Decision Support Systems for Sustainable Management of Water Resources: 2. Case Studies

by ***Slobodan P. Simonovic, M.IWRA***
Department of Civil Engineering
The University of Manitoba
WINNIPEG MB R3T 2N2
CANADA

ABSTRACT

The new ethic of sustainable development extends the main principles of water resources management. Computer-based decision support systems are explored in order to identify their role in the implementation of these principles into water resource management practice. The first part of this research (see the previous article in this issue) has demonstrated that sustainable development is a global concept that needs to be made reality in any component of every decision support system to be developed for successful management of water resources. This article presents four successful case studies of decision support systems (DSSs) for sustainable management of water resources. Development of a DSS for sustainable water resource management is seen as a process, and while the issues covered in these four examples are the priorities in their respective domains, it is certain that new issues will emerge in different fields of application. So, what is presented here is thus a snapshot of current best efforts.

INTRODUCTION

Sustainable management of water resource systems is a global concept that needs to be implemented. The following discussion provides a limited number of examples that have successfully met this challenge across a range of main issues discussed in the previous article in this issue.

Four examples have been selected for presentation: (i) A DSS for collaborative planning of water resource projects; (ii) A DSS for the reassessment of reservoir storage allocation and reservoir management strategies; (iii) A DSS for stage-discharge rating curve development, use and modification; and (iv) A DSS for the evaluation of flood control strategies. The first case study has been presented in more detail than the other three. Readers are directed to cited references for details of the latter three examples. They all are required in order to address some of the issues relevant to the concept of sustainable development. As such, they cover the main issues that DSS have to face when seeking to implement sustainable development practice. Nevertheless, there are issues that have not been covered.

The presentation format for the four examples includes: (a) a description of the problem domain; (b) a list of basic components of the DSS; (c) a description of tools used in the development; (d) a list of sustainability issues covered; and (e) lessons learned. The case studies are intentionally short, so that a flavor of dynamics, results, and lessons can be obtained in the space of a single journal article.

SUCCESSFUL STEPS TOWARD DECISION SUPPORT SYSTEMS FOR SUSTAINABLE MANAGEMENT OF WATER RESOURCES

Decision Support System for Collaborative Planning of Water Resource Projects

Description of the problem domain. There is a great interest in public involvement in development initiatives. However, it is primarily limited to public relations, or miti-

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gation of impacts after proposals have been developed. This example deals with a number of obstacles toward computer-assisted creative planning and stakeholder communication. The starting assumption, for potential stakeholder interaction with the proponent in early planning, is that creating ground for a common understanding will enhance motivation for creative solutions to impact mitigation.

The concept of collaborative planning is a novel idea that has seen limited use because of the complexities that prevent people with different backgrounds from communicating. Manitoba Hydro (a local power utility) is a proponent for resource development that experiences a great amount of external pressure to respond to stakeholders (affected or interested parties) concerning impacts on the environment caused by activities such as hydroelectric development. One way of reducing tensions between proponents and stakeholders is to allow them more direct involvement in the early planning of a potential project (before licensing).

This example presents a framework for facilitating collaborative early planning. The planning approach demands a synthesis of physical modeling with subjective priorities of various stakeholders. It stresses careful, deliberate, definition of the physical scope of planning, and allows individual objectives to be explored in a cooperative, multidisciplinary environment.

This work, still in progress, on the application of a collaborative planning approach, in the form of a decision support system (DSS), is presented as a Collaborative Planning Support System (CPSS). The basis for its functionality is the integration of modeling and decision tools, a management system for allowing adaptation of design proposals, a method of administering project goals and objectives, and a technique for providing feedback to stakeholders involved in the decision process.

An example problem has been selected to demonstrate the implementation of ideas and decision tools. Two areas of project planning expertise are used, hydroelectric power generation and fish passage, in a case study based on possible development of the Wuskwatim and Three Point Lake area on the Burntwood River system northwest of Thompson in northern Manitoba. Manitoba Hydro has selected the Wuskwatim Lake area as a site with good hydroelectric potential and water supply reliability in order to plan for future demands. Like all forms of power generation, hydroelectric power produces external impacts to various ecosystems. However, it is promoted as being "cleaner" than most forms of power. Manitoba has invested heavily into the use of hydroelectric power because of the abundance of water in the province. Most of the generating capacity is in isolated northern areas. Development of northern water supplies has caused a number of impacts to the natural resources and cultural integrity of the region during the past 30 years. Some impacts were not sufficiently mitigated, but in fairness, many of the impacts were either not understood, expected, or considered valuable. Changing social attitudes, along with alert and even militant opposition from traditional communities, environmental groups, and government regulatory agencies, have brought many new concerns to the project licensing process.

Manitoba Hydro works through a long process of review before a proposal is acceptable for licensing. A proposal for developing a generating station, such as at Wuskwatim Lake, passes through a variety of regulatory agencies — each with a particular agenda. Then, finally, the proposal is presented to the Public Utilities Board, which conducts a number of public hearings and debates. Throughout the lengthy licensing process, a large number of stakeholders or interested parties are given an opportunity to assess the proposal. It is possible that a number of changes are required, and the entire project may sometimes be in jeopardy.

One of the issues that are often involved with dam construction is fish passage. Fish passage involves both upstream and downstream migration of fish for spawning, or feeding, based on fish life cycles or seasonal variations. In some cases, obstruction of certain species such as salmon, can accumulate a large economic value in impacts or even deplete entire populations of fish. There are numerous design alternatives and technology options that can be considered. Typically, environmental impacts such as fish passage are considered after a proposal is prepared. Such treatment suggests that fishery impacts are minor and of small economic concern. Lack of consideration may result in unnecessary fish mortality. Alternatives with minor economic tradeoffs may produce (or avoid) significant (negative) benefits for fishery management. It is easier, though, to include some of these alternatives before any final proposal is drafted than to wait for a licensing review process.

This problem is still being used to test the development of effective hydropower reservoir management decision-making capabilities that include fishery objectives [1].

Basic DSS Components

In addressing a forum for stakeholder participation in early planning decisions, object-oriented management of database information is combined with artificial intelligence techniques. These tools, along with spatial data management and analysis, are integrated and applied to surface water resource management questions. While each technology is available for specialized tasks, a state-of-the-art hybrid has enormous potential for assisting in decisions related to water resources. Many of the assumptions for application and difficulties in achieving full integration are explored.

The system combines five major components into a productive environment to assist the consensus-reaching process. A spatial analysis toolkit is used to define and control the depiction of a watershed and to present results of the analysis affecting spatial change of physical parameters and interrelationships. A Geographic Information System and an associated set of spatial analysis tools

allow comparisons of impacts in conjunction with changing hydrological conditions and operating policies.

A decision process coordinator is developed as an expert system module for controlling decision processes and user interaction. This component of the system allows different mitigation options to be considered and assists the collaborative process. Experience in applying ecological and social objectives provide the basis for many function of the decision process coordinator.

A database module is responsible for management and manipulation of spatial, hydraulic, and user-specific data. The purpose of the database is to assist in qualifying issues, making information available, and quantifying tradeoffs between alternate solutions.

Analytical tools incorporated in the CDSS support the consensus-reaching process. The modelbase module consists of various systems analysis tools and analytical models used to evaluate impacts, risks, and uncertain tradeoffs associated with different alternatives. The major effort is aimed at development of multiobjective methodologies to incorporate conditions for ecological integrity in fishery management. Incorporation of habitat objectives in reservoir management models will affect development and operation policy in a number of ways. Resource economic models to be used within the modelbase component of CDSS are being reformulated for implementation of sustainable development policies for renewable resources [2].

The decision-maker communicator module is guiding user development of policy statements 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 tradeoff analysis expressing preference sensitivity and evaluating consequences of stakeholder positions. The decision-maker communicator provides a vehicle for common understanding and generation of direction suggestions.

Tools Used in the DSS Development

The platform for CDSS development is a Unix workstation. The spatial analysis toolkit combines the GRASS GIS package and a set of tools available with it. The ORACLE relational database manager has been used for the development of the database module of CDSS. The decision process coordinator is being developed using SMART ELEMENTS (a new version of NEXPERT OBJECT) and is fully integrated with ORACLE through a database bridge. Structured Query Language (SQL) is used to transfer the instructions provided by the ES into the ORACLE. Data from other components of the system are loaded into ORACLE and manipulated using SQL commands to be output in the format required by pertinent models for flood damage analysis. Most analytical models, systems analysis and multiobjective tools are programmed using classical programming languages and are integrated in the CDSS using unix scripts.

Sustainable Issues Covered

CDSS illustrates one of the ways available for societies to move toward sustainable development: preparation of processes and tools that foster creativity in the selection or preparation of alternatives. Processes for creative decision-making may span disciplines and problem types. Tools are very likely specific to a problem type. Development of processes and tools for creative decision-making, more than anything else, suggests that participation of stakeholders in the decision process is important for achieving sustainability. Sustainable decision-making that relies on criteria or indicators can only achieve stakeholder participation as far as selecting weights for each criterion — assuming regulation of indicators/criteria allows for manipulation.

Conceptually, sustainable design of projects can be treated differently from sustainable management of infrastructure. In CDSS practical application of sustainability in development and management of resources focuses on two types of problem. One is for design of new projects; the other type is remediation of existing infrastructure. Certainly, it is much more flexible to plan a new project than to work around previous decisions. At least, a more efficient and sustainable set of solutions is expected.

The system deals with ecological, economic, and social subsystems

The number of prior decisions produces a set of constraints that grows with the number of decisions that have already been made, and project classification may become fuzzy. If there exists a specific set of sustainability criteria for the problem, the difficulty in achieving satisfaction of those criteria increases with the number of constraints on the project. Of course, in all problems there will be legal, political, economic, and technological constraints that may be independent of prior project decisions.

CDSS is one of the first decision support systems being developed to address all issues raised by the implementation of the sustainable development principles to water resource planning. The system deals with ecological, economic, and social subsystems. It allows implementation of "what if" scenarios in order to deal with expanded spatial and temporal scale. Multiobjective analysis is the main decision tool incorporated to assist the multiple decision-makers in the process of reaching a consensus.

Experience in applying ecological and social objectives provide the basis for many of the functions incorporated in the CDSS. Many of the analytical tools, and the framework for multiobjective dispute resolution in water resource development are becoming parts of flexible software to be used as a mediation aid between stakeholders. Knowledge based on experience, data management, and

manipulation, both hydraulic and hydrologic modeling, and habitat modeling, act together in a seamless environment that relates spatial and temporal alternate tradeoffs.

Lessons Learned

Work on the development and implementation of CDSS is still in progress. First experiments in developing fuzzy multiobjective methodologies to incorporate conditions for ecological integrity in fishery management have been successfully completed.

Implications of both spatial and temporal scale are aimed at implementation of sustainable development policies for renewable resources. Economic tradeoffs are also examined for various market scenarios, resource conditions, and discounting practices [2].

Reassessment of Management Strategies for a Multi-Purpose Reservoir

Description of the problem domain. The reservoir management process can be very dynamic [3], reflecting the role of reservoirs in a region's economic and social life. Unfortunately, reservoirs have been constructed and managed to serve a static environment. Historically, many water controversies arising from dynamic conditions have been resolved by construction of new facilities or modification of existing ones. Some of the rationales for reassessment of reservoir management strategies are external, and some are internal to the project. Three general groups of needs for reassessment are: (a) physical; (b) economic; and (c) environmental.

Changing physical conditions. The main need for reassessment of management strategies is the availability of additional hydrologic data. Overall understanding of processes related to the reservoir operations increases with additional hydrologic data. Reservoir inflow is of primary importance. However, additional information on precipitation, evaporation, seepage, and land use is valuable for the reassessment process. Any other change in physical conditions related to the dam itself, as well as associated structures will require modification of management strategies.

Changing economic conditions. Reservoirs play a very important role in the economy of a region. Any change in economy is usually reflected in the change of water use and vice versa. The change may be the increase in demand for water, or change in the demand distribution in time, or change in the water quality requirements. Another aspect of changing economic conditions may be reflected in the change of reservoir purposes. New purposes may be added, some eliminated, and some may never develop to the originally planned level. All this information will play an important role in the quantification of reservoir management objectives.

Changing environmental conditions. This group includes needs rising from the change in societal priorities toward the environment. Being major structures imposing stress on the environment, reservoirs and their management are very closely scrutinized by the public. Management strategies have impact on the water quality in a river downstream, and the water quality in a reservoir itself. Beside water quality issues, impacts on the environment may include fish and wild life habitat change. One additional need for reassessment of reservoir management strategies may come from the impact that changing environmental conditions imposes on the people living in the close vicinity of reservoirs. Needs for reassessment identified in the relationship to changing environmental conditions imply change in the objectives used to plan reservoir management.

Identified needs and implications are indicating that there is a considerable difference in planning for new and existing reservoirs. One major difference is that from relatively unconstrained analysis for new projects, analysis of existing projects is substantially constrained. Physical reservoir characteristics, like conservation storage, spillway capacity, outlet capacity, and others, are fixed, leaving very little flexibility for finding new reservoir management strategies. Other differences, as presented by Israel and Lund [3] include: (a) legal differences; (b) differences in data; (c) historical differences; and (d) different public participation.

Major implications of presented differences between planning the management of new and existing reservoirs, are on modeling and analysis. An appropriate modeling procedure is necessary to take into account the changing objectives, use additional available data, respect all existing constraints, and address the uncertainty of the future reservoir role. In many ways, an appropriate modeling procedure can be derived using the same expertise, models, and procedures as for any new project. Simulation, optimization, and multiobjective analysis are capable of supporting the reassessment process.

Basic DSS Components

DSS for reassessment of a multipurpose reservoir includes: (i) database; and (ii) modelbase. The database component stores all the reservoir, economic, and hydrologic data. Beside providing storage for data, within this component an autoregressive moving average (ARMA) model has been incorporated to assist in generating synthetic sequences of inflow data. The modelbase component is based on the combined use of simulation and optimization.

Approach proposed in this research for reassessment of management strategies for an existing reservoir is based on the combined use of simulation and optimization. The main objective of the approach is to determine: (a) the active reservoir storage requirement based on the current demand; and (b) the best management strategy for a reservoir. First part of the objective is achieved by using simulation algorithm named RESER [4]. The second part of the main objective is attained by using reservoir yield optimization [5] without predefined demand for water

from a reservoir. Therefore, the approach developed in this research provides a recommendation on how to use a reservoir, based on the optimal compromise between the physical, economic, and environmental conditions.

Simulation. The simulation model used within the proposed approach is based on the continuity equation and set of probabilistic criteria. The model makes use of a direct search technique for finding minimum required reservoir capacity. Using the initial storage value, provided by the user, the monthly operation of the reservoir is simulated. By simulating the reservoir operation under given inflow and demand conditions, four reliabilities are calculated and compared with desired values. Four probabilistic criteria are: (a) reliability of reservoir water supply (α); (b) yearly reliability (β); (c) yearly (γ); and (d) monthly (δ) vulnerability of reservoir water supply. The first two criteria are used to control the number of reservoir failures. The latter two, however, are used to take into account the severity of reservoir failures. If these four criteria are not met, the reservoir size is increased by a step size. The simulation procedure is repeated. This process continues until the reliability constraints are satisfied. From the use of simulation and direct search, the model arrives at a value of optimal required reservoir storage capacity.

Within the reassessment process simulation model is used to indicate the availability of reservoir capacity to be used for new purposes. Four calculated reliability values are also provided to the user in order to help in evaluating how efficient is the current use of reservoir storage. Due to the use of the direct search technique, the storage is known at all time periods during a simulation, so the storage-dependent losses can be directly calculated and storage failures monitored.

The simulation model is using the following information as input: reservoir storage-elevation curve; monthly inflows; monthly evaporation; monthly seepage; capacity of reservoir outlet structures; monthly water demand; starting reservoir storage; increment for increase in storage; reservoir maximum capacity; and minimum reservoir storage reserved for sediment deposition.

Reservoir yield optimization. In the reassessment process for an existing reservoir, the physical characteristics of a reservoir are known. The mathematical model for the reservoir yield optimization includes the three following principles: (a) equal treatment of the reservoir users; (b) use of failure magnitude and number of failures in the analysis; and (c) multipurpose use of reservoir conservation storage for municipal, industrial and irrigation water supply, and hydropower generation [5].

Originally, the reservoir yield optimization model had been developed to assist in the long-term comprehensive water management planning. Using only the character of different water demands, represented by the relative demand coefficients, the model provides planners with the optimal value of reservoir yield. For the purpose of the reassessment of reservoir management strategies, the original model has been modified to find the best combination of reservoir uses and monthly reservoir releases for different purposes. The best combination is the combination that maximizes the reservoir yield. Maximization of reservoir yield is providing the planner with the physically "optimal solution." Existing physical conditions and requirements are introduced into the model through the set of constraints. Optimal yield and resulting reservoir releases for different purposes (called reservoir management strategies) are obtained using only the relative demand coefficients. The inherent assumption in using this model is that the remaining water needs will be satisfied from other reservoirs, or other water sources in the region (groundwater aquifers, direct river intakes, or water transfer). The issue of left-out users and possible increase in their cost to meet their demands is not discussed in this article. This assumption is justified by the principle of sustainability, which may be translated into finding the best possible physical solution for long-term use of reservoir conservation storage. Results of the analysis can be used in different ways. If the reservoir is promising better performance for the combination of purposes different from the current one, the transition should be performed to allow for operating the reservoir in such a way as to maximize its yield. This transition may require identification of new water sources or modification of the physical system used for water supply in a region. Modification may require new structures or innovative solutions. New structures can include dam height increase, building new reservoirs, developing new aquifers, water transfer, or connecting existing reservoirs so that they can perform as a system. Innovative solutions may include nonstructural measures like demand management, supply management, change of the regional economy, diversification of industrial production, controlled distribution of the population, and the like. Once more, note that the economic criteria are incorporated in the reassessment process indirectly through the relative water demand coefficients and relative weights assigned to different demands for water.

A three-level algorithm is proposed for the reservoir yield computation. The first level consists of a simulation model used for calculation of reservoir releases. Starting from a designated initial storage level, all future levels are checked to ensure that the release policy does not violate the continuity constraint. In order to determine the reservoir storage levels and releases it is assumed that the reservoir releases can be expressed as a function of reservoir inflow, forecast of future inflow, and the reservoir water demand. Using regression analysis, it is shown that in most situations the appropriate form of the release function is quadratic. A second level is used for derivation of the reservoir release rules. The problem is formulated as an optimization problem. Unknown coefficients in the quadratic function have been optimized in order to minimize the total loss. The loss function is a measure of water insufficiency in regard to water demand. Because the problem is multivariable, nonlinear, and unconstrained, the Powell search technique is used at this level. The multipurpose reservoir yield is defined as a percentage

of mean reservoir inflow used to satisfy the total demand. At the third level, a single variable, nonlinear constrained objective function is minimized. In this case, however, the objective function is devised in such a manner that its minimization would cause a maximization of the reservoir yield. For an optimization problem such as this, the Fibonacci single variable search procedure has proven to be the most effective technique. Mathematical details of the algorithm are presented in Ref. 5, pp. 2162-2164.

The main input into the optimization program consists of the physical and inflow information for a reservoir, and the relative demand requirements for each user. In addition, the program requires information on supply reliability for each user. For the purpose of the reassessment process, four sets of relative coefficients are required. One set is needed for each of the three users (municipal and industrial water supply; agricultural water supply; hydropower generation) representing the monthly percentage of their individual total demand. These coefficients may be determined by analyzing the past demands or by making projections for the future. The fourth set of relative coefficients divides the total amount of water available for use among the three principal users of a reservoir conservation storage.

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In the current version the main deficiency of the DSS for a multipurpose reservoir reassessment is lack of a user-friendly interface and shortage of an expert system module for capturing the existing experience in reservoir operations.

Tools Used in the DSS Development

A set of systems analysis tools is used in the development of the DSS for a multipurpose reservoir reassessment. An ARMA model has been implemented as a component of the database. A simulation algorithm named RESER [4] is performing simulation tasks of the modelbase component. A reservoir yield optimization algorithm is using a three-level approach, taking advantage of the Powell and the Fibonacci search techniques [5].

The integration of database and modelbase components is done within the PC environment. Interpretation of the results and "what if" analysis is not automated yet.

Sustainable Issues Covered

The reservoir reassessment system is capable of addressing a number of important issues related to sustainability. By reassessing the reservoir use the spatial and temporal scales of the reservoir analysis are changed. Considering the best physical use for the existing reservoir requires evaluating alternate resources for meeting the demand for water. Alternate sources require a considerably larger spatial scale to be used. Using a longer historical sequence of reservoir inflows for reservoir storage allocation reassessment is affecting the temporal scale.

Through the ability to generate numerous hydrological scenarios (ARMA model within the database component) the reassessment DSS is capable of supporting "what if" analysis. Different hydrological scenarios can be examined and an appropriate decision reached for the reservoir storage allocation.

Maximization of reservoir yield provides the decision-maker with the physically "optimal solution." This solution can be used instead of using the reservoir for what it was designed for. As presented, the optimization model is inherently dealing with the changing objectives, finding the reservoir yield as a product of the best compromise between different users of the reservoir storage. DSS can react to changes identified earlier by adjusting the relative demand coefficients. The final benefit of the proposed reassessment approach is that it provides direct response to physical, economic, and environmental conditions surrounding the reservoir.

The DSS deals with future uncertainty on two levels. Firstly, within the simulation, four reliability criteria are used in evaluating the reservoir storage necessary to satisfy the current reservoir demand. Secondly, the developed optimization model belongs to the group of implicit stochastic techniques. The main input into the model may be a historical sequence of monthly reservoir inflows or a synthetically generated sequence of inflows.

Lessons Learned

DSS for reservoir reassessment has been applied for the Wonogiri Reservoir in Central Java, Indonesia [6]. Due to the attainment of self-sufficiency in rice production and industrial growth in the region, a reassessment of Wonogiri management strategies to take into consideration the needs for hydropower production and industrial and municipal water supply has been performed. The analysis of the conservation storage of the Wonogiri Reservoir demonstrates that the present storage capacity is greater than that required for the irrigation of 25,319 ha. Reallocation of the existing conservation storage to include hydropower generation and municipal and industrial water supply, without ignoring the present function of the reservoir, is feasible. The water supply/irrigation/hydropower demand reliability combination of 40%/40%/20% generates the "best" tradeoff among the three water users resulting in the 97 per cent overall reservoir yield. Therefore, a modification of Wonogiri Reservoir management is strongly recommended to include the other two purposes.

The analysis was done efficiently but lack of a good

user-machine interface was acknowledged. It has been also obvious that the reassessment procedure, and the DSS, can benefit from incorporating a module containing the expertise related to a particular reservoir operation. This knowledge can be used to enhance and evaluate solutions suggested by the DSS.

Stage-Discharge Decision Support System

Description of the problem domain. Discharges in rivers are typically estimated by combining water level records with a functional relation, or suite of relations, describing variations in measured discharges with changing water levels. The functional relation between water level (or stage) and discharge is known as a Stage-Discharge Curve (S-D Curve), Stage-Discharge rating, or rating curve. Procedures for measuring both stage and discharge have been established through a series of national and international standards. As well, standards for the development of stage-discharge relations have also been developed [7]. The actual practice of developing and applying rating curves varies between agencies.

A DSS framework has been developed to model the processes of stage-discharge curve development, modification, and use, and to evaluate the effectiveness and implementation implications for using the DSS in an operational organization. The Stage-Discharge Decision Support System (SDDSS) is capable of addressing channels in which the rating relation is stable, or variances in the rating curve are attributable to a change in the energy slope of the water in the gauging reaches as well as channels that are subject to changes in channel geometry, such as aggradation, degradation, and changes in hydraulic controls [8].

SDDSS provides a means for classifying a gauging station, its respective hydraulic control, and the overall reach in question. The process of developing curves, modifying curves, using curves, and extrapolation beyond established curves is dependent upon the classification, and the stage-discharge decision support system provides an environment to perform all tasks whether a classification of stable or nonstable is reached. The end result of providing the analysis for stage-discharge rating curves is to formalize and standardize the analysis using hydraulic and hydrologic reasoning and principles. These principles will help develop the selection criteria to develop rating curves specific to certain hydraulic parameters in time and over the entire stage range.

Five process knowledge elements for modeling a rating relation for stable and nonstable channels were identified: the identification of stable and nonstable S-D regimes; the classification of these regimes; the segmentation of S-D measurements to appropriate stability regimes; and the modeling and evaluation of S-D relations. The basis for the analysis is forwarded through the development of rating curves, their use, modification, and extrapolation. Each function represents a user mode that has been incorporated into the SDDSS system.

Basic DSS Components

The overall control of the SDDSS is performed by a system control manager (SCM). From an operational perspective, it is the SCM that is responsible for the coordination of specific processing tasks of the various DSS components and the integration of their information. It is also responsible for communication between the system and the user. An expert system module has been developed to perform the role of SCM.

The expert system module, containing a number of knowledge bases, provides the integration between the various DSS components, communication between the system and user, and the knowledge of the S-D analysis problem domain.

Operational use of an SDDSS requires the ability to manage large quantities of water-level data, anecdotal data (field observations and site descriptions), river cross sections and streamflow measurements. The Relational Database Management System was selected to provide the database management component in the SDDSS because of the ease in developing relational links. For an operational system, an external flat file structure for the time series data is employed to minimize system overhead and to decrease data retrieval times.

Another essential characteristic . . . is its ability to communicate with its end user(s)

Another essential characteristic of the SDDSS is its ability to communicate with its end user(s). This characteristic alone may determine the ultimate success or failure of a DSS. Therefore, the user-interface component of an SDDSS presents information that is easy and simple to comprehend. Graphical user interfaces (GUI) incorporate computer graphics and colors to display information to users in logical and visually pleasing formats. Several of these GUI concepts are incorporated in the SDDSS. S-D data and rating curves are displayed visually using an external graphing utility. Two additional windows are provided by the expert system module for the user interface. User input is handled exclusively by the Session Control window, which is responsible for prompting the user for input and providing options to be selected whenever possible. An apropos windows provides the second window for displaying processing messages and numerical results to the user.

The final component of the SDDSS deserving particular attention is the modeling facility. The SDDSS represents S-D relations as mathematical (regression) models. With respect to the system design, the modeling procedure is an external process, called from the system control man-

ager. This modeling task is performed by a Unix script and Fortran program.

The user manual provides a comprehensive library of explanations regarding the use of the SDDSS, as well as explanations for the methods, and background theory behind the processes of the SDDSS. The manual icon is displayed as a window during the operation of the SDDSS. The operation and manual page selection are totally window- and menu-driven.

Tools Used in the DSS Development

The Sun Sparc station running a Unix operating system provides the hardware development platform. Maintaining and expanding the expert system module was performed using the NEXPERT OBJECT [9] software. Success was also maintained through the use of ORACLE [10] relational database management system (RDBMS), because of NEXPERT OBJECT's ease of communication and data retrieval with this software. NEXPERT OBJECT also provided easy access and control over any FORTRAN or script routines that eased any computational burden, or provided any requisite data manipulation. Graphical presentation is still provided by the public domain software XGRAPH and XPLOT by DUX software.

As for the on-line help manual, another public domain software has been applied. XMAN provides an excellent means to look up explanations for keywords highlighted by the SDDSS system. Keywords are stored within sections that correspond to the user modes of the system. Manual pages are accessed through this hierarchy of pull-down section menu and look-up keywords.

Sustainable Issues Covered

Analytically developed rating curves are reproducible and can be highly accurate. With analytical fitting, independent hydrometric practitioners can produce identical rating curves from the same data set. Current practice is subjective. Hand-drawn curves and mathematically-fitted curves can be quantified in terms of "goodness of fit." This is essential in the quantification of accuracy of streamflow estimates. Therefore, the SDDSS is providing an effective tool for dealing with different uncertainties involved in the stage-discharge analysis.

SDDSS is shown to be an excellent tool for "what if" analysis. Given the reduction in effort required in creating S-D relationships, rating curves may be updated more frequently and the effects of curve modifications can be instantly analyzed in terms of effects on discharge estimates. Using current methods, such changes are extremely time-consuming and tedious, and the evaluations of consequences are not routinely undertaken.

The SDDSS is recognized as a powerful training tool. It is being used to illustrate a broad range of conditions and the related consequences of such conditions to the computation of discharge estimates. Developed as a fully operational tool, novice users would be guided along through the entire process of creating rating curves and using them to publish discharge estimations.

Lessons Learned

Operational application (currently in progress in Environment Canada) of the SDDSS has a number of implications hydrographically and culturally for the agencies responsible for surface water quantity data management: (a) Rigorous observations of controlling influences, such as the quantification of ice conditions, must be developed and employed rather than simple coding of categories of influences; (b) A greater range of pertinent site conditions must be quantified, such as type, density, and height of aquatic vegetation, channel form and processes, and climatological conditions during measurements (the importance of these factors varies geographically); (c) Dual water-level recorders should be employed at selected sites in order to quantify variable backwater effects; (d) The expertise base should be enhanced with an emphasis on hydraulics and channel form and processes, and computer technologies; (e) Extracting expert knowledge from operational staff is a difficult process; and (f) In a highly structured, process-focused operation, at least initially, there is a reluctance to accept new approaches and technologies. However, the current experience of Environment Canada's field offices is strongly supporting the use of SDDSS and modification of monitoring practice.

Using statistical analysis techniques, the system considerably reduces the time required and the subjectivity of the manual hand-drawn curve fitting utilized in many hydrometric programs. Significant advantages are being observed in the ability to fit curves rigorously and precisely to develop stage-discharge relations, and to quantify confidence limits in the use of these curves. In order to utilize the advantages of present SDDSS framework, Environment Canada is investing in the employment of the technology and training for operational application. In order to fully exploit the capabilities of the SDDSS, additional observations of site conditions must be quantified, staff expertise enhanced, and operational procedures revised.

Decision Support System for Flood Control Management

Description of the problem domain. The Flood Control DSS (FCDSS) provides support for flood management [11]. The first part of the procedure comprises the survey

The Flood Control DSS (FCDSS) provides support for flood management

of all information related to the floodplain, including location and structure data. The process of generating the *initial state* usually includes: conducting a field survey of the region; geographic data input; and updating the relational database. This data is used in the second part of the procedure to develop aggregated elevation-damage curves for each reach. *Data preparation* is the second important task supported by the FCDSS. An expert system component assists in the input of data into the models to be used in flood damage analysis. The third part of the procedure is *generation of flood management alternatives.* The selection of type of structural and/or nonstructural flood control measures to use in a given situation depends on factors such as the physical and economic feasibility of the proposed measure, the stage of the expected flood, the amount of flood warning time, and the velocity and duration of the expected flood. The flood management process ends with the *disaster analysis.* This analysis use the elevation-damage relationships produced during the data preparation task and performs flood damage computation for different flood management alternatives.

Initial state. A field survey is normally carried out to obtain detailed information on the characteristics of the study area. Information collected during a field survey includes: type; cost; and ownership of structures in the region. Data from this process is stored in the study area database. Data may consist of several map layers, each containing features that contribute toward the complete description of the study area. A typical cross-section of map layers that make up a study area is:

Layer 1	Designated Area	(e.g., airstrips, golf courses);
Layer 2	Building	(e.g., fire stations, houses, schools);
Layer 3	Structure	(e.g., storage tanks, smoke stacks, antennas);
Layer 4	Roadway/Railway	(e.g., roads, bridges, rail lines, tunnels);
Layer 5	Utility	(e.g., electrical poles, water towers);
Layer 6	Hydrography	(e.g., rivers, ditches, dykes, ponds);
Layer 7	Hypsography	(e.g., contours, water levels);
Layer 8	Land Cover	(e.g., fields, orchards, trees); and
Layer 9	Textual	(e.g., road names, cities, villages).

The existing conditions in the floodplain are efficiently documented by using the information from the field survey. The completely updated database can be output to a file, making such information available for use by the structure inventory analysis model.

Data preparation. The data preparation task uses initial state data and processes them for the mathematical models to be used in flood damage analysis. The data preparation procedure is following a hierarchical scheme that improves the comprehension of the user toward the analysis procedure as a whole and helps in selecting different alternatives to be examined. The hierarchical approach leads to a greater acceptance of the FCDSS, allowing the analysis procedure to more easily blend into the decision-making process.

The system basically inquires whether any nonstructural flood control measures will be applied to structures in the floodplain. Three options are provided in the FCDSS, namely, raise-to-target-elevation analysis, flood-proofing analysis, and relocation of structures analysis. The process continues by inquiring about information related to the floodplain such as the number of damage categories, the number of damage reaches, and the different damage functions that may be applied to a particular category. The damage function for a particular structure represents the manner in which the elevation-damage relationship is defined for that particular category or structure. Using this hierarchically-organized consultation process the user can generate several different scenarios and obtain the elevation-damage relationships for them.

Generation of the flood management alternatives. This task includes the selection of the type of structural or nonstructural flood control measures to be used in a given situation. The optimal choice of implementation of structural or/and nonstructural measures is based on the physical parameters and also on engineering expertise. Expertise is required to take into account the human factor, which may lead to some unexpected situations. For example, incentives provided to householders in the floodplain to implement certain measures may be refused if the anticipated floods have not materialized in the recent past. Attractive flood insurance rates may also be not taken advantage of due to a false sense of security by these residents.

Disaster analysis. A flood management process ends with the disaster analysis. Flood damage analysis for alternate flood control plans is performed within this task. Again, a systematic hierarchical consultation is used to conduct the analysis. Basically, two types of information are inquired about from the user: (a) a period of analysis; and (b) number of different flooding scenarios to be used. Data may be input in three different formats, exceedance frequency values, flow values, or stage values. All the data received from the user are written to data files that are transformed to be used in the flood damage analysis of alternate flood control plans.

There are several measures that are computed in order to determine the consequences of a particular flooding event or a series of events. These measures are used to rank the set of alternate control plans generated. The measures used in the analysis are: expected annual damage; specific event flood damage; area flooded by a specific event; and individual structure damage.

Basic DSS Components

The central component of the FCDSS is the system manager, which controls the various parts of the system.

The system manager has been designed using ES technology. FCDSS contains a number of knowledge bases designed to perform different tasks. Each of these knowledge bases has access directly to the other modules of the FCDSS, e.g., the database management subsystem, the modelbase subsystem, and the display subsystem.

The main role of the ES is overall system coordination. Different modules are linked together using the knowledge specific to the flood control management process. The whole process has been transferred into the set of rules that create a number of knowledge bases. Specific characteristics of the problem and types of measures used in the flood damage analysis are used to lead the process. Beside a coordinating role, the system manager provides assistance in data preparation, running different mathematical models, and presenting the results in the graphical form using GIS.

The Database Module is a part of the system that facilitates data storage and manipulation. It has been found to be important, in the development of large applications programs that utilize large amounts of data and have several programs communicating with each other, to have a module that has the capability of providing efficient data storage, handling, and manipulation services.

The Modelbase Component of the FCDSS contains mathematical models that are accessed by the system manager to perform procedural and analytical tasks. For the flood control management, this module comprises software for: (a) structure inventory damage (SID) analysis; and (b) computing the average annual damage or flood damage from a particular flood event (EAD).

The major role of the display module is to improve the comprehension of the spatial and time-dependent information utilized in flood control management. This component aids the decision-maker in analyzing the results of various alternatives, thus leading to an optimal choice of flood protection.

Tools Used in the DSS Development

A Sun Microsystems Sparc workstation was selected as the platform for the development of the DSS. The computer is also connected to a cartridge tape drive and a Sparc laser printer for data entry and printing output respectively. There are several major reasons for developing FCDSS on a workstation platform. First, the computing power of these platforms allows fast and efficient system development and application. The multitasking capability of workstations enables several applications to be run simultaneously. The multiple windowing display programs often coupled with these platforms allow several screens to be displayed at once; thus, the user can interact easily with different components of the FCDSS.

Maintaining and expanding the system manager module was performed using the NEXPERT OBJECT [9] software. A relational database manager named ORACLE has been selected for the development of the database module of DSS for flood control management. The system manager developed using NEXPERT OBJECT is fully integrated with ORACLE through a database bridge. Structured Query Language (SQL) is used to transfer the instructions provided by the ES into the ORACLE. Data from other components of the system are loaded into ORACLE and manipulated using SQL commands to be output in the format required by pertinent models for flood damage analysis.

The SID program [12] is part of the flood damage analysis package. It is designed to assist in the systematic collection, management, and processing of data related to structures subject to flooding. Its main function is to generate elevation-damage functions by damage categories and reaches. SID can also perform an analysis of nonstructural flood control measures. The EAD program [13] has been developed to assist in economic evaluation of floodplain management plans. The program can compute flood damage in three modes: (a) damage for a specific event; (b) expected annual damage for a specific year or years; and (c) equivalent annual flood damage. Damage calculations can be performed for several damage categories such as urban, agricultural, and residential. Expected annual damage can be calculated for the conditions existing in the past or expected in the future.

A Multiobjective Compromise Programming technique is incorporated as one component of the system modelbase. Flood control alternatives analyzed by the system are evaluated according to a number of objectives. The evaluation process is conducted by using a Compromise Programming routine.

The Geographic Resource Analysis Support System (GRASS) [14] is a public domain GIS. It is an integrated set of programs designed to provide digitizing, image processing, map production, and GIS capabilities to users. GRASS provides many routines that assist in analyzing watersheds and also provides capabilities of displaying geographic data for visual comprehension by the user. GRASS has been used within the DSS to facilitate the task of data input and management by providing the routines for analyzing and extracting data from the map layers listed in the previous section of the article. Using GRASS, a complete inventory of the floodplain can be generated. The area flooded by a specific event and individual structure damages are also presented using GRASS. The elevation corresponding to the particular event is input to NEXPERT OBJECT and the flooded area corresponding to this stage is displayed on the elevation map. The GRASS is then used to generate a report on the total area taken up by the displayed area, and this is then multiplied by the actual area of each cell to arrive at the actual flooded area. Individual structure damage is determined by comparing the flood stage for a particular flood and the ground elevation of the buildings in the floodplain. If flooding is found to have occurred, then the damage done to the structure is computed using the damage function for the particular structure and the cost of the structure. The total damage data is then displayed using GRASS.

The system is designed with a large degree of flexibility for "what if" analysis

Sustainable Issues Covered

FCDSS is designed to provide "what if" capability in the process of evaluating different flood control alternatives. The system is designed with a large degree of flexibility for "what if" analysis. Different flood control alternatives (structural and nonstructural) can be evaluated by the system. Two particular damage analyses can be performed: (i) damage for a specific flood event; and (ii) expected annual damage over a 50-year period.

Multiobjective analysis of different alternatives allows direct consideration of important issues relevant to sustainable flood control management. Criteria like flooded area, total damage, cost, evacuation, and impact on wildlife are directly considered in the analysis.

Use of the GIS software provides an effective way of displaying and manipulating the results of the analysis. FCDSS uses GIS for visual support to the planning process in two different ways: (a) Showing the flooded areas. To examine the consequences of flooding from specific events, flooded areas resulting from different measures can be displayed both in two-and three-dimensional overlay on an elevation map layer; and (b) Displaying damage by elevation. For each point in the area and for every level of elevation, a display of the resultant damage can be provided. This display is useful in locating areas at high risk of sustaining major damages due to a particular flood at a particular elevation. In deriving these maps, the damage function relationship for each structure is utilized to obtain elevation-damage relationships. GRASS Ginfer program is then applied to generate a new map that is an aggregation of the damages incurred by each building in the reach at a particular elevation.

Lessons Learned

Emphasis of the development was on integrating ES, GIS, database manager, and analytical models into an efficient planning tool. ES technology helped in the management of the overall process of analysis and provided support for strong interaction between the user and the machine. GIS played a key role in addressing the spatial aspects of the problem domain. Activities ranging from spatial data input and analysis, to visual presentation of the results were supported by the GIS component of the system. The use of a relational database to handle the storage and retrieval of data facilitated the data management process. An example study area (south of the city of Winnipeg, Manitoba, Canada) contained 1,213 buildings [11]. With a larger and more built-up area, the data requirements would become large and use of an efficient tool for their management will be essential for a successful analysis.

Several directions have been identified for future system enhancement: (a) incorporation of knowledge bases containing engineering expertise to be applied in the selection of the type of nonstructural measures; (b) inclusion of the model for hydrologic computations of water-surface elevation; and (c) incorporation of animation to simulate floodwave movement along the floodplain, and sound effects that will be used to indicate the flood magnitude.

CONCLUSIONS

An examination of current water resource management practice confirms the need for incorporation of the main principles of sustainable development. With population, economics, and environment inextricably linked with water resources, this research examines the complex challenges presented by the goal of sustainable development. Decision support systems technology may be of assistance in addressing some of the issues related to the sustainable management of water resources. Four case studies, showing existing best practice, provide a model of how decision support systems can adapt and contribute to the crucial goal of sustainable development.

Decision support systems technology may be of assistance in . . . the sustainable management of water resources

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