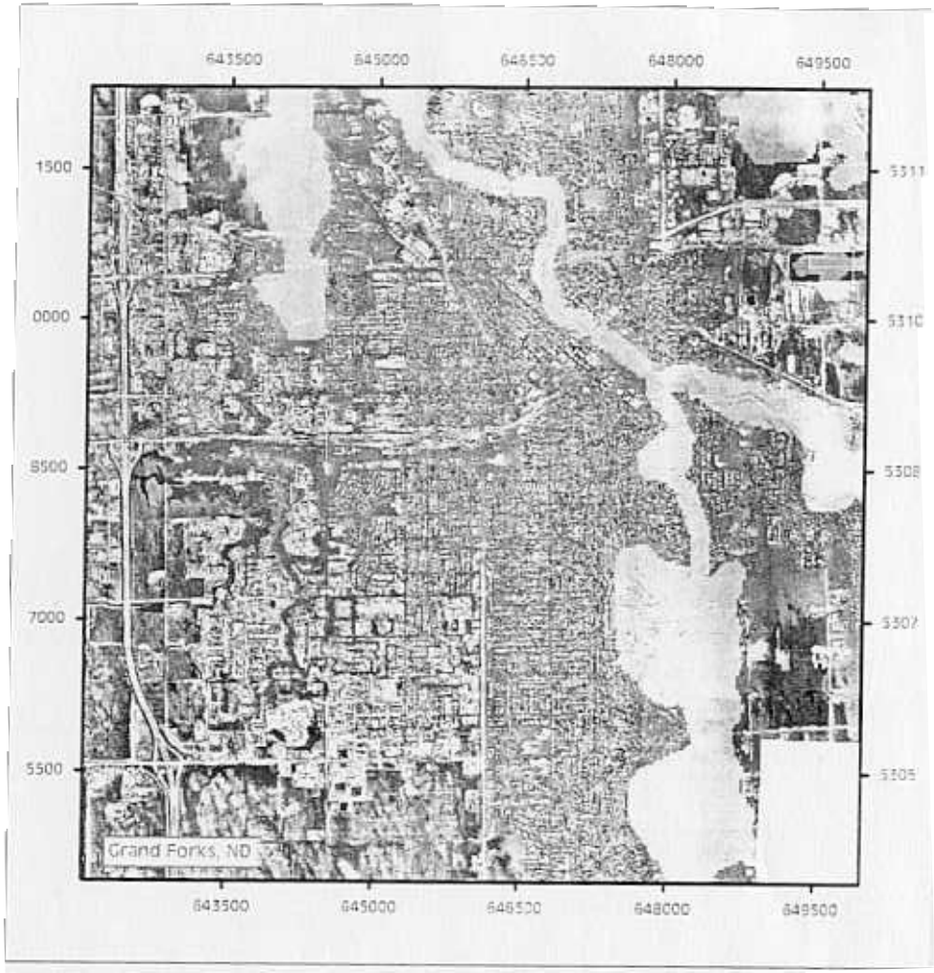


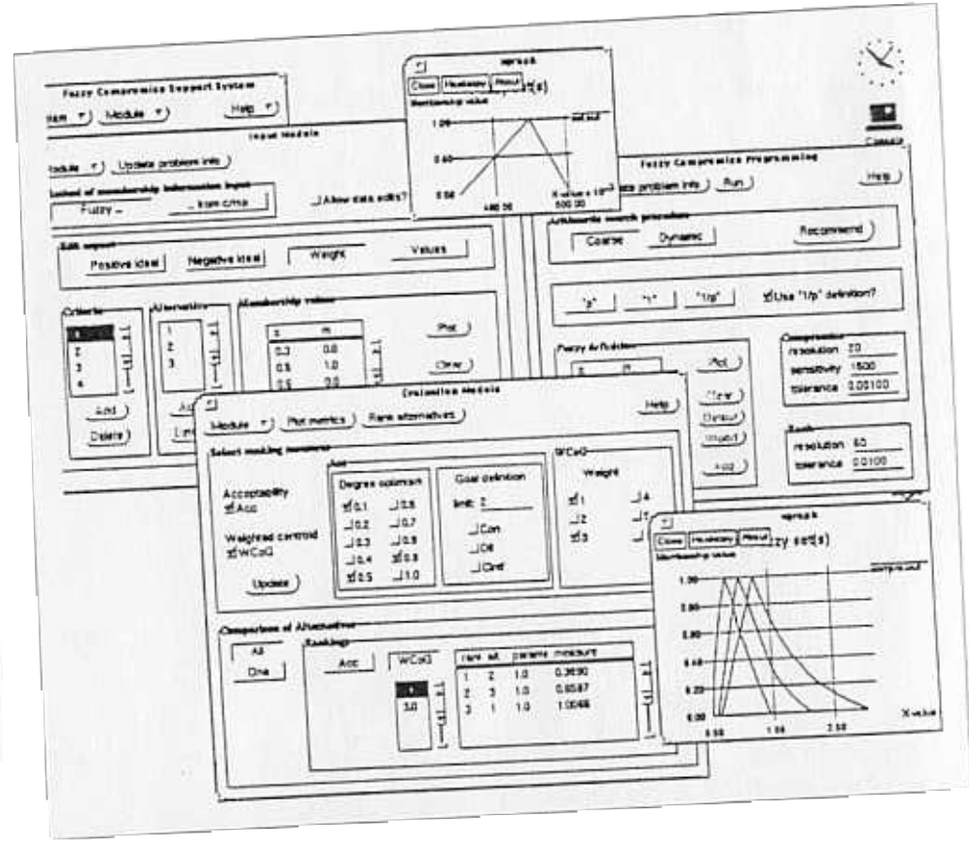
Figure 8: Example of Application User Interface (Bruzewicz, *et al.*, 1997)

- Identifying data sets which each provider can make available to the database (priorities are based on database components in Table 1 but this list is not exclusive);
- Identifying and eliminating duplications; and
- Determination the capability of data providers to serve data and if necessary, identify a possible partner for serving the data.

A 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 3, Windows NT-type servers will be required at each of the sites. They should be equipped at least 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. All listed software products are optional choices. Many other commercial tools can be used to serve the same purpose. In addition to the above list many utility programs and decision-making 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 can be addressed using modeling tools such as geographical information systems. Figure 8 illustrates a portion of the flood delineation results in the Grand Forks ND area (Bruzewicz *et al.*, 1997). It can serve as an example of application user interface.

Virtual database. Technical requirements for virtual database development are not unique, due to the fact that databases will be developed at different sites by different agencies. However, the development of

- Identifying all potential data providers in the basin;
- Identifying all internet information providers during the 1997 flood (federal, provincial, state, county, municipality, agencies, towns, watershed boards, the general public, universities, private industry, media, commissions, police);
- Identifying actual data providers to the Red River virtual database;



Conclusions

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

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some models may be stored at the entrance sites servers. Minimum required utility tools include a Java compiler; C++ compiler; text processing tool; and graphing tool.

Modelbase. The REDES modelbase will be of the 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 (1999).

Implementation Planning

REDES implementation is a joint effort to be coordinated by the IJC Red River Basin Task Force 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 will permit the implementation of REDES will be contributions from the organizations associated with the activities of IJC in the basin, as below:

- 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.

The IJC Red River Basin Task Force is conducting a number of studies that will generate REDES components: (a) hydraulic models for Red River (MIKE-11© and MIKE-21© in Manitoba and UNET in USA); (b) detailed digital elevation model for Pembina area; (c) metadata development for the Canadian part of the Red River Basin (PhaseFour, 1999); (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 accordance with the GDIN mission, the US Department of Defense has agreed to apply a number of program resources to support REDES activation: a report on user needs assessment, provision of ENGLink Interactive applications for user interface development, and support of experts to develop web-based content and site structure. REDES implementation is planned as a prototype development with emphasis on information and application and the development of an operational system, and the second phase on support for technical users.

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