Knowledge-based systems and operational hydrology[1]

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Received January 25, 1990
Revised manuscript accepted June 6, 1990

Knowledge-based systems were brought to the attention of hydrologists almost a decade ago. The application of knowledge-based systems technology is natural and appropriate for the field of hydrology because it contains numerous procedures developed from theory, actual practice, and experience. The emphasis of the present paper is on demystifying knowledge-based systems of artificial intelligence. After a detailed review of the most important applications to the field of hydrology, the original concept for applying knowledge-based technology is presented. The discussion ends with the list of possible benefits from the application of knowledge-based technology. An expert system for the selection of a suitable method for flow measurement in open channels is used as a case study to illustrate the discussion in the paper. The system has been designed for potential use in Environment Canada.

Key words: expert system, water resources, hydrology, flow measurements.

Les hydrologistes ont pris conscience de l'existence de systèmes à base de connaissances il y a près d'une dizaine d'années. L'application de cette technologie est naturelle et convient au domaine de l'hydrologie parce qu'elle comporte de nombreuses procédures élaborées à partir de la théorie, de la pratique et de l'expérience. Cet article a pour principal objet de démystifier les systèmes à base de connaissances. Après un examen détaillé des plus importantes applications dans le domaine de l'hydrologie, le concept original d'application de la technologie à base de connaissances est présenté. La discussion se termine par une liste des avantages possibles de l'application de cette technologie. À titre d'exemple, un système expert pour sélectionner une méthode appropriée de mesure de l'écoulement à surface libre est utilisée comme étude de cas. Le système a été conçu en vue d'une utilisation possible par Environnement Canada.

Mots clés : système expert, ressources hydrauliques, hydrologie, mesures de l'écoulement.

[Traduit par la rédaction]

Can. J. Civ. Eng. **18**, 1–11 (1991)

Introduction

Hydrology is the study of water in all its forms and from all its origins to all its destinations on the earth (Bras 1990). The segments of the hydrology field this paper refers to are those pertinent to planning, design, and operation of engineering projects for the control and use of water, later called operational hydrology. Some professional discussions indicate that a gap still exists between the basic scientific facts in hydrology and their application for solving water management problems. A pertinent reason for this is the "scale difference" (Klemes 1983). The hydrologic scale is largely outside the human direct sensory comprehension, making us incapable of creating meaningful conceptualization. Another major reason is the very strong perception that hydrology is an appendage to hydraulics and hydraulic engineering (Yevjevich 1968).

The major objective of this paper is to bring to the attention of hydrologists the research within the field of artificial intelligence (AI). This is not because of the lack of "natural" intelligence, but with the honest belief that some of the principles of artificial intelligence may help in the application of existing hydrological concepts and act as an inspiration for development and new discoveries.

When an engineering problem is complex with much scientific uncertainty and high demand for judgement, AI seems to have something to offer. Knowledge-based engineering, called also expert systems or production systems, is a way to successfully build human expertise and some degree of intelligent judgement into decision-supporting software. Knowledge-based engineering is concerned with the representation of knowledge and with symbolic reasoning (Rolston 1988). One of the most distinguished characteristics of expert systems is their potential to deal with challenging real-world problems through the application of processes that try to mimic human judgement and scientific intuition. The most general definition of an expert system is that an expert system is a computer application for solving problems that would require extensive human expertise (Rolston 1988). To perform this task, expert system simulates the reasoning process by combining knowledge and search techniques (usually referred to as inferences). Rolston (1988) characterizes an ideal expert system as one that includes the following: (*i*) extensive specific knowledge from the field of interest; (*ii*) the application of search techniques; (*iii*) support for heuristic analysis; (*iv*) a limited capacity to infer "new knowledge" from existing knowledge; (*v*) symbolic processing; and (*vi*) an ability to explain its own reasoning.

Knowledge-based systems are finding their place in the field of water resources engineering with all the dangers of being oversold or missued. Recent publications by Ortolano and Steinemann (1987) and Simonovic and Savic (1989) present a survey of expert systems in environmental and water resources engineering, respectively. The following paragraph briefly summarizes the review of Simonovic and Savic (1989) because of its relevance to this paper.

The roles of water resources engineering and the science of hydrology have expanded beyond the traditional concepts of design and synthesis to a large multidisciplinary function serv-

NOTE: Written discussion of this paper is welcomed and will be received by the Editor until June 30, 1991 (address inside front cover).

[1]The National Research Council of Canada's Associate Committee on Hydrology identifies, solicits, and promotes the preparation of state-of-art papers on hydrological topics that require research. The Committee has requested the preparation of this report and is pleased to bring it to your attention. The views expressed are those of the author.

Printed in Canada / Imprimé au Canada

ing a broad social environment. Development, in time, of these fields follows three basic phases: (*i*) construction (emphasis on the design and construction); (*ii*) planning (emphasis on the examination of wider range of alternatives); and (*iii*) operation and maintenance (emphasis on the careful management of existing projects). This has created a pressing need for an overall review of engineering education with the main accent on its increased multidisciplinary character, supported by the available knowledge base and experience (Simonovic 1989*b*).

Since their first introduction to the field of water resources in the early 1980's, expert systems have been used in design, planning, and operation. The following contributions have been made to *water resources design*. HYSIZE and its simple modification HYSTOR are expert systems for determining the optimum layout for a particular hydroelectric site. These systems are able to rank alternatives in order of economic priority and to test the sensitivity of assumed variables (Dotan and Willer 1986). SISES is an expert system used for selecting an appropriate site for a specific use (Findikaki 1986). DMWW is an expert system for designing a municipal water well (K. Strzepek, University of Colorado, personal communication, 1988). The design process can be very complex and require much information on procedures and related knowledge (Russell 1989). The design is created in the first phase, and then modified in the second phase until the user feels comfortable. Experience and judgement play important roles in both phases, and this is why expert systems by exploiting experience may help, thereby, enhancing the design process.

Planning a water resources system is another field of expert systems application. RAISON is a system developed for the analysis of acid rain data. It is designed to examine the relationship between the terrain sensitivity index, which assesses susceptibility to acid rain deposition and possible deposition levels (Swayne and Fraser 1986). WATQUAS is an expert system for extracting knowledge from a large quantity of available historical water quality data and interpreting it in a useful form (Allen 1986). ARIANE is an intelligent decision-support tool for guiding the user through the multi-annual operation planning process in Hydro-Quebec (M. Hanscom, Hydro-Quebec, personal communication, 1988). RRA is an expert system for the administration of the acreage-limitation provision of the US Reclamation Reform Act of 1982. It provides a means for determining the status of the landholder, as well as the number of acres on which subsidized reclamation water can be received (K. Strzepek, University of Colorado, personal communication, 1988). SID, Seattle Water Department's integrated drought management expert system, is an expert system designed to evaluate and display information for drought-management planning. A linear programming model is used to generate optimal operating policies as a function of numerous past drought experiences. These policies are incorporated into an expert system and the user is required to identify the degree to which the current drought situation is similar to past events (Palmer and Tull 1987; Palmer and Holmes 1988).

For the *operation* of water resources systems, expert systems are slowly taking their place in practice. SID, an expert system already mentioned, is used for planning and operation of Seattle water distribution system during the drought. JOE is an expert system designed to aid in operations of the Jenpeg generating station in Manitoba. Manitoba Hydro's Jenpeg generating station is located near the outlet of Lake Winnipeg into the Nelson River system. The operation of Jenpeg during the freeze-up period is very complex, involving many judgemental calls, and has a major impact on the hydro power generation downstream (Raban 1989). EMMAES is an expert system built around the EMMA model used within Manitoba Hydro to plan the integrated operation of hydro and thermal power generation and tielines, as well as with maintenance considerations. The system is being designed for three purposes: (*i*) preparation of an annual budget; (*ii*) preparation of weekly schedules for releases, thermal and hydro power generation, and imports and exports of energy; and (*iii*) long-term planning that includes such tasks as evaluation of benefits from installing additional capacity, and examining particular operational conditions that may occur in the system (Nagy *et al.* 1989; Grahovac and Simonovic 1990).

The relative importance of expert systems to improvements in water resources projects has not yet been established, but some practical experience has already been documented (Nagy *et al.* 1989; Raban 1989; Palmer and Holmes 1988).

The following sections present definitions and approaches appropriate for the application of expert systems in the field of hydrology. These are followed by an review of present research. To illustrate their development, a case study of the use of an expert system for the selection of a suitable method for flow measurement in open channels is presented.

Knowledge-based systems and operational hydrology

Introduction to expert systems

Expert systems have been identified, by a number of authors, as a way to successfully apply AI techniques. Through the application of AI techniques, expert systems capture the basic knowledge required to assist an individual dealing with problems of varying complexity (Rolston 1988). Expert systems function as an assistant to an expert; a partner to an expert, or a replacement for part of an expert's knowledge. The following definition, derived by the author, seems appropriate for the field of water resources. *A water resources expert system is a computer application that assists in solving complicated water resources problems by incorporating engineering knowledge, principles of systems analysis, and experience, to provide aid in making engineering judgements and including intuition in the solution procedure* (Simonovic 1990; Simonovic and Savic 1989).

An expert system is a computer model composed of the following components: user interface; explanation subsystem; knowledge acquisition subsystem; knowledge base; and inference engine. Figure 1 illustrates the basic structure of an expert system. The *user interface* is responsible for requesting and translating user input, and presenting generated results to the user. The *explanation subsystem* is a very important part of an expert system, as it is responsible for explaining the reasoning behind any conclusion the system reaches. The *knowledge acquisition subsystem* is used to perform modifications to the knowledge base. The *knowledge base* contains the facts and rules associated with the application field. These rules can vary from being strictly procedural (well-defined and invariant) to heuristic (practices and procedures that are valuable but are incapable of proof and are gathered through experience). The *inference engine* controls the execution of the system and determines how to solve a particular problem. It uses the knowledge base to modify and expand the contents of working memory. In simple words, the inference engine is a search mechanism. Most expert systems are based on backward or forward search techniques. In backward chaining, the system begins with the desired goal and works towards the

requisite conditions to satisfy this goal; whereas forward chaining uses the known conditions and works towards the desired goal of the consultation.

Knowledge is the main source of an expert's ability to perform. Therefore, expert systems use a collection of the rules and facts to mimic expert behaviour related to problem solving. In an expert system, knowledge can be represented in the form of the rules, semantic nets, or frames. *Rules* are the simplest and most popular knowledge representation scheme. They are most appropriate when the domain knowledge results from associations between facts that have evolved through years of problem solving. Another approach is to represent domain knowledge through a network of nodes and arcs, known as a *semantic net.* The nodes represent the objects, concepts, or events; and the arcs represent the relationships between the nodes. Finally, the term *frame* refers to a special way of representing concepts and situations. Essentially, it is the same as a semantic net, in that it consists of a system of nodes and arcs. However, in the case of a frame representation all the properties of an object or concept are collected together at a node in a package. Frames and semantic nets are most helpful in grouping and structuring a large number of rules.

The tools for developing an expert system can be divided into three main classes; (*i*) general purpose languages; (*ii*) representational languages; and (*iii*) expert system building shells and environments. At the base level, an expert system can be written in any *program language*, such as FORTRAN, C, or PASCAL. Using these languages, the developer has complete flexibility, but the entire expert system structure must be developed and this is very costly in time and required resources. *General purpose representation languages*, such as PROLOG, SRL, or OPS5, require only organization and expression of the domain knowledge. As with the programming languages, a significant portion of the code necessary to produce an expert system must be written by the developer. *Expert system building shells and evironments* are packages that aid in the rapid prototyping of application expert systems. They usually provide one or more knowledge representations and inference mechanisms. Using these tools, the level of effort that must be applied to developing expert systems is greatly reduced, allowing the developer to focus on acquiring knowledge and refining the system behaviour.

Throughout the expert system literature, the knowledge acquisition phase is constantly being labelled as the "bottleneck" for expert system development. Typically, human experts are not used to describing everything they do in connection with solving a particular problem. There are a number of different approaches for gathering the information to be contained within the knowledge base of an expert system (Barlishen 1989). In the *engineering expert system approach* currently used at the University of Manitoba, the knowledge engineer is replaced with an engineer in the field of interest (domain) who has additional knowledge about expert system techniques. The existence of easy-to-use expert system tools, many for use on personal computers, makes engineering expert system approach very popular.

Operational hydrology

Hydrology is geophysical science with the mission to advance knowledge about an understanding of a physical system known as the hydrologic cycle (Klemes 1988), and a major component of hydraulic engineering. Basically, hydrology is divided into a number of disciplines (Chow *et al.* 1988), which

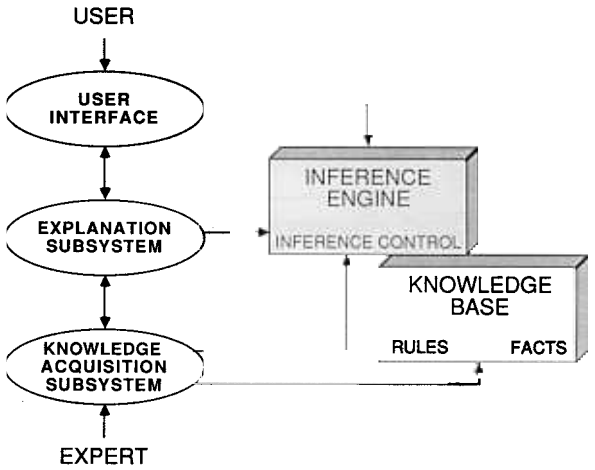

FIG. 1. Basic structure of a knowledge-based system

should not be studied independently. They are

(*i*) *Hydrological processes.* Hydrological processes transform the space and time distribution of water throughout the hydrological cycle. The motion of water is influenced by the numerous physical properties of the system like temperature, pressure, humidity, etc.

(*ii*) *Hydrological measurements.* Hydrological measurements are used to provide data on hydrological processes. These data are further used to improve the understanding of governing processes and to provide input for hydrological analyses and design.

(*iii*) *Hydrological analyses.* Hydrological analyses emphasize computational methods in hydrology for specific tasks such as rainfall-runoff modelling, flow routing, and analysis of extreme events. The major difference between computational methods is the way in which the analyses treat the space and time variability and the randomness of the hydrologic system behaviour.

(*iv*) *Hydrological design.* Hydrological design is the process of assessing the impact of hydrological events on water resource system and selecting values for the major system components so that it will perform adequately. Hydrological design may be used to develop plans for a new structure (spillway, flood control levee, etc.), or to develop management strategy for more efficient operation of an existing system (reservoir release policy, flood plain land-use mapping, etc.).

Operational hydrology is defined as a combination of hydrological measurements, analyses, and design. This field is advancing, leading to the need for radical specialization and, thus, the scarcity of expertise. The computer has encouraged the creation of more complicated models, and facilitated the collection and analysis of large amounts of data.

Problems in the field of hydrology can be categorized, according to Alim (1987), by their (*i*) inherent imprecision; (*ii*) the paucity and incompleteness of data; (*iii*) fuzzy decision processes; and (*iv*) heavy reliance on expert views (which are themselves vague and imprecise). In view of this, it is apparent that expert systems have a useful role in the conceptualization and development of operational hydrology. This role is illustrated in Fig. 2 and is based on the extended role of the computer through the design of hybrid decision support systems (Fedra *et al.* 1986; Simonovic 1989*a*). Expert system technology can be combined with computer graphics, systems analysis techniques (simulation and optimization), hydrologic expertise,

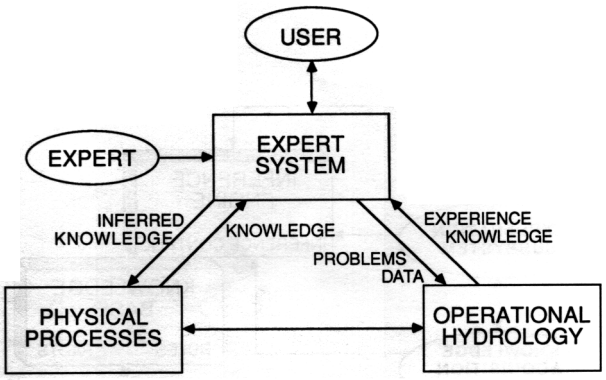

FIG. 2. Schematic presentation of the role of expert systems in hydrology.

and databases. The resulting hybrid system is envisioned to produce a computer application that can act as a mediator and translator between experts and other affected parties (public, politicians, etc.), or, in other words, science and policy. The computer application then becomes a "vehicle for communication, learning, and experimentation" (Fedra *et al.* 1986).

Possible roles of expert systems

The field of hydrology is complex and the importance of experience is obvious. Jenkins and Jowitt (1987) refer to the three most prominent problem-solving assets of an expert: *archived data*; *theoretical knowledge*; and *operational expertise*. Hydrological problem solving is achieved through a combined use of these three knowledge sources.

Data collection and analysis can be considered as a fairly structured aspect of a hydrologic problem-solving process. The questions requiring answers include (*i*) how representative are the data (temporally, spatially)? (*ii*) are the data correct, and how accurate are they? (*iii*) can any data be justifiably excluded? (*iv*) what is the statistical significance of the analysis results? and (*v*) what is the method of analysis?

An expert may often rely on what he has seen take place in the past to determine how representative the data are. Statistical techniques are usually employed as well to aid in judging the significance, accuracy, and reliability of the data. Much of the data problem component can be represented through a knowledge base that guides the user as to how to collect data, what tests to perform, and how to interpret the results of the analysis. Because there is a relatively little judgement involved, the expert's approach can be encoded and a user may be able to conduct the analysis with little input from the expert. Of course, there will be portions of the problem-solving process that are more experience oriented and here an expert system can make suggestions, but the final decision calls for an expert's judgement.

The second asset of an expert system is a storehouse of *theoretical knowledge*. This knowledge base in the field of hydrology usually includes scientific aspects of the physical system and its components; factors that may affect the data; and analytical or modelling techniques (modelling broadly defined includes the use of formulas, procedures accepted in practice, and complicated computer algorithms). An expert is capable of developing connections between the data available, theoretical knowledge, and operational experience. The choice of a modelling approach depends on knowledge of the available techniques. Experience is used to match the characteristics of a given problem with an appropriate analysis or modelling approach. An expert system can capture the logic behind the analysis or model process.

Operational experience is ultimately what distinguishes a novice problem solver from an expert. A hydrologist builds up his expertise incrementally through experience. This usually involves integrating new facts, adjusting reasoning procedures, adding and (or) deleting heuristics. Accomplishing this goal requires that the hydrologist note the range of failures and successes, and the differences and similarities between different cases. A hydrologist learns by doing and comparing. In this way new knowledge is generated. This knowledge should be stored away in heuristic form, so that it can be used later when a similar situation arises. Experts in hydrology demonstrate expertise during the acts of "clarifying the problem, suggesting the kinds of procedures to use, judging the reliability of facts, and deciding whether a solution is reasonable" (Duda and Shortliffe 1983). Therefore, expertise in hydrology is dependent on both experience and theoretical knowledge.

Current application of expert systems in hydrology

HYDRO

It is interesting that the first effort in applying AI methods in water resources engineering is related to hydrology. This work was initiated at the Stanford Research Institute in 1980 as an expansion of the PROSPECTOR knowledge-based system for mineral exploration. Project 1619 (Gashing *et al.* 1981) was named HYDRO. HYDRO was developed as a domain-independent reasoning mechanism and applied to aid in determining appropriate numerical values for various parameters that describe the physical characteristics of a watershed. The values computed by HYDRO serve as input to the Hydrocomp HSPF simulation program for evaluating various hydrological aspects of the region of interest (Grimsrud *et al.* 1979). The HYDRO system is intended to provide advice comparable to that of an expert hydrologist in selecting parameter values characteristic of the watershed under consideration. HYDRO, as being a domain-independent reasoning mechansism, is applicable to different problems. Knowledge about a specific topic (such as hydrology) is incorporated through a knowledge base about that topic.

HSPF program was developed by Hydrocomp, Inc., to simulate the physical processes by which precipitation is distributed through a watershed. HSPF program results include calculations of soil moisture and river levels in the watershed. To apply the HSPF system to a new watershed, the user must describe watershed characteristics in the form of numerical parameters which requires a considerable amount of hydrological expertise. HYDRO contains the hydrological expertise necessary to numerical parameters. Knowledge about specific parameters is encoded in a computational model representing observable features such as soil type, land use, vegetation, and geology. The approach has been tested by developing models for the 16 most important parameters used in the HSPF system. HYDRO incorporates 16 models for choosing values for the HSPF parameters: slope of overland flow; lower zone nominal storage; fraction of watershed in which vegetation is adjacent to perennial streams; upper zone nominal storage; infiltration parameter; interflow parameter; resistance to overland flow; fraction of flux that recharges deep groundwater; length of surface runoff; active groundwater recession constant; fraction of watershed in which vegetation can reach groundwater;

interception storage capacity; interflow recession constant; fraction of previous land segment covered by conifer forest; correction factor for variable groundwater recession rates; and index to deep-rooted vegetation.

During the consultation with HYDRO, the user answers questions about physical characteristics relevant for estimating the parameters. Because a high degree of uncertainty might be associated with many of these answers, the user is provided with a double scheme for expressing the degree of confidence in the given answers. The range of values may be specified when furnishing input data to HYDRO, or a degree of certainty may be associated with the user's answers. The authors of HYDRO have not reported the results of any validation studies. HYDRO was developed as a new "knowledge language" for expressing judgemental expertise about physical parameters required by the HSPF model. The work incorporated the development of a new knowledge representation scheme, user interface, inference mechanism, and explanation subsystem. Hardware and software requirements were not discussed. Since the system is a modification of PROSPECTOR, the symbolic manipulation computer language LISP may be used in its development. It is important to note the limitations of expert system technology related to possible fundamental problems in the model structure. If the model is "bad," the expert system developed to use the model will not have any value.

FLOOD ADVISOR

The next documented application of expert systems in hydrology is from 1985. FLOOD ADVISOR is a computer-based consultant whose goal is to provide interactive advice about flow estimation under five generalized situations (Fayegh 1985; Fayegh and Russell 1986). The basic motivation for the development of FLOOD ADVISOR is the use of different conventional computer programs in hydrology as a tool for solving well-defined flow estimation problems. According to the authors, the choice of estimation model (and consequent program) most suited to a given problem is not always apparent. The hydrologist must exercise good judgement and expertise in selecting an appropriate model.

The model selection problem is made quite trivial in FLOOD ADVISOR by narrowing down the model choice to five categories based on the type and quantity of available data. Five generalized cases used in FLOOD ADVISOR are (*i*) a long period of streamflow record is available at or in the vicinity of the location of interest; (*ii*) a long period of record is available on the stream of interest downstream or upstream of the location of interest; (*iii*) a short streamflow record is available on the stream of interest; (*iv*) no records are available on the stream of interest but records are available for nearby streams in the region of interest; and (*v*) no streamflow records are available for the region.

User consultation begins by providing a description of assumptions being used by the solution technique. Then the system invokes appropriate procedures to verify that each of the assumptions has been satisfied before proceeding. After verification, the user is informed of the most suitable computational model, and is given advice on how to use the recommended model properly. For cases (*i*) and (*ii*), FLOODS program (Russel 1982) is the final choice and the system calls and runs the program. For cases (*iii*) and (*iv*), regional frequency analysis is the final choice. The FLOOD ADVISOR does not incorporate a conventional program for regional analysis. For the final case the unit hydrograph approach is recommended. The FLOOD ADVISOR incorporates EPFFM, an interactive program written in FORTRAN, for this particular application. For the knowledge presentation, the frame structure has been used in the FLOOD ADVISOR. The system is developed in C language and has been implemented on a VAX minicomputer. Results of any validational study are not available probably because of the major shortcoming of only addressing five cases and limiting the system expertise to one important input parameter.

EXSRM

The next application is EXSRM, an expert system for snowmelt runoff modeling. The snowmelt runoff model (SRM) is a simulation model developed for forecasting daily streamflow in mountain basins where snowmelt is a major component of the annual water balance (Martinec 1975). Input data to the model are air temperature, precipitation, and snow cover area. Model parameters include a runoff coefficient, a degree-day factor, a recession coefficient, and a time lag. Each of these can be changed and modified by the user to adjust the simulation results. Typical applications require several iterations that involve changes in parameters. It is during these iterations that the experienced user works with a sequential plan based on accumulated knowledge whereas the inexperienced user will resort to a trial-and-error strategy.

EXSRM is the expert system incorporating SRM to assist an unfamiliar user to set up and run the simulation model (Engman *et al.* 1986, 1989). At the front end of EXSRM a series of help windows and menus assist the user in setting up the model and loading hydrologic and climatologic data. The different model variables can be easily edited. After the user enters certain basin-specific data, the system provides initial estimates of the SRM parameters and executes SRM's FORTRAN code. Typical applications usually require several iterations that involve changes in parameters. Depending on how good the initial simulations were and what types of discrepancies exist between the measured and simulated hydrographs, the user chooses different strategies to improve the simulations. EXSRM also makes heavy use of interactive graphics. Basin contours and overlays of a real snow cover can be displayed to the user. Graphical comparison of simulated and measured runoff enables the user to make immediate decisions regarding the adequacy of parameter values used.

The only shortcoming of the presented application is that EXSRM is being developed on a very expensive harware (SYMBOLIC 3670) using very expensive development environment (ART, automated reasoning tool). The system is partially operational and developers expect when completed, the system can be transferred to a smaller, less expensive microcomputer for use in the offices of water managers. Building an expert system around an existing simulation model allows inexperienced users to run the model in a relatively short time. Another advantage is that parts of the expert system can be implemented as they are completed without affecting the model operation.

SWMM

The last documented application is an expert system for calibrating EPA's storm water management model (SWMM) developed to simulate all aspects of the hydrologic cycle and water quality aspects (Environmental Protection Agency 1971). SWMM can be used in simulating surface runoff, transport through the drainage network, storage and treatment, and the

effects of the storm water in the receiving waters. It consists of several blocks: the runoff block for runoff estimation, the transport and extended transport block, and the receive block for mixing of the runoff in the receiving water body. An expert system has been developed for calibration of the hydrologic parameters of the runoff block of SWMM (Baffaut and Delleur 1989). Physical parameters incorporated in the model include the area of each subcatchment, the corresponding slope, and the diameter and length of the pipes in the storm sewer system. Hydrological parameters include the width of the subcatchments, Manning's coefficients, depression storages, and infiltration rates or coefficients. The expert system has been developed with three tasks in mind: (*i*) to select computational options and provide reasonable initial values of the input parameters; (*ii*) to evaluate the simulation results by comparison with observed hydrographs; and (*iii*) to modify the parameters to provide for a better fit between the simulated and the observed hydrograph. The expert system prompts and guides the user for the values of all hydrologic parameters that are required.

For the third task, to select the parameters that need adjustment and determine the required adjustment, the system needs objectives to interpret the results. The objectives used by the developers are close agreement of the volume of runoff, correct magnitude of runoff peaks, correct times of occurrence of peaks, and correct shapes of the hydrographs. Once the diagnosis has been reached on what to change, new values have to be proposed that will improve the fit of the predicted hydrographs. The system deducts the parameters that need to be adjusted and the direction of the adjustments, i.e., increase or decrease in value in order to reduce the difference between the prediction and observation below a tolerance level. This is done by using production rules (Baffaut and Delleur 1989, pp. 284–290). Not all of the parameters in the simulation are used for calibration. The authors have classified the parameters from the most sensitive to the least as follow: percentage of impervious area, characteristic width, Manning's coefficient, slope, depression storages, and infiltration parameters. Although the value of the percentage of impervious area can be estimated with precision from maps and aerial photographs, the authors found that it is the most sensitive parameter. Width, slope, and Manning's coefficient are combined within SWMM into one parameter. Appropriate changes in any of these three parameters cause equivalent variations of the results. The value of combined parameter has both a storage effect and a shape effect. Finally, the authors have found that the model output was sensitive to infiltration parameters only in certain cases.

An early version of the expert system was written in PROLOG. However, PROLOG language does not allow forward chaining. The current version of the expert system was developed in an expert system shell, KES, written in C. The use of a shell allowed the authors to concentrate on the development of rules without being concerned with the details of the inferencing procedure. The system has been tested on a number of watersheds (the Ross Ade in Indiana, St. Paul in Minnesota, Glen Ellyn in Illinois, and four watersheds in Florida). Results of this study indicate that the expert system yields calibration results which are comparable to and sometimes superior to the results obtained by a human expert.

As all these examples show hydrologic analysis can benefit from the integration of expert system methodologies by expanding the analysis in areas such as reasoning by analogy and by providing an interactive user support framework for system administration. A case study of a current application is described in detail in the next section.

Case study: an expert system for the selection of a method for flow measurement in open channels

In response to a demand for an increase in the quantity, diversity, and reliability of available data, Environment Canada is moving toward establishing an integrated environmental data acquisition network. A proposal to integrate hydrologic and engineering expertise, systems analysis, computer graphics, and expert system technology into a unique intelligent decision support system for surface water quantity data management has been prepared for and is being examined by Environment Canada (Simonovic 1989*a*). For the purpose of building an intelligent decision support system, the following objectives were identified: (*i*) classification of current procedures and practices employed by Environment Canada for surface water quantity data acquisition; (*ii*) determination of decision support modules to be used in the process of building a general system; (*iii*) completion of a comparative analysis of expert system tools which are candidates to be considered for application; (*iv*) building a decision support system in modular form; (*v*) testing, verifying, and improving the system; and (*vi*) training users in Environment Canada through the preparation of reports and user manuals, and through hands-on experience.

In the preliminary phase, six modules have been identified for the development (Simonovic 1989*a*), one of them being a real-time operations module. This module is the core of the intelligent decision support system and contains submodules linked together to support the operation of the existing gauging stations. The major division of advisory tools within this module will be in support of water level data aquisition, flow measurements, and equipment maintenance. Expert systems are planned for equipment selection, selection of measurement method, and the description of the appropriate procedures to follow during the measurement.

To illustrate the possible application of expert system technology, an expert system for measurement, method selection has been chosen for detailed discussion. The science of stream gauging has evolved through the years, mainly from the experiences and innovations of its practitioners. Stream gauging procedures are standardized on the national and international level. However, the selection of a suitable method for flow measurement is still a fairly complex process. The knowledge-based system which will be described is designed to aid the user in the selection process. A detailed presentation of the system is available in Simonovic (1990). The system has been designed for potential use in Environment Canada. The tool used in the development is VP-Expert (Paperback Software 1987).

The choice of method for flow measurement will depend on the characteristics of the site, particularly those affecting the stability and sensitivity of the stage-discharge relation. The expert system for flow measurement method selection uses criteria established by the International Organization for Standardization (ISO 1986). The expert system structure is divided into three major parts as illustrated in Fig. 3. In phase 1, the system checks all the important physical conditions and required data accuracy. The final recommendation of the first phase contains a number of methods applicable for site-specific conditions. The second system, phase 2, selects from

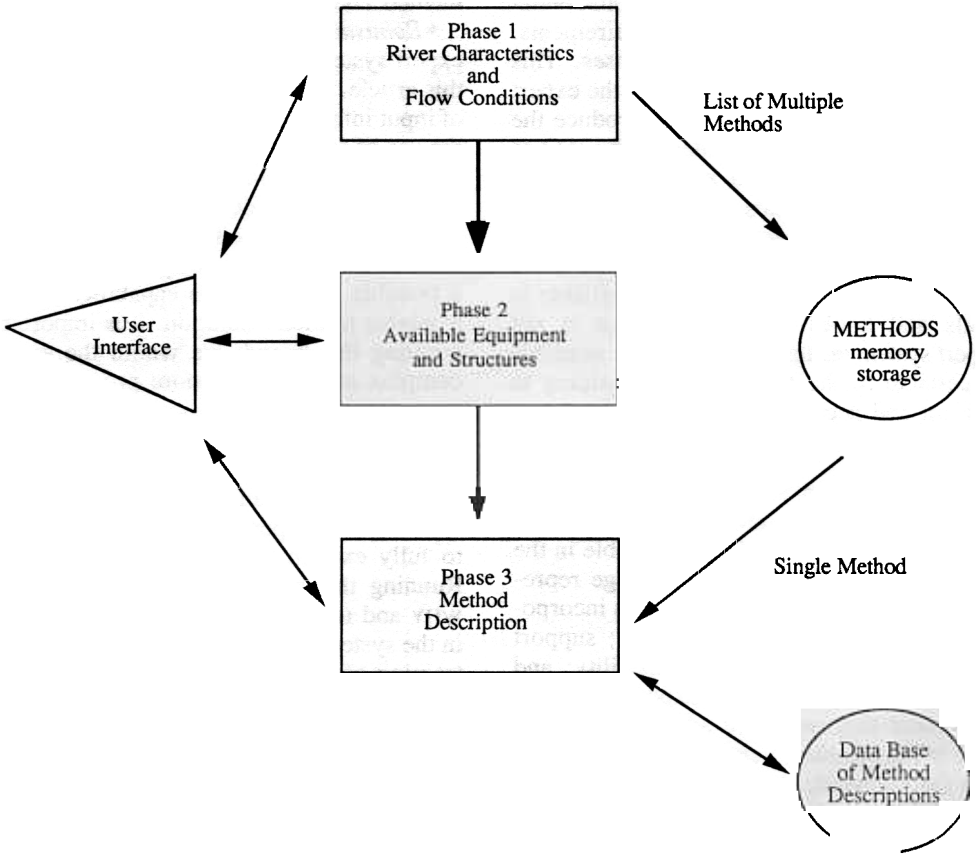

FIG. 3. Structure of the expert system for flow measurement method selection

the multiple choice provided by the first system, the most appropriate method considering the available equipment and measurement structures at the particular site. The third system, phase 3, contains detailed descriptions of available methods, and after final method selection the relevant description is available for the user. The description contains basic methodology, necessary theoretical background, equipment description, and the procedure to follow during the measurement.

Physical characteristics of the site play an important role in the selection of a suitable method for flow measurement. According to ISO (1986), the following characteristics are used: channel width; channel depth; velocity; sediment load; approach condition; and time factor. The set of physical conditions has been expanded with two more characteristics: minimum uncertainty and special conditions. Since the approach condition and time factor criteria contained complex descriptions, they were divided further. The approach condition has been divided into flow characteristics and channel characteristics. The time factor was also divided into two characteristics: measurement time and special time conditions. All 27 methods specified by ISO were characterized by the 10 criteria listed above. Every criterion has a specific description provided by ISO. The methods incorporated in the expert system as presented in detail by Simonovic (1990) are velocity area by wading; velocity area from bridge; velocity area from cable; velocity area from static boat; velocity area moving boat; velocity area by floats; slope area; ultrasonic; electromagnetic; continuous injection chemical dilution; sudden injection chemical dilution; sudden injection radioactive tracer dilution; continuous injection radioactive tracer dilution; cubature; sharp crest V-notch thin plate weir; rectangular suppressed thin plate sharp crest weir; rectangular sharp crest thin plate weir; sharp upstream edge broad crested weir; sharp downstream broad crested weir; triangular profile weir; flat V triangular profile weir; broad crested V-shape weir; rectangular flume; trapezoidal flume; U-shaped flume; rectangular channel free overalls; and non-rectangular channel free overalls.

Why an expert system?

Expertise in the selection of the most suitable stream gauging method for a particular site under consideration is fairly complex, and much of the decision process is based on a combination of field and theoretical experience. This system will provide rational and consistent advice needed to meet the highly varied requirements of a national service.

By whom and how will the expert system be used?

The system has been designed for potential use by Environment Canada. The system can help in three ways: (*i*) provided physical conditions at the measurement site, it recommends a list of gauging methods which match service needs and policies; (*ii*) based on the recommended list and additional information about available equipment and structures at the measurement site, the system proposes the best suited method; and (*iii*) for the recommended method, detailed instructions are provided to help the user in preparing for measurements. This is the operational purpose of the system under consideration.

A second use of the system is for planning purposes. The users are Environment Canada specialists responsible for data acquisition and manpower distribution. By applying the system to all measurement sites within the region of responsibility, the

specialists obtain background information and recommendations for assessing equipment and manpower requirements. The third use of the system is for training purposes. This involves using the system and special cababilities of the expert system tool, used for its design. The system can produce the information on selection procedures recommended by ISO as well as detailed information on how to apply a particular method. Using available characteristics of the development tool (HELP, WHY, and HOW), user is able to trace the "reasoning" process used in making the recommendation and learn from it. Note that system knowledge will be available in the form of manuals and books. New knowledge is not provided, but the expert system technology makes this available knowledge more accessible to the users, thereby helping to provide a more efficient and accurate service.

Expert system development

Specific requirements are given serious consideration in selecting the tools for expert system development. Since the problem is well defined, and the knowledge is available in the form of ISO recommendations, rule-based knowledge representation has been selected. Other tool characteristics incorporated in development are good selection cabability; support capability; integration capability; robustness capability; and teaching capability. It was concluded that VP-Expert rule-based expert system development tool would be adequate for such applications. The tool is PC oriented, very flexible, and menu driven. In VP-Expert the knowledge base contains three basic elements: (*i*) the ACTIONS block; (*ii*) rules; and (*iii*) statements.

•*Selection capability.* The selection of the most suitable flow measurement methods depends on several factors discussed earlier in the paper. This knowledge has been stated in the form of rules. The FIND statement is used in the VP-Expert knowledge base to identify variables whose value is needed to successfully complete the selection process.

•*Support capability.* If the expert system requires some optimization, simulation, regression, or other analysis, support from external programs is needed. The CALL, BCALL, and CCALL clauses let VP-Expert run external programs. This capability is utilized only once within this example. When the measurement method is selected and the user requires a detailed description, a third-party program named LIST is called to read and display the content of the particular text file on the screen. Another support aspect, interaction with database files created using other software packages, was very important in the development of an expert system for flow measurement method selection. In our case database files are used as information basis. The database files (text files) containing descriptions of the measurement methods and instructions for measurements are accessed after a recommendation has been provided indicating which method seems to be best suited for the particular site.

•*Integration capability.* As illustrated in Fig. 3, the expert system for flow measurement method selection has modular structure. The modular structure requires that the different knowledge bases to be linked together. In VP-Expert, the CHAIN, LOADFACTS, and SAVEFACTS clauses link or chain knowledge bases together. The determination of the most suitable flow measurement method requires the use of this VP-Expert option to link the three modules: phase 1, which diagnoses proper flow measurement method; phase 2, which matches the measurement method with the available structure at the particular site; and phase 3, which provides the description of the method and procedure to follow during the measurement.

•*Robustness capability.* This is a new characteristic of the expert systems tested and used within the system described in this article. The ability of the expert system to check the logic of input information is incorporated in all three phases through the use of forward chaining and WHENEVER rules. The system permanently monitors the user's answers and when a conflicting answer is provided a warning is issued that the system will not be able to find the solution. A conflicting answer is the one that, in combination with previous answers, does not lead to a possible solution. This capability is used to prevent a "no available method" solution. It is important to note that incorporating this knowledge within the expert system was very complex and required more programming than the selection procedure.

•*Teaching capability.* Considering the third purpose of the expert system, discussed earlier, the explanation capability was one of the main issues in the system development. Three different VP-Expert features, HELP, WHY, and HOW, are used to fully explain the line of reasoning of the expert system. Running the system for different site conditions and using WHY and HOW can provide the basic knowledge incorporated in the system. This process is recommended for use during the training of field personnel.

Consultation session

The first phase of the SFMAS expert system contains two parts: (*i*) information input and (*ii*) method selection. The input portion addresses the questions of the physical characteristics and flow conditions of the channel. An example of consultation is included in the Appendix. The user is led through a series of questions, in order that the system can logically define the situation. Once all the information is entered into the system, the RULE section is consulted to make method selections. The second phase of the SFMAS expert system is used to establish one single method recommendation. In the phase 2 knowledge base, the user is prompted to enter the type of measurement equipment or structure that will be used to measure the flow in the channel previously characterized in phase 1. Phase 2 was designed to request information in a different fashion than was used in the previous knowledge base. It is designed to ask only specific questions, depending on the users previous responses. The phase 3 knowledge base does not require any user responses. It simply reads the final method recommendation from the file and then consults a set of RULES which determines the name of a text file to be viewed. The VPX statement, CCALL, is used to execute an executable program, LIST.COM, which displays the text file on the output monitor. Once the list program is terminated by the user, SFMAS returns to phase 3. The user can then exit SFMAS, or begin a new consultation with phase 1.

Conclusions and recommendations

This paper has two objectives: (*i*) to describe the present state of expert systems research and development and (*ii*) to analyze its possible use in the field of hydrology. A detailed review of existing applications provided the basis for discussion. The expert system for selecting a method of flow measurement in open channels was used as an example.

Based on the hydrologic expert systems review, the following major conclusions have been reached: (*i*) expert systems have a significant role to play in the field of hydrology; (*ii*) successful applications are demonstrable; (*iii*) further development is necessary to explore all the benefits, and to test and verify

existing applications; and (*iv*) present research is focused on the development and application of expert system technology, as it directly relates to the use of hydrologic models (HYDRO, EXSRM, SWMM) and to some operational tasks (SFMC). It is obvious that the field of hydrology offers much more opportunity for the application of expert systems. Tasks requiring collecting and analyzing hydrological data offer considerable potential for expert system application. Another application is the extension of existing simulation models, using reasoning by analogy, and providing intelligent decision support framework for their application. Finally, the opportunity exists to use expert system technology to bridge gaps between scientific and operational aspects of hydrology. The idea is to learn from the expert system development process "how little" we really know and to use the present knowledge and existing techniques as a basis for further development and for new discoveries.

Realization of these possibilities requires (*i*) strong commitment from governmental and other agencies responsible for the development and application of hydrological science; (*ii*) more efficient communication of research needs and results between the users and research institutions (universities and institutes); and (*iii*) more efficient decision making in respect to providing financial support for the research in the application of hydrological science.

Acknowledgements

The work presented in this paper was supported by grants from the Natural Sciences and Engineering Research Council of Canada and Manitoba Hydro. Help and cooperation of Mr. Klaus Wiebe from Environment Canada was valuable (Head of Hydrometric Methods Section, Water Resources Branch). Programming of the expert system for flow measurement method selection has been done by my student Glen Douglas. All this support is gratefully acknowledged. Two anonymous reviewers have provided valuable suggestions which have improved the original manuscript of this paper.

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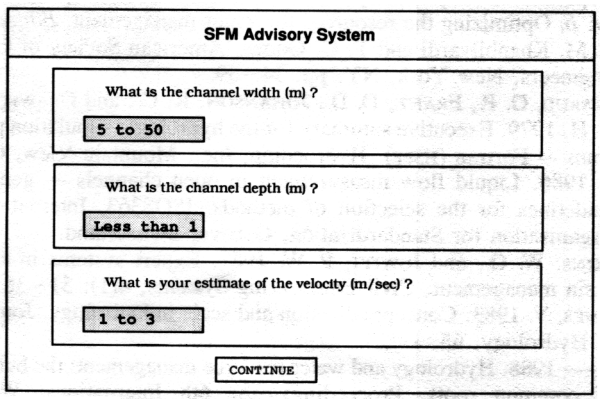
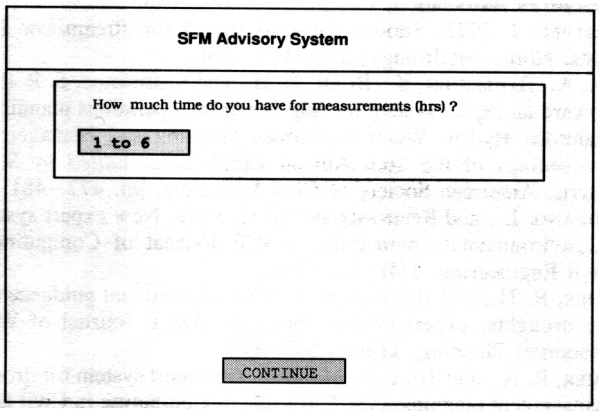
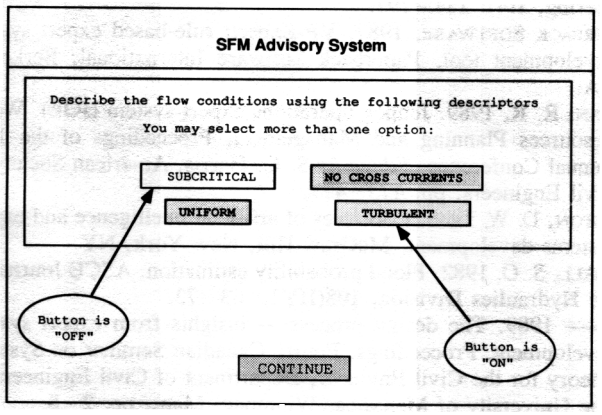
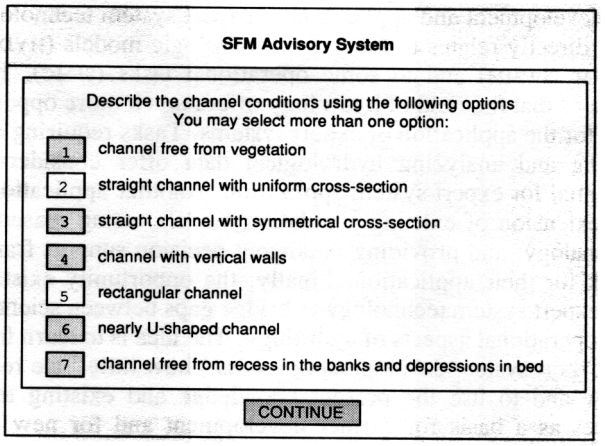
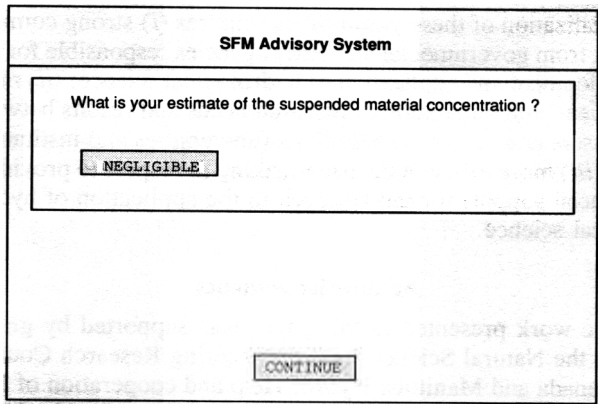
Appendix. Example of a SFMAS consultation session

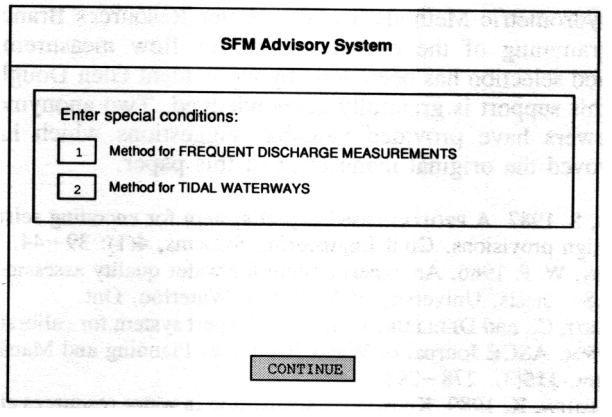


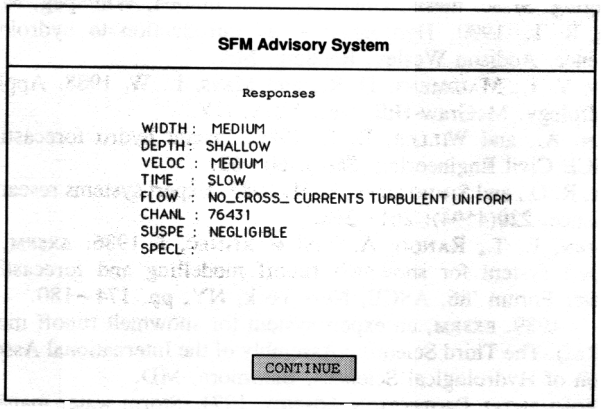












SFM Advisory System

Methods Available :

VELOCITY_AREA--WADING
CHEM_TRACER--SUDDEN_INJECTION
CHEM_TRACER--CONTINUOUS_INJECTION
RADIOACTIVE_TRACER--SUDDEN_INJECTION
RADIOACTIVE_TRACER--CONT_INJECTION
CUBATURE_METHOD

CONTINUE

SFM Advisory System

What TYPE OF TRACER will be used ?

CHEMICAL

CONTINUE

RESPONSES

Device : INSTRUMENT

Instrument : TRACERS

SFM Advisory System

Suitable method(s) selected from PHASE 1

VELOCITY_AREA--WADING
CHEM_TRACER--SUDDEN_INJECTION
CHEM_TRACER--CONTINUOUS_INJECTION
RADIOACTIVE_TRACER--SUDDEN_INJECTION
RADIOACTIVE_TRACER--CONT_INJECTION
CUBATURE_METHOD

CONTINUE

SFM Advisory System

What TYPE OF INJECTION will be used with the TRACER ?

SUDDEN

CONTINUE

RESPONSES

Device : INSTRUMENT

Instrument : TRACERS

Tracer : CHEMICAL

SFM Advisory System

What kind of MEASUREMENT DEVICE will be used ?

INSTRUMENT

CONTINUE

SFM Advisory System

Method Recommendation

CHEMICAL_TRACER--SUDDEN_INJECTION

CONTINUE

SFM Advisory System

What kind of INSTRUMENT will be used ?

TRACERS

CONTINUE

RESPONSES

Device : INSTRUMENT

SFM Advisory System

What would you like to do next ?

PHASE 1	Start SFMAS again,	Part 1 . . . RIVER INFORMATION
PHASE 1	Repeat this session,	Part 2 . . . EQUIPMENT INFORMATION
PHASE 1	Continue SFMAS	Part 3 . . . METHOD DESCRIPTION
QUIT	QUIT SFMAS	