Integration of heuristic knowledge with analytical tools for the selection of flood damage reduction measures

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Abstract: Heuristic knowledge has been integrated with analytical tools to support decision making for flood management. Development of an expert system called Intelligent Flood Management System for the selection of appropriate flood damage reduction measures for a given area is described. The selection of flood damage reduction measures is based on hydraulic, hydrological, geotechnical, environmental, and economic factors related to the river system and the area to be protected from floods. The knowledge base of the Intelligent Flood Management System is generic and can be used to identify a suitable flood management option for any area. The model base of the Intelligent Flood Management System consists of the hydraulic analysis package HEC-RAS, the flood damage analysis program HEC-FDA, and a model for economic analysis. The graphical user interface is developed for effective communication with the system. The developed system has been implemented to identify appropriate flood damage reduction options for the town of Ste. Agathe in Manitoba, Canada using data from 1997 flood in the Red River Basin.

Key words: flood control, flood management, structural measures, heuristic knowledge, decision support systems, expert systems.

Résumé : Des connaissances heuristiques ont été intégrées avec des outils analytiques afin d'aider à la prise de décisions pour la gestion des crues. Le développement d'un système expert appelé « Intelligent Flood Management System (IFMS) » (système intelligent de gestion des crues) pour la sélection de mesures appropriées de réduction de dommages dues aux crues sur une région donnée est décrit. La sélection de mesures de réduction de dommages dues aux crues est basée sur des facteurs hydrauliques, hydrologiques, géotechniques, environnementaux et économiques reliés au système de la rivière et à la région qui doit être protégée des crues. La base de connaissances du IFMS est générique et peut être employée pour identifier une option appropriée quelle que soit la région. Le bloc de modélisation comprend l'ensemble d'analyse hydraulique HEC-RAS, le programme d'analyse des dommages dues aux crues HEC-FDA et un modèle pour analyses économiques. L'interface graphique usager est développé pour permettre une communcation efficace avec le système. Le système développé a été appliqué pour identifier les options appropriées de reduction des dommages dues aux crues pour le village de Ste-Agathe au Manitoba, Canada, en utilisant les donnés de la crue du bassin de la rivière Rouge en 1997.

Mots clés : contrôle des crues, gestion des crues, mesures structurales, connaissances heuristiques, systèmes d'aide à la décision, systèmes expert.

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Introduction

The complexity involved in selecting a flood management option most suitable for a given area is enormous. Any comprehensive system for the selection of flood management options requires simultaneous consideration of technological, hydraulic, hydrological, geotechnical, environmental, and economic factors. Economic analysis plays an important role in formulating plans for flood management (Wurbs 1996). Moreover, implementation of any selected flood management measure involves serious social implications. The background information required for flood management work is characterized by a broad range of disciplines and is subject to a variable degree of resolution and uncertainty. The flood management process, therefore, requires a strong element of human expertise and judgement in addition to the more formal, scientifically based, analytical knowledge. The variety of aspects to be considered for selection and the complexity of the selection process can easily overwhelm a

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novice in the field. Typically, simulation models are used to analyze flood management options; however, they can not incorporate heuristic, subjective, and judgmental information, which is also needed for the selection of flood management options. Expert systems can handle heuristic knowledge and are capable of reproducing the expert's decision process of solving the complex problems within a confined problem domain. Considerable advantages can be realized by combining analytical tools (simulation) with an expert system (heuristic knowledge). Integration of heuristic knowledge with analytical modelling provides a powerful tool for formulating a problem, performing "what if" analysis and choosing the appropriate flood damage reduction measure for a given area.

The main strength of the integrated approach lies with the concept of expert systems. An expert system allows the capture and formalization of the knowledge of a human expert within a computer program, so that the program can draw inferences from the data with which it is presented and then recommend a course of action. Traditional computer programs are composed of interrelated procedures where the sequential execution of the algorithms is explicitly controlled and efficiency is achieved by optimizing the iterative process. In contrast, expert systems are rule-based programs with independent IF–THEN statements and the development of the rules is based on the heuristic knowledge (rule-of-thumb) of the problem domain. Expert systems are data driven (it is the data that determines the action and not the procedure) and have the ability to efficiently use symbolic data (nonnumeric) and explain to the end-user how the inference procedure arrived at a conclusion. The use of heuristic knowledge, the inference procedure, incorporation of symbolic data, and the ability to explain how the system derived a conclusion, are the main strengths of expert systems.

The discipline of water resources planning and management involves procedures developed from theory and actual practice thus a considerable amount of knowledge exists in a heuristic form. Numerous subjective decisions and, therefore, linguistic variables are involved in the problem domain of flood management. The necessity to utilize the valuable heuristic knowledge leads to the idea of integration of heuristic knowledge (expert systems) with analytical tools.

The integration of heuristic knowledge with analytical tools has been suggested for a variety of tasks in the field of water resource planning and management; ranging from design, planning, management, and operations. Some important applications are briefly described in this section. León et al. (2000) have developed a hybrid expert system for water network management. Mohammadabad and Riordan (2000) have reported an advisory system for the feasibility study of small hydropower plants. Arumugam and Mohan (1997) coupled knowledge derived from field experts with an optimization model to aid the operation of a tank (small-scale reservoir) irrigation system in south India. Chang et al. (1996) developed an expert system for daily drought monitoring. DeGagne et al. (1996) have discussed a decision support system for the analysis and use of stage–discharge rating curves. Shepherd and Ortolano (1996) have described an expert system for water supply system operations. Simonovic (1996*a*, *b*) discussed the structure of a decision support system for sustainable management of water resources and demonstrated the applicability of the proposed system with two case studies. Simonovic and Bender (1996) developed a collaborative planning-support system. The system focusses on fish habitat issues relating to a hydropower development project. Marsi and Moore (1995) integrated design theory, expert methodology, and information processing technology for disaster planning analysis. They used the developed system to evaluate the costs and benefits of the Los Angeles earthquake damage mitigation strategies. Bender and Simonovic (1994) developed a rule-based decision-support system for long-range stream flow forecasting. Evans et al. (1993) combined the rule-based reasoning with spatial data representation and analysis to develop an expert geographic information system. An expert geographic information system for long-term regional water resources planning is reported by McKinney et al. (1993). Raman et al. (1992) used an expert system and linear programming model to develop a decision support system for crop planning during droughts. Simonovic (1992) describes an expert system for reservoir management and operations. Davis et al. (1991) developed a prototype decision support system for analyzing the impact of catchment policies. Engel and Beasley (1991) developed an expert system for dam site selection. Simonovic and Savic (1989) presented an intelligent decision support system for reservoir management and operations. Palmer (1987) developed an expert system for drought management planning.

The Intelligent Flood Management System (IFMS) presented in this paper selects the suitable flood damage reduction option for a given area. The modelling and analysis approach presented here combines hydrologic and economic simulation models with heuristic knowledge. The hydrologic and economic simulation modelling approach is based on conventional methods. Combining the simulation models with heuristic knowledge is the more innovative aspect of the methodology presented here. The Red River Basin in Canada has been used as a case study. The paper is divided into four sections. The first section covers the introduction. The selection process of flood management measures, along with details on the modelling tools, used in this study is presented in the second section. The third section discusses the architecture of the system and details on knowledge representation. Finally, in the fourth section an application of the developed system to the case study area is presented. The conclusions emanating from the study are also presented in the fourth section of the paper.

Selection of flood management measures

Floodplains provide advantageous locations for urban and agricultural development. Unfortunately, the same rivers that attract development periodically overflow their banks causing loss of life and property. Flood management is a broad spectrum of water resources activities aimed at reducing the potentially harmful impact of floods on people, the environment, and the economy of the region. A variety of structural and nonstructural measures can be implemented to reduce flood damages; however, complete control of floods or prevention of all damage is seldom economically feasible. Thus economic analysis plays an important role in formulating and selecting plans for reducing flood damages.

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The selection process of suitable flood management option for a given area starts with the review of available information and data related to the river system and area to be protected from floods. Based on preliminary information, feasibility of different flood management options is evaluated. Feasibility studies for engineering projects depend on an understanding of the various components of the problem, a broad knowledge of techniques yielding possible solutions, the constraints related to these solutions and their significance. An experienced professional with knowledge of flood management domain and using available data and (or) information may discard some flood management options without going into detailed analysis. For example, a reservoir is not a practical option when floodplains are very flat and no storage space is available. Similarly, construction of a dyke is not the preferred option in an area where the soil type is clay. Going through a similar process, different flood management options are analyzed one by one based on the available information and the heuristic knowledge. Finally, one or two potential flood management options are selected for detailed analysis using modelling tools. The detailed analysis covers technical and economic evaluation of the selected flood management options thus, leading towards the final selection of flood management measures. The heuristic knowledge and local expertise play an important role in the selection of flood management options. Local knowledge about the river system and floodplains is very valuable.

Tools used in the selection process

The integrated approach presented in this paper makes use of an expert system shell for knowledge coding and inferencing and employs modelling tools HEC-RAS (United States Army Corps of Engineers 1998*a*) and HEC-FDA (United States Army Corps of Engineers 1998*b*) for hydraulic and flood damage analysis, respectively. The following section will discuss details on theoretical basis of tools used for hydraulic modelling, economic analysis, and heuristic knowledge presentation.

Hydraulic modelling

The tool used for hydraulic analysis of flood management option is HEC-RAS. This program is developed for the simulation of one-dimensional steady flow based on the Manning equation. The model calculates water surface profiles (elevations) and flow velocities in a river from given geometry, discharge data, and boundary conditions. Data required to set-up the model include: schematic presentation of the river reach; cross section data; length of the channel until next cross section; length along the left and the right bank; coordinates for the left and the right bank; Manning's n values for banks and the main channel; and contraction and expansion coefficients. The basic computational procedure is based on the solution of the one-dimensional energy equation. Energy losses are evaluated by friction and contraction–expansion (coefficient multiplied by the change in velocity head). The momentum equation is utilized in situations where the water surface profile is rapidly varied (hydraulic jumps, hydraulics of bridges, and river confluence). The model uses the standard step method for calculation of water surface profiles and can handle subcritical, supercritical, and mixed flows. The model can analyze flood management plans involving flow diversion, channel modification (dredging), and dykes. The most important output of the model is surface water profiles. First, surface water profiles for "without project conditions" are generated. Then by introducing different flood management options into the model, for example, diversion, dredging, and dykes, the modified surface water profiles are obtained. The surface water profiles are the main input to the flood damage analysis program.

Flood damage analysis

The HEC-FDA is used to estimate the benefits (reduction in damages) derived from the implementation of selected flood management plans. For the calculation of flood damages, as a first step, flood management plans to be analyzed by the model are identified. A plan consists of one, or more, flood damage reduction measures and may involve several streams and damage reaches. A plan starts with the base year of implementation and exists over an analysis period, normally fifty years. The without project condition is always the first plan against which all subsequent plans are compared. Damage reaches are spatial floodplain areas used to define data for plan evaluations, and to aggregate structure, and other potential flood damage information by the flooding stage.

A water surface profile is the water surface stage along a stream length associated with discharge values of a hypothetical or observed flood event. In HEC-FDA, a water surface profile data must consist of eight flood events. Each water surface profile has stream stations, invert elevations, and discharge–stage values. The probabilities of each profile are used to generate exceedance probability functions at index locations normally associated with water surface profile cross-sectional stations. The default set of eight water surface profiles are for the 0.50, 0.20, 0.10, 0.04, 0.02, 0.01, 0.004, and 0.002 exceedance probability flood events. The water surface profile data is imported from HEC-RAS. An exceedance probability function can be specified as either analytical (discharge–exceedance probability) if it can be fitted by a Log Pearson Type III distribution, or graphical (discharge or stage-exceedance probability).

For calculation of flood damages either general depth-damage functions (McBean 1988) are directly provided or the program computes an aggregated stage-damage function by damage category at the index station using structure inventories. The program requires the uncertainty of depth-percent damage functions, first floor levels, structure and content values to be defined, and a complete set (eight profiles) of water surface profiles to be available. The computation for damage is based on the residual damage associated with a specific exceedance probability event. Performance targets are essentially the zero damage stage. The flood damage associated with a plan is calculated in average annual equivalent terms. The procedures discount the expected annual damage stream to the beginning of the period of analysis or the base year. Future year damage values are linearly interpreted between the base and most likely future year conditions and are assumed to be constant from the most likely future year to the end of the analysis period. The ex-

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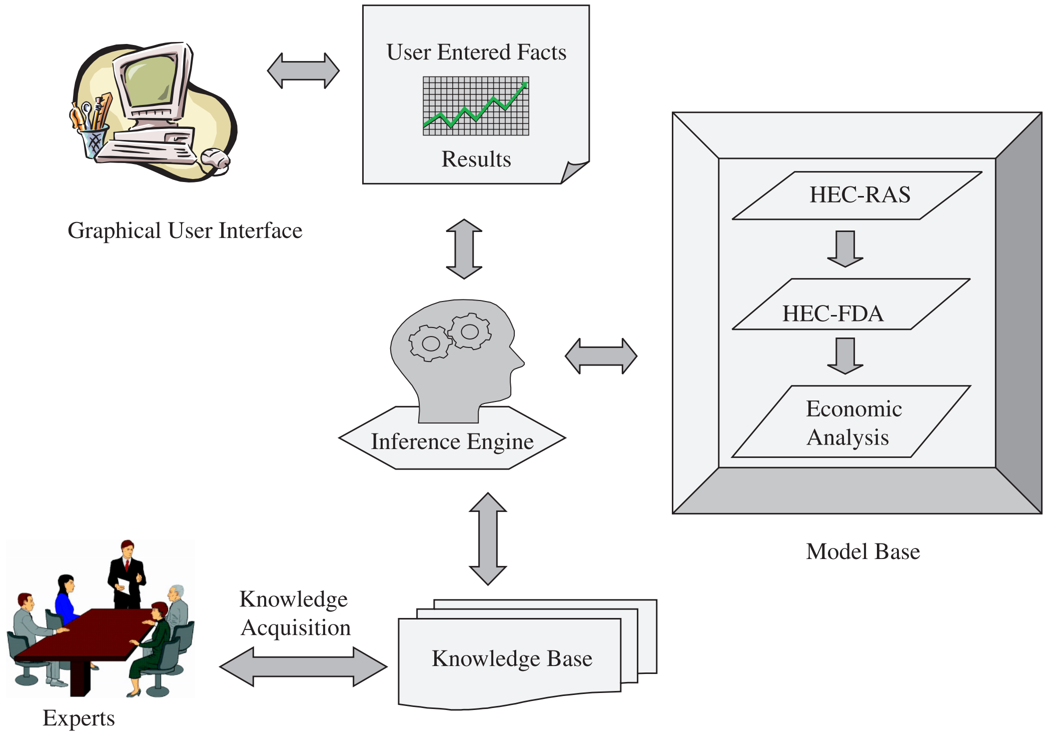
Fig. 1. Architecture of the Intelligent Flood Management System.



pected annual damage for each year in the analysis period is computed, discounted back to present value, and annualized to get the equivalent value over the analysis period (project life). The HEC-FDA also calculates reduced annual damages, that is, benefits of implementing a flood management option that are used for benefit-cost analysis.

Heuristic knowledge representation

An expert system shell (Cimflex Teknowledge Corporation 1991) has been used to code the expert knowledge and develop an inference mechanism. The shell provides a rule-based programming language environment integrated with both procedural and object oriented language support. The main strengths of the integrated system developed include both backward and forward chaining, pattern matching, backtracking, recursion, iteration, certainty factors, symbolic list processing, value checking, and explanation. Extended capabilities include meta-facts, meta-propositions, procedural control methods, and retraction. Powerful object-oriented features like classes, instances, slots, and methods with inheritance and message passing, round out the knowledge representation. The syntax representation of rules is very close to natural language and any ASCII based text editor can be used for writing the knowledge base. In the following section the architecture of the flood management system developed for this study is discussed.

Intelligent Flood Management System

The Intelligent Flood Management System (IFMS) is an interactive consultation program that, through dialogue with the user and by consulting the knowledge base and analytical models, determines the suitable flood damage reduction measure for a given area. The problem domain is focussed on the flood management options. An expert system that is capable of formulating the problem and selecting appropriate options requires knowledge about the flood management problem domain, flood management options, hydrological–hydraulic modelling, and economic analysis. The knowledge system is built from facts, rules, procedures, and objects that relate to flood management issues. The inference engine performs the reasoning process and assists in solving a problem by drawing conclusions based on perceived facts. This is achieved by using knowledge stored in the knowledge base and comparing it with input from the user. This way a large number of possible conclusions are narrowed to select the appropriate measure.

Architecture of the Intelligent Flood Management System

The architecture of IFMS consists of four main components: (1) graphical user interface; (2) model base; (3) knowledge base; and (4) inference engine. The communication between these components is shown in Fig. 1. The graphical user interface (GUI) allows interaction between the system and user providing transparency to the model and its functions. In an interactive session using the GUI the user enters information about the river system and the area to be protected from floods. Results are also communicated to the user through the GUI. Built-in help facilities and menu-driven commands are the features that make the GUI user-friendly. An explanation facility has also been provided to the user through interface that explains why a particular question has been asked or a certain recommendation has been made. The model base consists of three models: (1) river analysis

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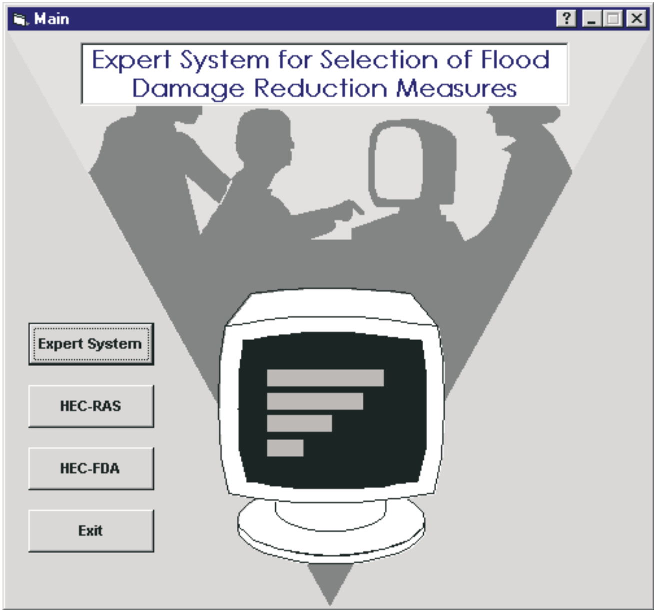
Fig. 2. Graphical user interface of the Intelligent Flood Management System.



model; (2) flood damage analysis model; and (3) economic analysis model. The river analysis model simulates the flow in the river and floodplains. The most important output generated by the river analysis model is surface water profiles that are used as input to flood damage analysis program. The flood damage analysis model estimates the reduction in damages (benefits) as a result of implementing a flood management plan. The economic analysis model performs benefit cost analysis for the selected flood management option. The knowledge base contains the knowledge specific to the flood management domain. The heuristic knowledge, that is, knowledge developed through experience is collected through a series of interviews with experts in the field of flood management. The acquired expert knowledge is coded in the form of rules using the IF–THEN construct. The inference engine is the heart of the IFMS. The user, through the GUI, enters known facts about the river system and the area to be protected from floods in the knowledge base. Following its control strategy, the inference mechanism locates the potentially applicable rules, those whose condition portion is matched by the facts in the context, selects one of these rules and fires it, that is, causes its action to be executed. The result of any action is to add to, or modify some aspect of the context; thus, new rules become candidates to be fired, and a cycle of matching and firing is repeated in an infinite loop until a goal is satisfied or there are no more rules remaining to be fired.

Consultation process

The user can start the consultation process by activating the expert system from the user interface (Fig. 2). Through an interactive process, the IFMS asks the user a series of questions. Questions are related to hydraulic, hydrological, topographic, geotechnical, and environmental aspects of the river system, and the area to be protected from floods. The expected question response varies from a simple yes or no, to multiple choices, or entering values. The user has an option to provide a confidence factor on a scale from 0 to 100 with all, or some, of the answers. The default value for a confidence factor is 100. The flow diagram of the complete consultation process is shown in Fig. 3. The flood management options considered by the IFMS are (1) levees and (or) dykes; (2) floodwall; (3) diversion (floodway); (4) retention basin and (or) controlled flooding; (5) dam and (or) reservoir; (6) dredging or increasing the hydraulic capacity of the channel; and (7) relocation of the town. The term diversion and floodway are used synonymously in this paper. Once all the information required to make a preliminary selection is compiled, through interaction with the user, the IFMS consults the knowledge base to recommend a single, or a combination of flood management options to protect the area under consideration from flooding. Following the initial recommendation of the flood management option, a detailed analysis of the recommended option is required to make a final selection. Detailed analyses using simulation tools provide answers to some important questions, like the extent to which the selected option would be able to protect the area from floods, and the dimensions of the required flood control structures. The information on dimensions of the flood control structure helps in calculating the construction cost for that option. The flood damage analysis package HEC-FDA calculates the reduction in the damages (benefits) resulting from the implementation of a selected flood management plan. The final recommendation on the flood management option is based on the benefit cost analysis carried out using the economic analysis model.

Detailed analysis starts with the river analysis program HEC-RAS that can be activated through the graphical user interface (GUI) of the IFMS. The user needs to establish the river system by providing the data on river cross-sections, length of each river reach, and Manning's roughness coefficient. Rating curves, discharge series, and boundary conditions (either water levels or discharges) are also required. This completes the data files for the basic plan, which is always the without project situation. Then depending upon the recommended flood management measure, a separate plan has to be identified for each flood management scenario. For this study the flood management options of dykes, floodway, dredging, and a combination of floodway and dykes have been established in the HEC-RAS. As an output the HEC-RAS provides eight water surface profiles for a range of floods of different return periods. These water surface profiles are used as input to the flood damage analysis program HEC-FDA. The user needs to provide information on the number and category of structures in the area to be considered for flood protection, the monetary value of structures, and their contents. The level of the basement and the first floor along with a relationship between the depth of water and damages is also required. As an output, the HEC-FDA provides the reduced flood damages resulting from implementing a flood management plan. The reduced flood damages calculation is based on the comparison between the with and without project situation. With information on reduced damages (benefits) from HEC-FDA, and physical details (dimensions, capacity) of the flood control structure from HEC-RAS, the user consults the IFMS again. Now, the IFMS performs a benefit cost analysis and makes a final rec-

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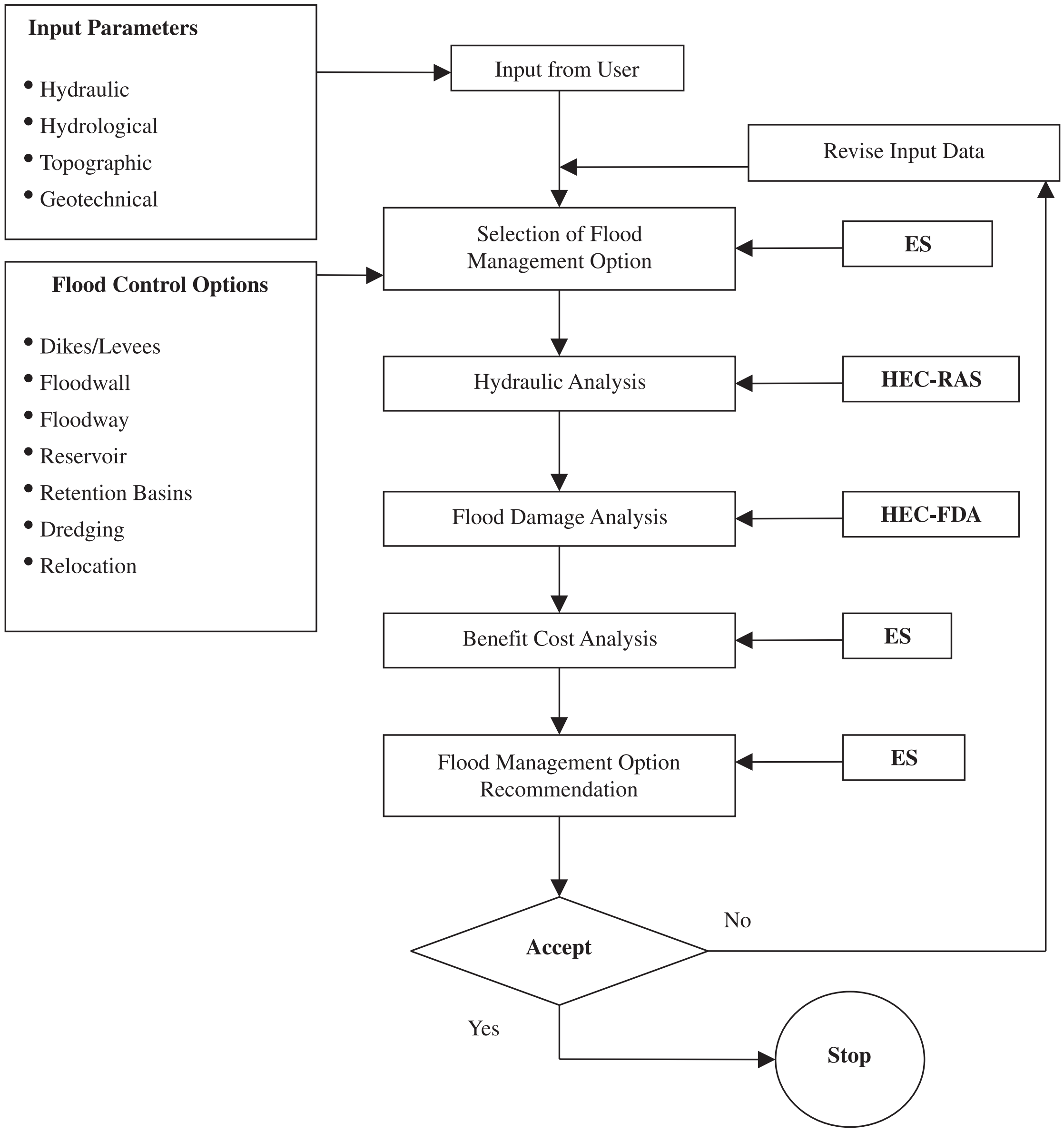
Fig. 3. Flow chart of the consultation process.



ommendation on the flood management plan to be implemented to reduce flood damages.

Knowledge representation in the Intelligent Flood Management System

This section describes the details of knowledge representation along with some salient features of IFMS.

Back-chaining and forward-chaining

The IFMS is capable of using both backward chaining and forward chaining. When a rule is used in an attempt to find a value for an expression, back-chaining is triggered, causing the IFMS to seek values for expressions tested in the rule's premise. For example, if the system is trying to find the value of recommended_measure by using the rule

If best_measure = floodway

then recommended_measure = floodway.

The IFMS may try rules that conclude best_measure in an attempt to determine if best_measure is floodway. Forward chaining is supported with the WHENFOUND and WHENCACHED constructs that cause actions to be taken after values for an expression have been sought.

Intelligent questioning

Intelligent questioning is incorporated in the system by using the PRESUPPOSITION command. For example, while considering a dyke as the flood management option the IFMS asks the user, "Is there enough space available to place a dyke?" If the answer is no, only then it will ask "Is it possible to acquire land to place a dyke?" If the answer to first question is yes the IFMS will omit the second question. In the following example the use of PRESUPPOSITION controls the sequence of questions. The second question (acquisi-

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tion) will only be fired when the answer to the first question (distance-to-river) is no.

question(distance-to-river) = "From inspection of the project area, is there enough space available for placing a dyke between river and area to be protected from flood?"
legalvals(distance-to-river) = [yes,no].
presupposition(acquisition) = distance-to-river = no.
question(acquisition) = "From inspection of the project area, considering number of structures close to river bank, is it possible to acquire land to place a dyke between river and area to be protected from floods?"
legalvals(acquisition) = [yes,no].

With each question one fact related to the problem under consideration is analyzed and information is stored in cache memory. Next time when the system tries to match that fact with the left hand side of any rule it will have ready-to-use information about the fact. The point is that the system will not have to ask the same question more than once. The IFMS has 78 separate parameters for collection of specific facts to reach the system goals. The number of questions (parameters) prompted by the IFMS to the end-user during a consultation process are dependent upon the path employed by the system to reach its goals, that is, not all questions are asked in every consultation.

Acceptable value of answers

The IFMS may ask the user for the value of an expression it is seeking, if it encounters a question meta-fact in the knowledge base. Additional meta-facts specify the acceptable values for the expression. Acceptable values are presented to the user in a menu or as an enumerated list following the question. Expressions are declared to be "integer" or "number" (real) and a range is specified. The IFMS is capable of accepting yes or no answers, multiple choices, integers, and real numbers.

The response to some questions posed to the users by the knowledge system is restricted. This includes specifying a question as single-valued or multi-valued (i.e., whether or not the answer should be limited to a single definite answer), and specifying acceptable values or ranges for answers. In addition, unknown and (or) certainty factors are allowed or disallowed for input. In the following example only a real number is allowed as an answer:

presupposition(channel-width) = selected-option = floodway.
question(channel-width) = "What is the bottom width of the floodway channel in metres? Please enter value in the form of real number."
legalvals(channel-width) = real.

or

question(foundation) = "Based on geotechnical information, how would you describe the strata underlying the top soil?"
legalvals(foundation) = [hard-rock,soft-rock,sand-or-silt, clay].

In this example the user is restricted to make a selection out of the four given options that is, hard-rock, soft-rock, sand-or-silt, and clay.

Rules

The rules are the storage of heuristic knowledge and they affect the way parameter values are inferred and ultimately determine the system goal(s). The rules use IF statements followed by the THEN statement, to inference a conclusion based upon parameter data. Some rules calculate a specific value based on input from the end-user. Rules are also used to derive new facts based on specified conditions. The premise of a rule specifies the conditions under which a new fact can be concluded. Symbolic, as well as numeric, comparisons or tests are combined with standard Boolean operators to form the rule premise. Also, basic arithmetic functions are used in the premise of a rule.

This rule provides a definition of "between":

if EXPRESSION = VALUE and
  VALUE > = LOWER_BOUND and
  VALUE < UPPER_BOUND
then between(EXPRESSION, LOWER_BOUND, UPPER_BOUND).

In some cases, the order of the rule is very important for guiding the application of knowledge.

Certainty factors

A certainty factor (CF) makes it possible to represent uncertain knowledge in the IFMS. Certainty factors are entered with user-input. The inference engine automatically deals with certainty factors, combining the certainty of input data, rule premise clauses, and rule conclusions, as well as accumulating the certainty of the same conclusion made by different rules. The use of certainty factors allows the IFMS to reach realistic conclusions when presented with incomplete, uncertain, or even conflicting data or knowledge.

Goals

More than one goal can be specified for the back-chaining search. The initial search will be performed to satisfy the first goal and then each subsequent goal will be satisfied in order. This gives knowledge engineers maximum flexibility in developing search strategies.

goal = [recommended-measure,next_step].

In this example first goal determines the appropriate flood management measure (recommended-measure) and second goal asks user what to do next, quit or another consultation. In case of another consultation it re-initializes the system.

Facts

Facts are used in knowledge base to represent information that is known statically about the domain. Facts may also be stored in cache files that can be loaded on demand.

Pattern-matching

Pattern-matching variables are employed in rules and facts to make them more general and powerful, combining into a single fact that would otherwise require a number of rules or facts.

Symbolic expressions

Symbolic expressions take on values (e.g., height of dyke, construction_cost), can be tested in rules, tested or manipulated in procedures, or given static values via facts. When

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the value of a symbolic expression is needed, the inference engine, guided by the knowledge base, may obtain the value from a fact, by using rules, by asking the user, and (or) by calling an external routine.

User friendliness

The IFMS is equipped with an explanation and trace facility. Basic level explanations are automatically generated by the IFMS to elaborate why a particular question is being asked. This explanation is based on the rule or procedure that caused the question to be asked. The trace facility can be used to display events as a consultation is run. The exact sequence of goals sought, rules invoked, facts or procedures used, instances created, and conclusions made by system during a consultation can be traced.

Logic of inference engine

In this section the logic and reasoning used by an expert (as captured in the knowledge base) to select a particular flood management option has been described. The heuristic knowledge (knowledge developed through experience) was collected from experts in the Water Resources Branch of Manitoba Department of Conservation through series of interviews. In addition to domain knowledge obtained from experts some rules were formulated from published information. The knowledge and logic were captured in the IFMS using the IF–THEN structure of rules. A brief description is given for criteria expressed by experts for selection of each flood management option.

Dykes

An important requirement for considering dykes as a flood management option is that either there should be space available, between the area to be protected from floods and the river bank, to site a dyke or it should be feasible to acquire the land. It is not feasible to construct a dyke if the soil type in the vicinity is clay or if the foundation is clay.

Floodwall

Levees and (or) dykes and floodwalls have been considered as two separate flood management options. Generally, dykes cover two or more sides of an area to be protected from floods. A floodwall, on the other hand, is along the bank of the river providing a barrier between the river and the area to be protected from floods. It is not feasible to construct a floodwall if either the soil type in the area, or the foundation, is clay. A floodwall is also not recommended, due to environmental considerations, if there are wetlands or marshes in the area, as they will dry out without natural floods. To consider a floodwall either there should be room available, between the area to be protected from flood and the riverbank, to place a floodwall or it should be feasible to acquire the land. There should also be a place available to plug in the floodwall at both ends like natural high ground, road, hill, etc. If there is a place to plug in the floodwall on sides and there are none or few wetlands or marshes in the area then a floodwall is preferred over a dyke.

Floodway (diversion)

A floodway is not an option for a small town or if only few houses are to be protected from floods. To consider a floodway either there should be no endangered animal species in the watershed area, or the corridor of movement for these species should not be interrupted by construction of the floodway. Excavation should be easily possible, that is, there should be no bedrock within the excavation depth of floodway. Another important factor is that either there should be a natural water body to dispose the diverted water, or there should be enough gradient available to drop the water back into the river without causing a serious backwater effect.

Retention basin

The willingness of farmers to allow their land to be flooded is very important for controlled flooding option. Water-logging (high ground water levels) should not be severe in the area. There should be no historic site of importance or it should be possible to protect the site from damages caused by controlled flooding by constructing a dyke around it or by using some other measures.

Dam and (or) reservoir

These are not an option for small towns unless the project can be economically justified by considering additional uses like hydropower generation, water supply, recreation, etc. They are not feasible in river environments where high sedimentation is an issue. Water-logging should not be severe in the area. Either there should be no endangered animal species in the watershed area or their corridor of movement should not be interrupted by construction of a reservoir. A good foundation must be available (e.g., rock, sand, or silt). The geology should not be permeable. There should be no wetlands in the area. Land use should not be forest, especially rain forest. There should be no historic site of importance, or it should be possible to protect the site from damage by constructing a dyke around it. There should be no endangered aquatic habitat in the river system. Most important of all there should be a suitable site available to build a reservoir.

Dredging

This is not an option for small towns or if there are only few houses to be protected from floods. It should not be considered if the majority of the watershed is bare land as surface runoff will bring lots of sediments. Water-logging should not be severe, as additional capacity would be lost due to increased groundwater flow into the river. The river path should be stable. Dredging is not an option if the sedimentation problem is severe in the river. The additional capacity of the river required to accommodate damaging floods should preferably be equal to or less than 50% of the existing river capacity. There should be no endangered aquatic habitat in the river system.

Relocation of town

This option should be considered only if it is a small town or there are only few houses in the area to be protected from floods, if damaging floods are frequent, if damages are high and all other options are not economically justified.

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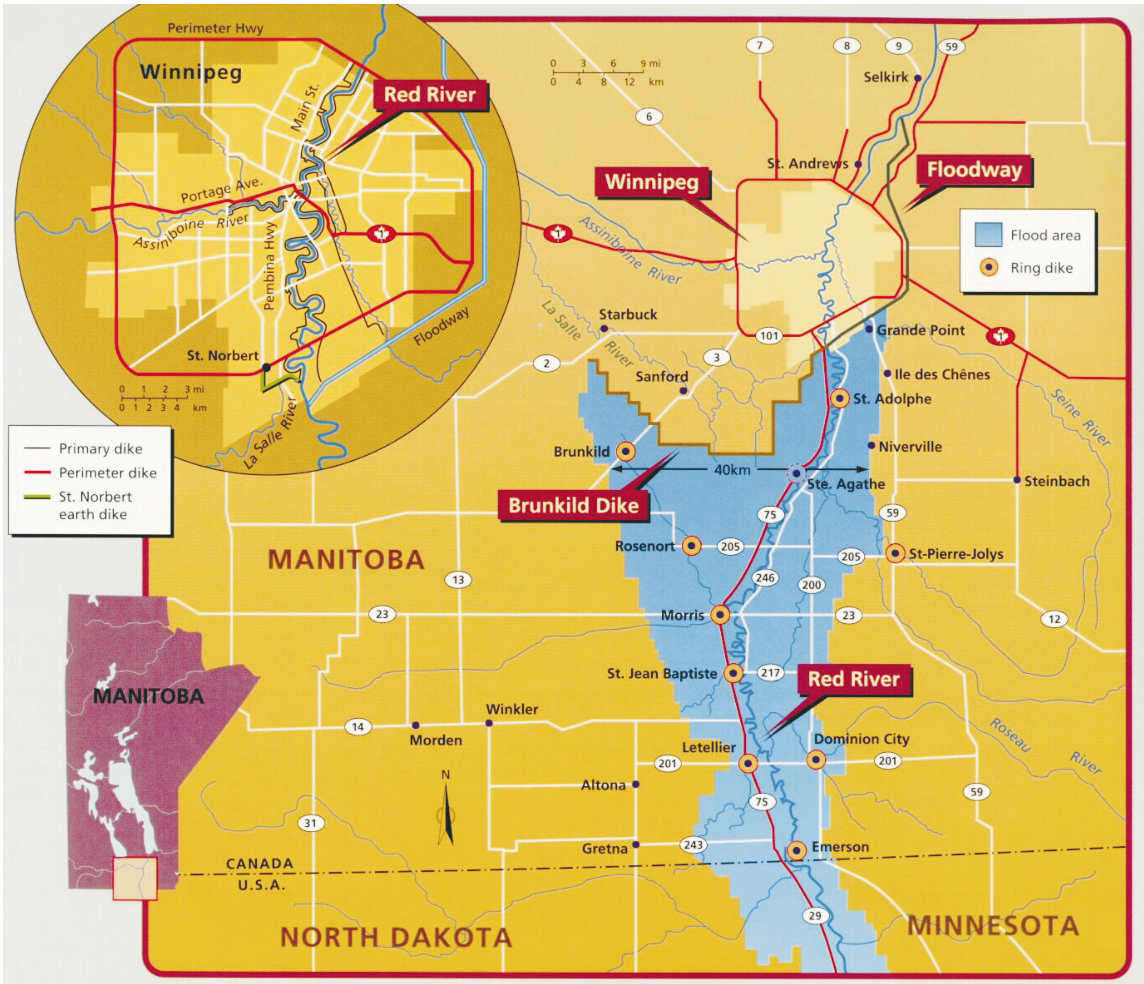
Fig. 4. Study area.

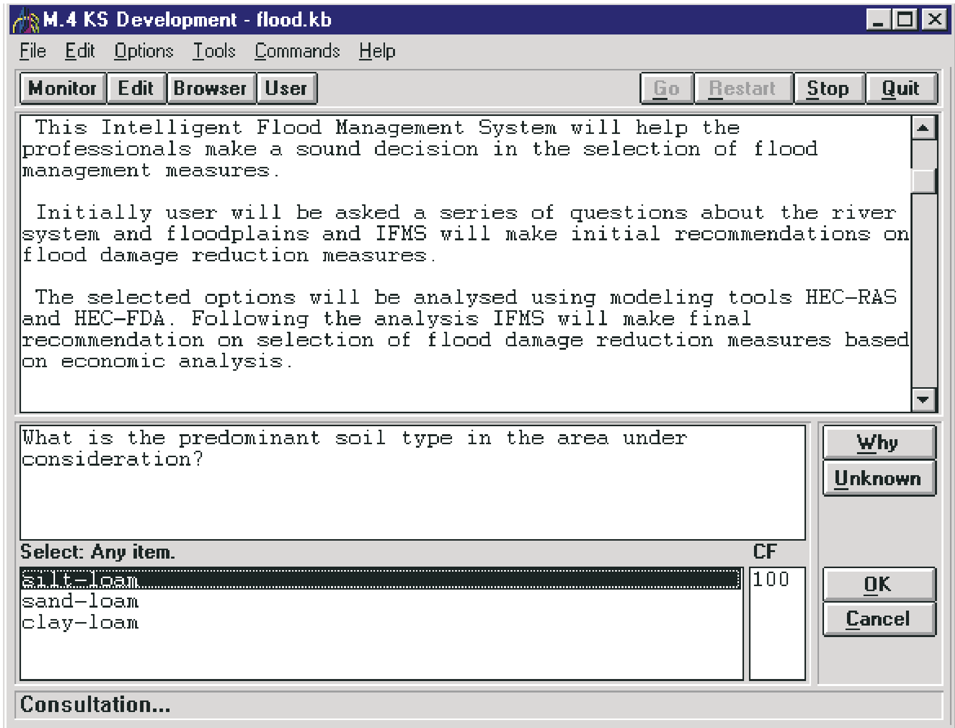


Illustrative case study

To demonstrate a sample application of developed intelligent flood management system, Ste. Agathe town situated along the Red River in Manitoba, Canada was selected as the study area. Actual topographic and river information was used to establish the Red River system in the model from Morris to the inlet of the Winnipeg floodway (Fig. 4). The flooding event of 1997 was used for analysis of all flood management options. The flood frequency estimates reported by Royal Commission (1958) were used as the basis for water surface profile calculation. The damage curves developed by KGS (2000) were used for the calculation of flood damages. The data used by the analytical models are case study specific. However, the knowledge base of the IFMS is generic and can be used to identify a suitable flood management option for any area.

Some important characteristics of flooding in the study area are described in this section. Situated in the geographic centre of North America, the Red River originates in Minnesota and flows north (International Joint Commission 1997). It forms the boundary between North Dakota and Minnesota and enters Canada at Emerson, Manitoba. It continues northward to Lake Winnipeg. The Red River basin covers 116 500 km^2, exclusive of the Assiniboine River and its tributary the Souris, of which nearly 103 500 km^2 are in the United States and the remaining 13 000 km^2 are in Canada. The basin is remarkably flat. The slope of the river is on average less than 9.5 cm per kilometre. The basin is about 100 km across its widest. During the major floods the entire basin becomes the floodplain. The flatness of the terrain also means few natural large water storage sites are available. The Red River Basin has a subhumid to humid continental climate with moderately warm summers, cold winters, and rapid changes in daily weather patterns. On average the Red River Basin mean monthly temperature ranges from –15 to +20°C. Most major floods occur following heavy precipitation during the previous fall, hard and deep frost prior to snowfall, substantial snowfall, sudden thaws, heavy rainfall, or wet snow conditions during the spring breakup. The low absorptive capacity of the basin's clay soils is a contributing factor. The 1997 flood on the Red River (4587 m^3·s^{-1} at Winnipeg) was the largest flood since 1852. Around 2000 km^2 or about 5% of Manitoba's farmland was flooded. With 28 000 Manitobans evacuated (6000 from Winnipeg), the damages of 1997 flood are in the hundreds of millions of dollars (International Joint Commission 1997). The town of Ste. Agathe was completely flooded in 1997.

Fig. 5. User consultation with the system.



Sample consultation with the Intelligent Flood Management System

A sample consultation with the IFMS is listed in this section. First the questions are given, which IFMS will ask during consultation, followed by list of possible answers to choose from (Fig. 5). The answers in bold are the ones selected for this sample consultation. A number next to selected answer shows the confidence factor for that particular answer.

Which option best describes the proximity of the area to be protected from floods?

(*a*) **Along major river (100)**; (*b*) coastal area; (*c*) along multiple streams

What climatic factors are mainly responsible for flooding?

(*a*) Snow melt; (*b*) rainfall; (*c*) **combination (80)**

How do you categorize the size of area to be considered for flood protection?

(*a*) Large city; (*b*) medium size city; (*c*) **small town (100)**; (*d*) few houses

To have an estimate of what volume of flood we are dealing with, Choose a range of flood discharges that best describes the maximum recorded historic flood in the area? Values are in cubic metres per second.

(*a*) More than 5000; (*b*) **2000–5000 (90)**; (*c*)1000–2000; (*d*) less than 1000

How do you describe the frequency of floods causing damages in the area? Make a choice based on return period.

(*a*) One in hundred; (*b*) **one in fifty (60)**; (*c*) one in twenty; (*d*) one in ten; (*e*) more frequent

How do you describe the topography of study area?

(*a*) **Flat (100)**; (*b*) hilly; (*c*) moderate slope

Where the area considered for flood protection is located with respect to river?

(*a*) **Close (100)**; (*b*) far

How would you describe the changes in river course and (or) path?

(*a*) **Stable (80)**; (*b*) changes frequently

How would you describe the river-channel cross-section?

(*a*) Unstable; (*b*) stable uniform; (*c*) **stable nonuniform (70)**

What is the predominant soil type in the area considered for flood protection?

(*a*) Silt loam; (*b*) sand loam; (*c*) **clay loam (75)**

Based on geotechnical information, how would you describe the strata underlying the top soil?

(*a*) Hard rock; (*b*) soft rock; (*c*) **sand or silt (70)**; (*d*) clay

How would you describe the floods based on response time of catchment?

(*a*) Flash floods; (*b*) **slow floods (65)**

How would you describe the level of study area with respect to existing riverbanks?

(*a*) Lower; (*b*) **same level (100)**; (*c*) higher

From inspection of the project area, is there enough space available for placing a dyke between river and area to be protected from flood?

(*a*) **Yes (90)**; (*b*) no

Are there wetlands, marshlands or swamps in the watershed?

(*a*) Yes a lot; (*b*) some; (*c*) **not at all (95)**

From inspection of the project area, are there suitable objects (e.g., roads, high ground, hills) available to plug in both ends of floodwall?

(*a*) Yes; (*b*) **no (100)**

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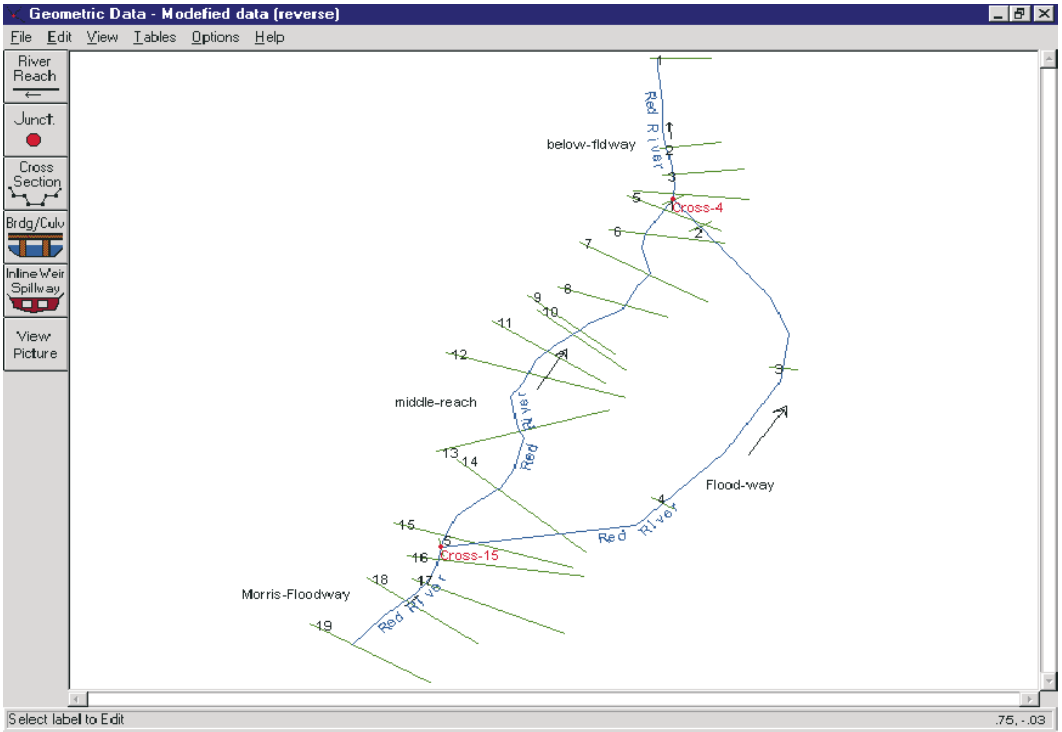
Fig. 6. Analyzing the floodway option in the HEC-RAS.



From inspection of the project area, considering number of structures close to river bank, would it be possible to acquire those buildings to place a dyke between river and area to be protected from floods?

(*a*) **yes (90)**; (*b*) no

Based on geotechnical information, considering the strata underlying the topsoil, is there a chance to encounter rock formation within excavation depth for floodway?

(*a*) Yes; (*b*) **no (90)**

Is there a large natural water body (reservoir, lake) available nearby, with a capacity to absorb floodwater?

(*a*) Yes; (*b*) **no (100)**

From inspection of the project area, is there enough slope difference available to drop the water from floodway back into the river without causing serious backwater effect?

(*a*) **Yes (100)**; (*b*) no

Are there any endangered animal or bird species in the project area?

(*a*) Yes; (*b*) **no (95)**

How would you describe the sedimentation process (silting and (or) scouring) in the River?

(*a*) Heavy; (*b*) medium; (*c*) **slight (70)**

To what extent is water logging, that is, ground water within the root zone, a problem in the watershed?

(*a*) Severe; (*b*) moderate; (*c*) **nil (95)**

From inspection of the project area, Is there a route available for the floodway, without building excessive infrastructure components like bridges, etc.?

(*a*) **Yes (90)**; (*b*) no

Is there any rare aquatic habitat (fish, etc.) in the river system?

(*a*) Yes; **(*b*) no (95)**

Is there any important historic site located in the area that will be affected by the project?

(*a*) Yes; **(*b*) no (100)**

What is the climate category of the watershed?

(*a*) **Subarctic (60)**; (*b*) marine westcoast; (*c*) humid subtropical; (*d*) Mediterranean; (*e*) rain forest; (*f*) desert

Choose a range of discharges that best represent the safe carrying capacity of river. Values are in cubic metres per second.

(*a*) More than 5000; **(*b*) 2000–5000 (75)**; (*c*) 1000–2000; (*d*) less than 1000

Considering the historic maximum-recorded flood and safe carrying capacity of river make a selection that best describes the additional capacity of river required to accommodate floods. Values are in percentage of existing capacity.

(*a*) More than 100; **(*b*) 50–100 (85)**; (*c*) 25–50; (*d*) less-than 25

What is the geology of the area?

(*a*) Permeable; **(*b*) semi-permeable (80)**; (*c*) impermeable

What is the land use and vegetation cover in the area considered for flood protection?

(*a*) Bare ground; **(*b*) crop land (90)**; (*c*) grass land; (*d*) forest cover

How do you rate the farmers' willingness to allow their land to be flooded (used as retention basin)? Use a scale of zero to ten where 10 is total acceptance and 0 is complete resistance?

2 (70)

Following the interactive session with the user the IFMS consults the knowledge base and makes preliminary recommendations.

- Build a Levee and (or) dyke CF (84%)
- Build a Floodway CF (60%)

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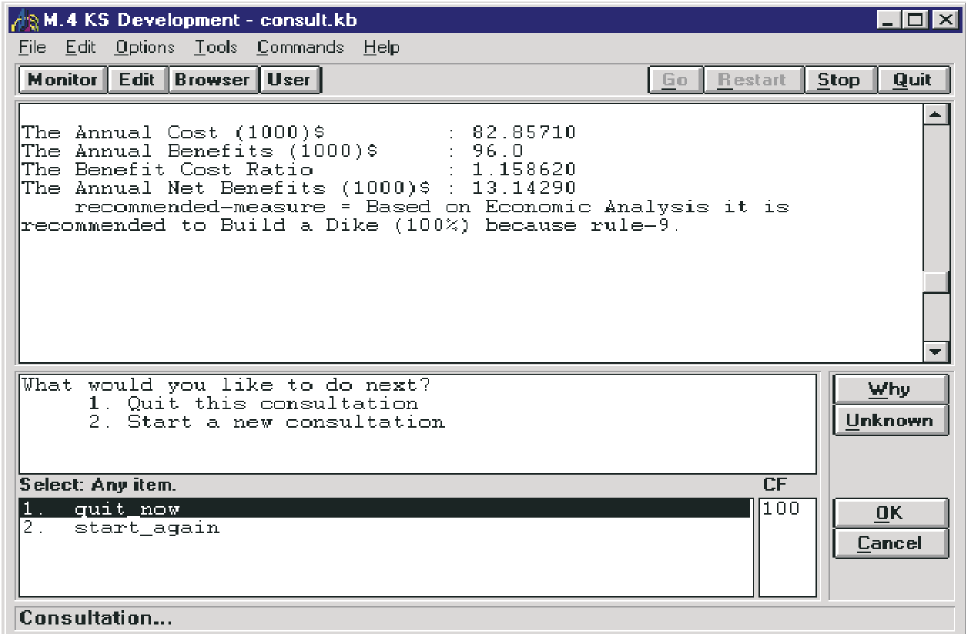
Fig. 7. Final recommendation of the Intelligent Flood Management System.



The two recommended options are analyzed using HEC-RAS and HEC-FDA. The analysis through HEC-RAS generates the modified surface water profiles due to the implementation of selected flood management option and also provides dimensions of the structure for reducing flood damages. The river setup and flow diversion through floodway as defined in HEC-RAS is shown in Fig. 6. Once technical feasibility of selected flood management option is evaluated through HEC-RAS the IFMS activates HEC-FDA to estimate reduction in flood damages by implementing a flood management plan. Analysis reveals that the flow diversion using a floodway is not able to reduce flood damages significantly. As the area is flat, there is not enough slope difference to accommodate the diverted water back in the river without causing serious backwater affects. This backwater is causing flood damages around the St. Agathe town.

Following the hydraulic and flood damage analysis IFMS continues the consultation and performs the benefit cost analysis to make a final recommendation. The benefit cost analysis is based on the analysis period of 50 years with the discount rate of 4.5%. The benefits and costs for each year in the analysis period are computed, discounted back to the present value and annualized to get the equivalent value over the analysis period (project life). The information collected by IFMS for economic analysis, through questions, is listed in the following section.

Which flood management option you want to choose for benefit cost analysis?

(*a*) **Levee**; (*b*) reservoir; (*c*) floodway; (*d*) floodwall; (*e*) retention basin; (*f*) dredging; (*g*) relocation of town; (*h*) unknown

What is the height of the dyke above ground surface in metres? Please enter value as real number (with decimal place), e.g., 1.0.

3.5

What is the top width of the dyke in metres? Please enter value as real number (with decimal place), e.g., 1.0.

3.66

What are the side slopes of the dyke? Enter the horizontal value against unit vertical value e.g., for 1V:4H you will enter 4. Please enter value as real number (with decimal place), e.g., 1.0

4.0

What is the total length of the dyke in metres? Please enter value as real number (with decimal place), e.g., 1.0

4400.0

What are the total damages (in 1000 of $) without project, calculated through HEC-FDA?

96.0

What is the cost of constructing a levee and (or) dyke per cubic metre of material used?

6.0

Based on the information provided by user, IFMS calculates benefit-cost ratio and net annual benefits and make final recommendation of a measure to reduce flood damages in the given area.

The Annual Cost (1000)$: 82.85

The Annual Benefits (1000)$: 96.0

The Benefit Cost Ratio: 1.16

The Annual Net Benefits (1000)$: 13.15

Based on economic analysis IFMS recommends building a dyke (Fig. 7).

Conclusions

The development of the flood management expert system (IFMS) has demonstrated the potential of integrating heuristic knowledge with analytical tools in facilitating the engineering planning and feasibility study work in the field of water resources. Coupling of artificial intelligence techniques with traditional simulation tools provides a viable al-

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ternative to deal with complex issues involved in selection of flood management option. The system is not only valuable as a training tool for "entry level" professionals, but can also act as an advisor to a decision maker with less exposure to flood management issues. It captures valuable expertise in the area of flood management and also allows for easy dissemination of that expertise to less experienced professionals. The codification of expertise has been done to ensure that, as new technology and knowledge in flood management options become available, they can easily be incorporated into the existing system. The salient benefits of Intelligent Flood Management System presented in this paper are:

- it captures and disseminates the valuable expertise in flood management area.
- it minimizes the time it takes to select the flood management option.
- it allows for the end-user the flexibility to try different criteria easily and efficiently (what-if analysis).
- the system is valuable as a training tool for entry-level professionals.
- it augments the experienced professionals as an interactive problem-solving and advisory system.

Environmental concerns related to different flood damage reduction measures have been addressed implicitly in the model. For example, the choice of a measure is influenced by the presence of aquatic life, endangered species, historic sites, wetlands, rain forest, etc, however, there are some environmental aspects that are not addressed in the current model for example impacts on river morphology, etc. The sedimentation process and river morphology may be considered by adding an appropriate modelling tool in the model base of the IFMS. Similarly, for benefit cost analysis, damages are calculated for infrastructure and buildings only. The cost of lost income due to flooding is not considered for the analysis; however, the model structure is flexible and more details can be added for analysis, if additional information is available.

Based on the performance of this system, the domain of flood management appears appropriate for the use of expert system technology. This project has also demonstrated that the model base (hydraulic analysis tool) is a very important part of the Intelligent Flood Management System. Currently work is in progress to integrate expert system with more sophisticated hydraulic and geographical analysis tools (two-dimensional hydrodynamic model and GIS) that will further increase benefits to the professionals dealing with flood management issues in complex topographic environments.

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