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Intelligent Manipulation and Calibration of Parameters for Hydrological Models

W. Chen[1] and K.W. Chau[2]*
[1]Third Institute of Oceanography, State Oceanic Administration, 178, Daxue Road, Xiamen 361005, Fujian, People's Republic of China
[2]Department of Civil & Structural Engineering, Hong Kong Polytechnic University, Hunghom, Kowloon, Hong Kong
*Corresponding author
(Email: cekwchau@polyu.edu.hk)

Abstract
It would be greatly helpful to neophytes if knowledge-based system technology incorporating the existing heuristic knowledge about model manipulation can be integrated into the hydrological system. This paper delineates the development and implementation of a prototype knowledge-based system for model manipulation for hydrological processes by employing an expert system shell. The architecture and main components of the system are presented. The prototype system is verified and validated in two real watershed applications. It helps inexperienced users of hydrological models make the right choice of the appropriate model and/or direct the users throughout the calibration process.

Keywords: hydrological models; model manipulation; knowledge-based system

Biographical notes

W. Chen is currently working in Third Institute of Oceanography, State Oceanic Administration of People's Republic of China. He received his Bachelor of Science in Fluid Mechanics from the Department of Mechanics, Zhejiang University, China in 1982. He previously worked as Research Assistant in Department of Civil and Structural Engineering of The Hong Kong Polytechnic University. His major research interests include numerical simulation of tidal current, water particle movement, pollutant diffusion and oil drift.

Dr. K.W. Chau is currently an Associate Professor in the Department of Civil and Structural Engineering of The Hong Kong Polytechnic University. He received both his BSc(Eng) and MPhil in Civil Engineering from the Department of Civil Engineering, The University of Hong Kong, Hong Kong. He received his PhD in Civil engineering from the Department of Civil Engineering, The University of Queensland, Australia. He is very active in undertaking research works and the scope of his research interest is very broad, covering numerical flow modeling, water quality modeling, hydrological modeling, knowledge-based system development and knowledge management.

Introduction

Over the past few decades, a diversity of models have become available for solving various hydrology and water resources problems (Abbott *et al.*, 1986; Chau and Lee, 1991; Cheng *et al.*, 2002; Connolly *et al.*, 1997; Huber and Dickinson, 1988; Lacroix *et al.*, 2002; Lal, 1998; Zhao, 1992). So far, the emphasis has been placed on algorithmic procedures whilst user-friendliness and knowledge transfers in interpretation are often lacking. It should be noted however, that the effective use of computer models requires an adopted model to be commensurate with: the nature of problems being studied; the available data; accuracy requirement; and, computer environment.

Experienced hydrological modelers can determine a model failure based on a heuristic judgment of the key environmental watershed surface and subsurface behavior under consideration and/or the simulated runoff or pollution results. However, many others do not possess the requisite knowledge to glean their input data on physiographic, climatic, and soil physical characteristics of the catchment such as precipitation, evapotranspiration, soil moisture condition, contamination, as well as to build algorithmic hydrological models and to evaluate their results. Owing to the large number of them now available, selection of an appropriate one, and its application to a site-specific problem, is becoming increasingly difficult for novice users in particular. They have no thorough knowledge of the underlying assumptions and principles on which the various hydrological models are based: the time frame for which their application is most appropriate; physical, chemical and biogeochemical processes which are considered; requirement on hydrogeological data; etc. Even if they are provided with high-performance software, they are often at a loss and cannot ascertain whether or not their modeling efforts have been successful during the simulation. Large gaps exist between model developers and practitioners which result in under-utilization of hydrological models. Of course, it is preferable that only experts should use hydrological models for engineering design. However, before they can become experts, training as well as practical experience are required. At this juncture, an expert system tool can furnish such an opportunity for these neophytes or experts-to-be to acquire the requisite training and guidance for practical use of these models. Thus, it is desirable to introduce expertise in the system with a view to helping neophytes to select and manipulate hydrological models.

Computer-aided decision-making for natural resources have advanced a great deal in recent years. Tools have been designed to act as intelligent front-ends for supporting the handling of simulation models for specific water resources problems (Abbott, 1993). Chau and Zhang (1995) implemented an expert system for flow routing in a river network. Jamieson and Fedra (1996) reported on a decision-support system for river basin planning. Bobba *et al.* (2000) incorporated intelligent environmental models to different hydrological systems. Cheng and Chau KW (2001) developed a fuzzy iteration methodology for reservoir flood control operation. Chau (2002) calibrated flow and water quality modeling using genetic algorithm. Cheng and Chau (2002) implemented a three-person multi-objective conflict decision in reservoir flood control. Madsen *et al.* (2002) compared different automated strategies for calibration of rainfall-runoff models. Ahmed *et al.* (2003) developed and verified of a decision support system for the selection of optimum water reuse schemes. Armstrong and Martz (2003) examined the scale effects of aggregation on square-grid digital elevation models. Yet, these studies, being restricted in scope, represent only a small part of the domain knowledge. Moreover, they do not address the core problem of knowledge elicitation and transfer.

The current development in modeling water resources is at such a stage that abundant heuristic knowledge relating the likely typical range of geological, physical, chemical, and biological parameters to outcomes and different techniques that can enhance modeling accuracy and/or efficiency are available. A knowledge-based system approach, which is characteristically heuristic, flexible and transparent to human users, could furnish intelligent model manipulation and calibration of these hydrogeological parameters. Moreover, literature on the incorporation of knowledge-based system technology into manipulation of water resources models is still scarce to date. Chau (2003) developed an expert system for manipulation of numerical coastal flow and water quality models. However, the domain knowledge is completely different. Coastal flow and water quality models are generally more specific and involve highly algorithmic computations whilst hydrological models cover a wider scope of processes, including rainfall-runoff, climate change, watershed acidification, surface and subsurface contaminant, etc. Whilst the system architecture from that expert system can be adapted, no common components can be made use.

In this paper, a prototype knowledge-based system for manipulation of hydrological models is developed and implemented by employing an expert system shell, Visual Rule Studio, as an ActiveX Designer under Microsoft Visual Basic environment. This expert system helps the user chose the right model first, and then guide the user through the calibration process.

Manipulation of water resources modeling

Water resources modeling can be denoted as a process that: transforms knowledge regarding physical hydrological phenomena into a primitive code; simulates for the behaviors; and, translates the numerical results back to a format comprehensible to people (Abbott, 1993). Whilst the processing from comprehensible knowledge to primitive information is the selection of an appropriate hydrological model and associated parameters, the processing from information to knowledge includes the post-processing of model outputs. Selection and manipulation of an appropriate model to solve a practical hydrological problem is a specialized task, entailing detailed knowledge of the applications and limitations of the model. In general, the process on manipulation of modeling is time-consuming, which depends highly on the experience of the hydrological modeler. Extensive and detailed expertise knowledge is entailed to distinguish the special features and limitations of these individual hydrological models for application in a specific situation. Experienced hydrological modelers may use the heuristic knowledge unconsciously, to undertake manipulation procedure of modeling.

It should be noted that hydrological experts tend to maintain certain basic choice of modeling unchanged in the manipulation process. For instance, when conceptually based lumped models (Huber and Dickinson 1988) were popular, the discretization method and algorithm scheme in many models were kept unchanged, and only some coefficients were altered. Recently, with a view to incorporating spatial variation of watershed characteristics in the modeling process, researchers frequently used physically-based distributed models (Connolly *et al.*, 1997). Whilst the co-ordinate system, grid setting, temporal and spatial numerical scheme were all maintained, only certain interactions amongst various processes were maneuvered. These examples reflect that human intelligence uses existing knowledge to reduce the number of choices in order to raise the effectiveness of modeling manipulation. In order not to get lost in the manipulation direction, modelers restrict themselves to alter at most one or two parameters simultaneously in the manipulation procedure.

Knowledge acquisition

In order to prepare for the development of this knowledge-based system, knowledge on modeling manipulation has been gleaned mainly from a thorough literature review and interviews with expert hydrological modelers. Heuristic and/or empirical relationships regarding application and selection of hydrological models have been reviewed and captured in the form of production rules. Experts' interviews have been carried out to complete the insufficient knowledge on specific points as well as to validate all the rules. It should be noted that no standard steps are at present generally recognized and model manipulation may vary from expert to expert. Nevertheless, this prototype knowledge-based system can be further developed and updated through frequent usage and feedback from users. The transparency of rules and knowledge bases, which facilitates addition of new knowledge, can be seen to be a significant advantage of a knowledge-based system approach.

The prototype knowledge-based system

Expert system shell

In this study, a latest hybrid expert system shell which combines the advantage of both the object-oriented programming paradigm and production rules is used. Under this programming environment, all the usual control objects are provided: list box; option button; command button; textbox; and, check box. The user-friendliness of the interface is another important deciding factor in its adoption. Furthermore, this software allows external programs coded in other traditional programming languages to be linked and executed directly.

System architecture

The architecture of the prototype system is shown in Figure 1. It is comprised of several key modules: knowledge base; inference mechanism; executable hydrological models; database; and, user interface. The integration amongst these modules is effected through add-in tools. The well-organized structure and architecture of this expert system can enhance the programming for complex problems and their future extension. Its modularity enables easy incremental development of new and updated knowledge. At the present moment, the scope of this prototype is so far limited to some commonly used yet widely different hydrological models. Although the prototype knowledge-based system does not address all different types of hydrological models, it is intended to serve as an initial model and will be easily extended to incorporate as many types of hydrological models as possible.

Knowledge base

This module is the central core of a typical knowledge-based system. In this knowledge base, knowledge on selection and manipulation of hydrological models is stored, incorporating inference rules relating to the manipulation direction and the user's requirements. The knowledge base represents on: how to select a specific hydrological model in response to user requirements; how to replace a type of hydrological model by another if none of the them suit all requirements; and, how to set a confidence level for those hydrological models which do not completely suit the user requirements yet can still be used in the circumstance.

This knowledge base is sub-divided into several sub-bases: relation base; selection base; question base; and, rule base. The relation base delineates the structure of the relation tree of model parameters which represents the related factors of the parameter. Figure 2 shows part of the relation tree of model parameters. The selection base describes the structure of a selection tree, with each node representing a parameter and its subsequent branches representing its possible selections. Both the relation tree and the selection tree are tailored to assist in the knowledge representation of the parameter relations and options. In the questioning process, all the related factors of the parameter are retrieved through searching the relation tree. In the selection process, all the feasible options of each parameter are acquired from the selection tree. Questions for guiding the user to input the problem specifications are stored in the question base, through factors related to the parameter. The questions will be dynamic and the ensuing questions will depend on the responses made by the user on the previous questions. In this regard, the relation base will be involved to furnish the requisite relevant parameters with order of priority. The question with the highest priority, together with the possible set of answers, is then deduced. The user's response on the question will be feedback to the system. After that, the inference engine will drive the selection decision process forward until the final solution is arrived.

The rule base stores inference rules from the user's specification to the parameter selection. Under the programming environment of the expert system shell, production rules can be written in the Production Rule Language format, together with an object-oriented paradigm. Fuzzy processes are employed to estimate whether or not the specifications of physical conditions and/or user's demands on modeling accuracy and/or efficiency match with the selection of parameters. The following is a typical example of production rule incorporating the fuzzy description:

> RULE to manipulate numerical method of model: 3 of 10
> IF the hydrological process under consideration is flow routing AND
>   the length of the river is long AND
>   the slope of the river bed is gentle AND
>   tidal flat is involved AND
>   demand on accuracy is very high
> THEN a 1-dimensional finite difference method is selected with a confidence factor of 80.

In this rule, the IF statement represents the requirements entailed for the adoption of a 1-dimensional finite difference method. For this conclusion to be fulfilled and hence this rule to be fired, the following conditions should be fulfilled: the hydrological process under consideration is flow routing; the length of the river is long; the slope of the river bed is gentle; tidal flat is involved; and, the demand for accuracy should be very high. Under these premises, the THEN clause of the rule furnishes the conclusion that a 1-dimensional finite difference method is selected with a confidence factor of 80.

The confidence factor, with range from 0 to 100, is employed as the controlling factor to monitor the inference process for model manipulation for each possible parameter. The confidence factors, representing the degree of confidence with which the statement is known, were set by experts based on heuristic and experience. At the end of the inference process, the prototype system computes a confidence value for each model available in the system. If the newly computed confidence level of a model falls below the user specified threshold value, that model will not be further considered.

Under the prototype system, all the parameters are classified into six main types on the basis of important branches in hydrological modeling research: method; scheme; geometry; hydrograph or water stage boundary condition; initial discharge, stage or concentration conditions; and, hydrological, geochemical or physical process. Table 1 shows the details of the classification system. A major advantage of this kind of classification system is that the formulation and search of a knowledge and rule base can be facilitated. It should be noted that the driving force for selection and calibration of hydrological model mainly comes from the needs of its user. Thus, the selection of modeling parameters is expressed in terms of four major aspects: the problem specifications; the user's purpose; the user's modeling experience; and, the user's expected model results.

In the intelligent system, the parameters allowed for modification are represented in the form of a parameter tree. The tree is managed and controlled by the rules in the knowledge base. It has a full skeleton during modeling selection. After users have specified their preference to accuracy and/or efficiency, some branches will be cut off and a set of suggested parameters will be listed in the interface for further modification. After the manipulation process is completed, the tree skeleton becomes a solid tree with fixed branches. Figure 3 shows an example of the tree formation in the manipulation process.

Inference mechanism

The key role of the inference mechanism is to drive the decision tree for exploration of the most feasible solution that matches the problem specifications. It governs the sequence of questions when it interrogates the rules in response to answers by the user. The confidence factor is the key variable used by the inference engine to drive the selection of various parameters for the models. Initially, a default value of 50 is set as the confidence factors of all parameter selection, representing a half-and-half chance for it to proceed successfully. In fact, the inference mechanism is designed so as to search and match for the path, which can lead to increasing confidence factors of parameter selection. After the user has selected a model prototype and has specified his preference for model accuracy and/or efficiency, the inference mechanism will use a mixed strategy of backward chaining and forward chaining to give the suggested selection of model and parameters.

Forward chaining is used to search from the user's response to a question in order to modify the decision tree and to execute the numerical process whilst backward chaining is used to determine the requisite parameters and then to find the prevailing question to the user. This inference process occurs in a cyclical manner until the preset threshold of error margin is fulfilled. The inference mechanism first searches the decision tree to determine the parameter, which will have highest potential confidence to model selection. The relation base enters the scene to determine the problem specifications or physical conditions related to that particular parameter. After that, the question base is searched to prompt the question together with the feasible answers for the user to provide the problem specifications. The rule base is involved to match the parameter and the specification, to cut away the impossible tree branches of the decision tree, to compute the confidence factors for a variety of selection options, and to recommend the one with the highest confidence factor. The new decision tree and the newly selected parameters are recorded. A new cycle of inferencing process is repeated until the entire decision tree is filled up. Figure 4 represents the overall flowchart showing linkages amongst various sub-bases in knowledge base and inference mechanism.

Executable models

The hydrological models currently incorporated in this prototype expert system include several commonly used lumped models, acidification models, saturated-unsaturated transport models, water quality models, addressing various hydrological and geochemical processes including rainfall-runoff, overland and channel flow, subsurface flow, contaminant transport, etc. These models are run-type versions of the independent executable programs in object linking and embedding automation format and thus their embedded source codes can be written in any traditional programming languages.

It is noted that different parameters are often named differently in different models. In order to address this problem, the system incorporates procedures to determine parameter values using model-independent physical data describing the watersheds. The integrated system is accompanied by a usage wizard, which provides assistance and guidance for use and direction for non-expert users. After the selection of the modeling parameters for setting the properties of the appropriate hydrological model, the system generates an ASCII input data file with appropriate format for running the model. After the execution of these models, an ASCII output data file is generated for further processing by other modules via the system interface.

Database

When the inference engine interrogates the knowledge base, direct communication takes place between the knowledge base and the database to retrieve the necessary information. This database stores many famous and useful models in hydrological simulation. It incorporates relevant information for all available hydrological models and furnishes the references for modeling. When the user of a system finishes all the parameter selections necessary for modeling, the system checks whether or not there are existing hydrological models in the database with similar consideration of parameter selections. It then asks whether the user would like to make the model selection based on that existing model. When only a few hydrological models are available in the database, it may be possible that no model will meet all imposed user requirements. The system offers then an easy method for loosening the requirements, and immediately allows the user to re-run the model selection process. New hydrological models can be easily added to the system.

User interface

The user interface conveys the required information for the system to infer in accordance with the rule base. The major role of the user is to: specify the physical problem; state the demand on accuracy and/or efficiency; and, obtain output results from the simulation. Direct communications with the system are driven mainly through the choice of parameters from menus. In cases that the user does not know what to enter, the system will query the user or will furnish more thorough explanations of the questions as well as valid user responses. Warning messages will be prompted to the user when the user input is internally inconsistent or contradictory, and options will be given to correct the input. In this way, first-time users can be tutored and trained in the use of the prototype system. Contemporary Windows-type graphical user interfaces with layers of display screens and pop-up windows are also used for message transfer.

Verification and validation

The usefulness and applicability of any system can only be affirmed by verifying its capability to mimic a particular case study with accurate depiction of real phenomena. This system has been verified and validated by applying to several strategically chosen real prototype hydrological problems: Shing Mun River in Hong Kong; and Changtan watershed in China.

The existing Shing Mun River has been trained for a length of about 2840 meters, from the Lower Shing Mun Dam to Sha Tin Tsuen. The bed is lined, above normal tidal level, for approximately 1900 meters. Extension of the river channel to Tolo Harbour, by reclamation of the adjoining areas for the Shatin New Town development, adds another 2750 m to its total length. There are three major tributary nullahs to the extended Shing Mun River: Tin Sam Nullah; Fo Tan Nullah; and, Siu Lek Yuen Nullah. The Shing Mun River carries not only runoff from the surrounding hills but also the spillway overflow from the Lower Shing Mun Reservoir, which in turn collects runoff from the catchment above the dam. The maximum flow at the river mouth for a 200-year storm, including the maximum reservoir overflow, is about 1500 m^3/s. It incorporates real hydraulic features including branched channels and tidal flats flooding and drying. For flood prediction purpose, the time histories of water stages and discharges are desired along the entire river channel. With the availability of appropriate initial and boundary conditions, a one-dimensional unsteady finite difference model is the proper selection (Chau and Li, 1991).

Changtan watershed is located in the northern area of the Guangdong province of China and covers an area of about 1990 km^2. There are two hydrometric stations at two main branch rivers at the middle watershed. They can be considered as two stream inflow sections. There is a reservoir at the outlet of the watershed. The river network considered in this project is the region from two hydrometric stations to Changtan reservoir. The area of interbasin is 284 km^2, which is separated into two sub-regions. With its relatively large contribution to the final runoff, the interbasin rainfall-runoff should be considered. The river is relatively short and its bed slope is steep. The average quantity of the precipitation of two hydrometric stations is considered to represent that of the upper sub-region. The inflow rate of the reservoir is established by means of the reservoir water balance and is used as the outflow of the river network. Forecasting of discharges only at the outlet is required for this case. Under these circumstances, the Muskingum method is the appropriate choice (Chau and Zhang, 1995).

In applying the intelligent system to simulate real case studies in Hong Kong and China, it was found that the processes used in selection of model and parameters, were reasonable. Figure 5 displays an example of the inference direction from parameter determination to user's responses in the case example. Figure 6 shows an inference direction from the user's specification through the inference mechanism. Figure 7 shows a sample screen of the user interface for tree selection whilst Figure 8 shows a sample screen of model selection for the application example. In both case studies, the most appropriate selection and manipulation of hydrological model was effective, with regard to: topography; concern on specific processes; data availability; demand on accuracy; demand on efficiency; and, numerical stability. Similar manipulation processes by human expert counterparts have also been undertaken. More detailed description and results of mathematical modeling for these study areas can be referred from Chau and Li (1991) and Chau and Zhang (1995).

Conclusions

A prototype knowledge-based system on intelligent manipulation and calibration of parameters for hydrological models has been developed and implemented**.** It is shown that, through establishing the requisite knowledge base as well as utilizing a proper reasoning inference engine, the integrated system has strong potential in guiding neophytes in both selection and manipulation of hydrological models. It is able to bridge the existing gap between hydrological modelers and practitioners in this domain. The prototype system also enables the inclusion of new models when they become available at a later date. Other useful characteristics of this system are the ease of its knowledge representation, and the ease of future extension of the knowledge base. It is strongly believed that further development of hydrological modeling should be undertaken in this direction. Further research in this area deserves more attention since more intelligence can be furnished to create more versatile and useful consultation systems on hydrological modeling.

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Table 1. Table listing details of the classification system in the knowledge base

Classification	*Characteristics*
Method	numerical method, uniform or non-uniform grid, numerical stability, lumped or distributed model, kinematic or dynamic wave routing
Scheme	explicit or implicit discretization, single-process or multi-process, single-component or multi-component
Geometry	dimensionality, co-ordinate system, extent of domain
Boundary condition	discharge hydrograph, water stage at open boundary, value and variation at close boundary
Initial conditions	initial discharges, initial water stages, initial solute concentrations
Process	convective transport, vapor phase transport, infiltration, advection, subsurface flow, groundwater flow, surface overflow, snow-melt, recharge, abstraction, turbulence

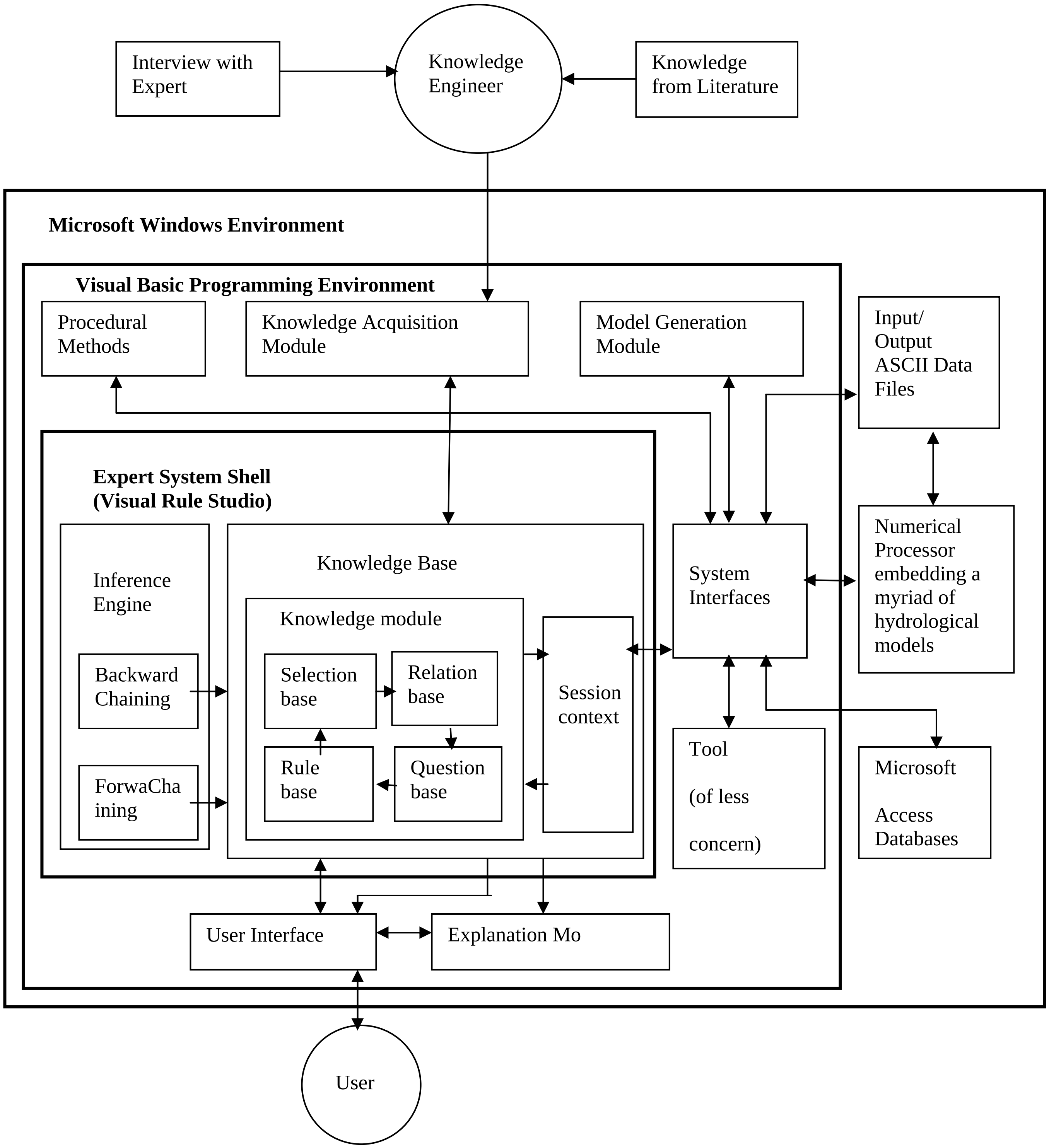

Figure 1 Architecture of the prototype system

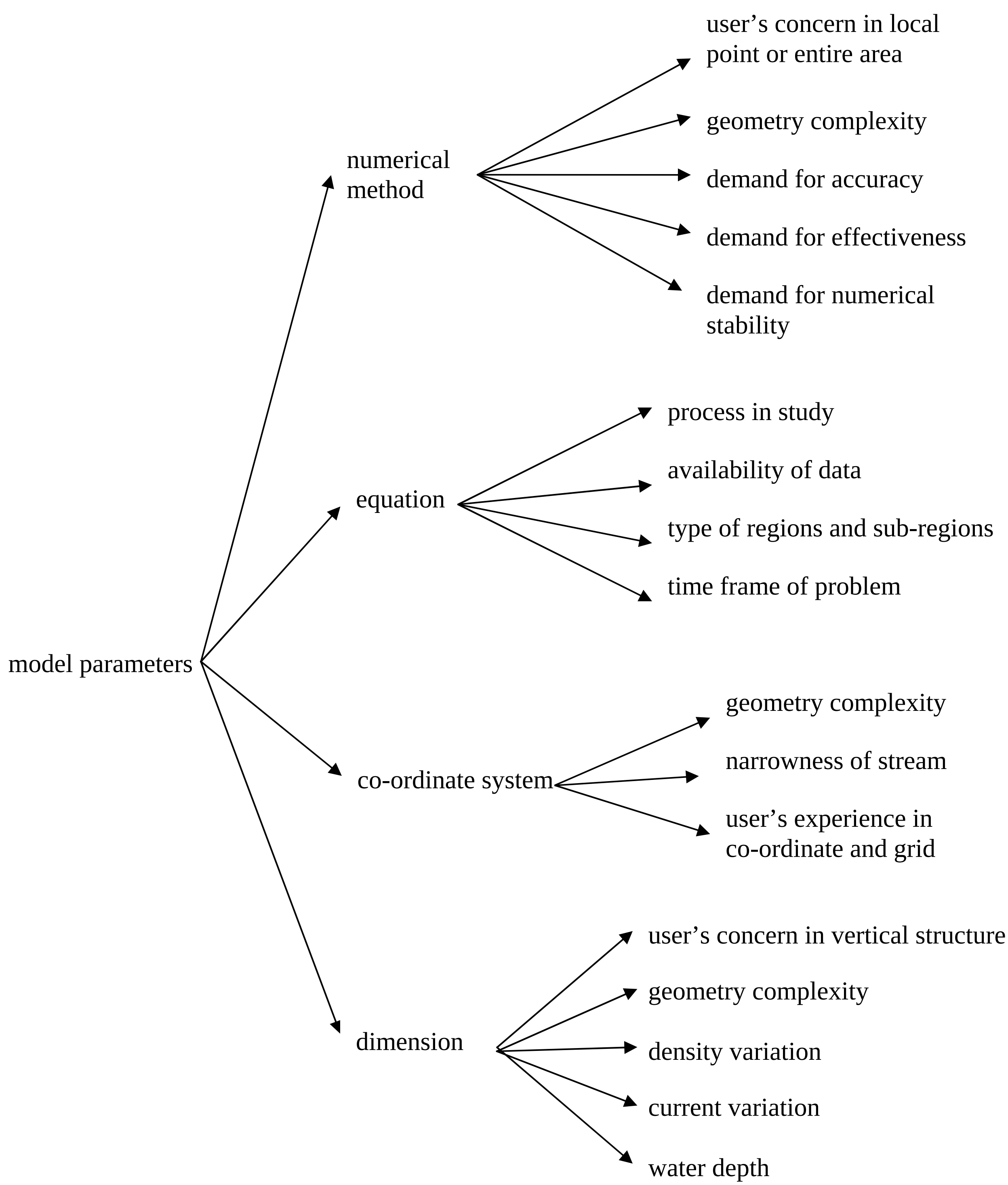

Figure 2. Part of the relation tree of model parameters

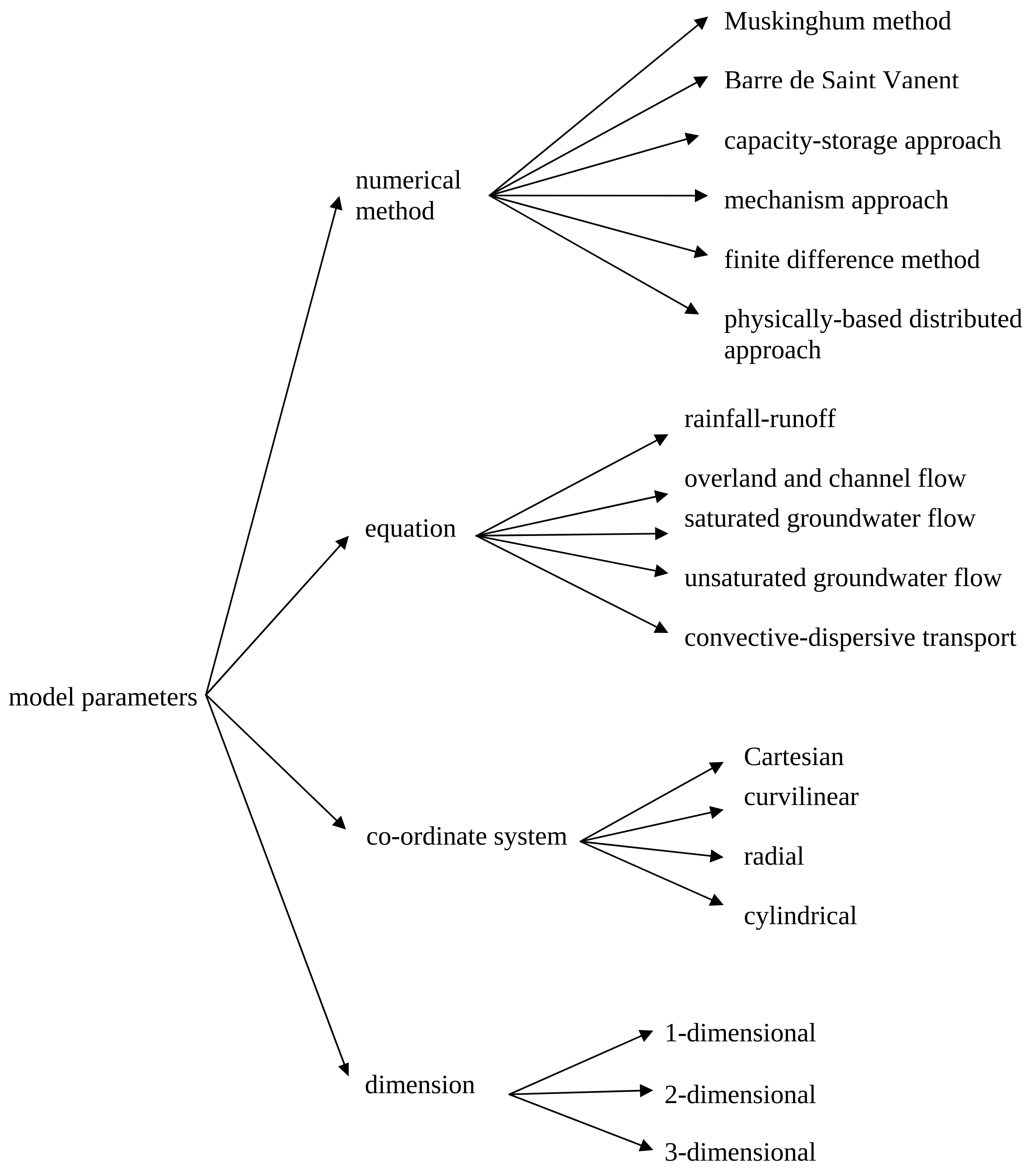

Figure 3. Part of the selection tree of model parameters

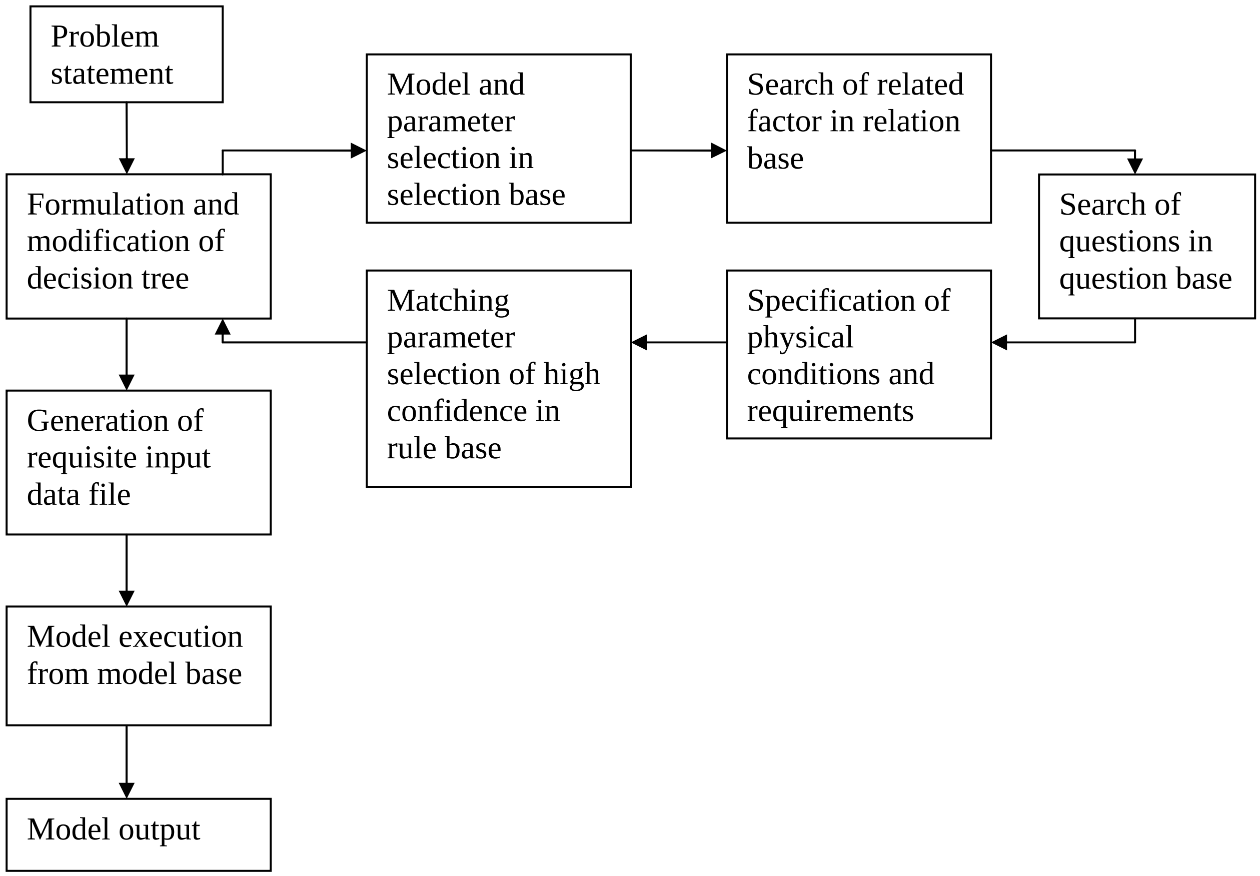

Figure 4. Overall flowchart showing linkages amongst various sub-bases in knowledge base and inference mechanism

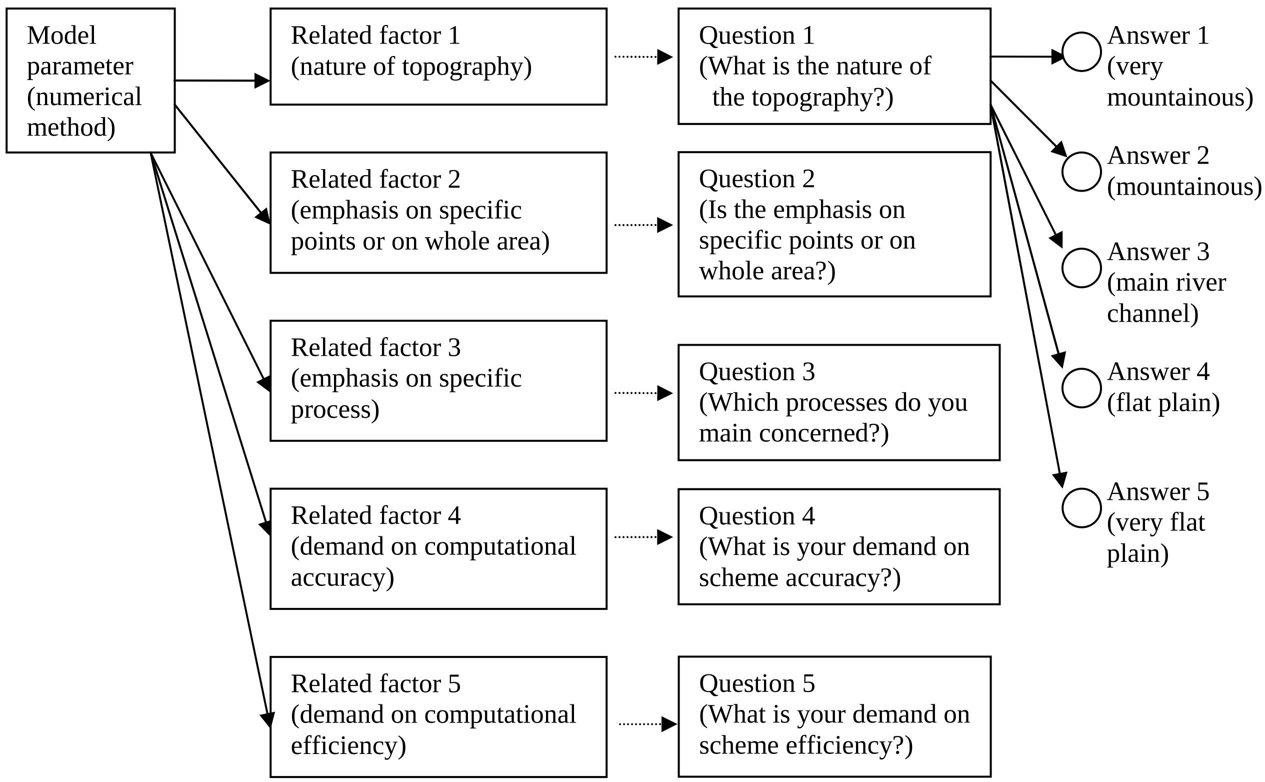

Figure 5. An example of the inference direction from parameter determination to user's responses in case example

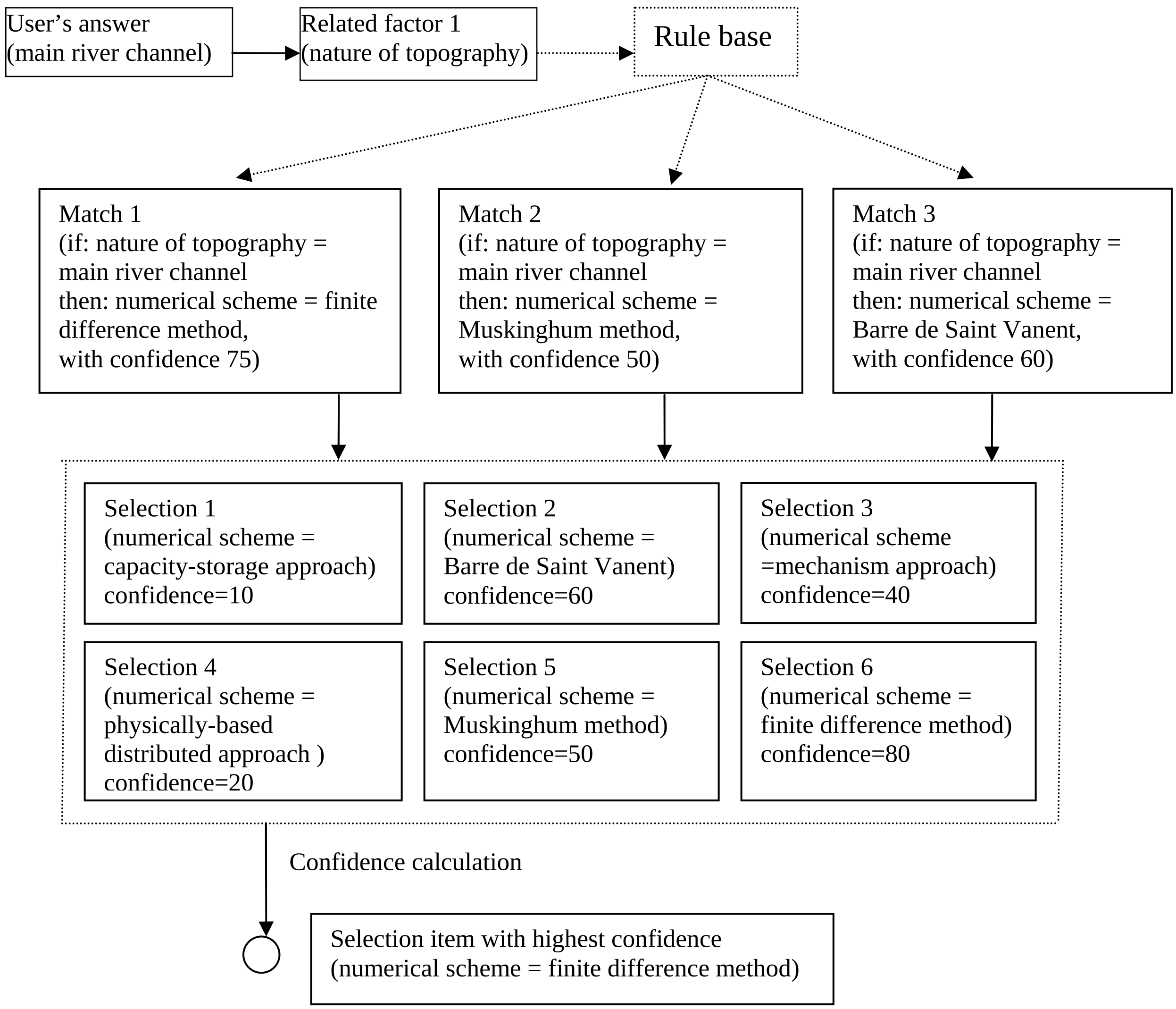

Figure 6. Inference direction from the user's specification through the inference mechanism in case example

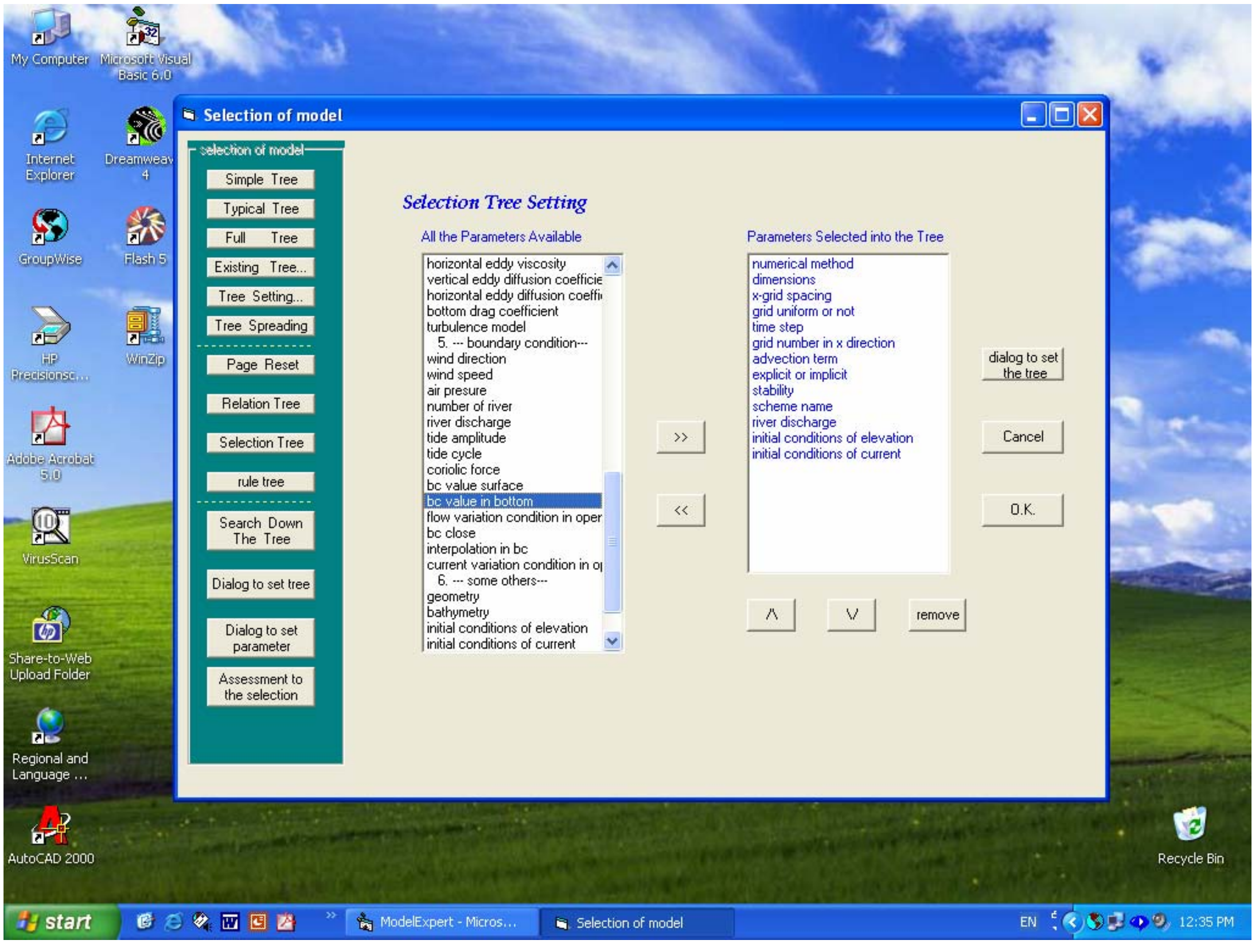

Figure 7. Sample screen of the user interface for tree selection in application example

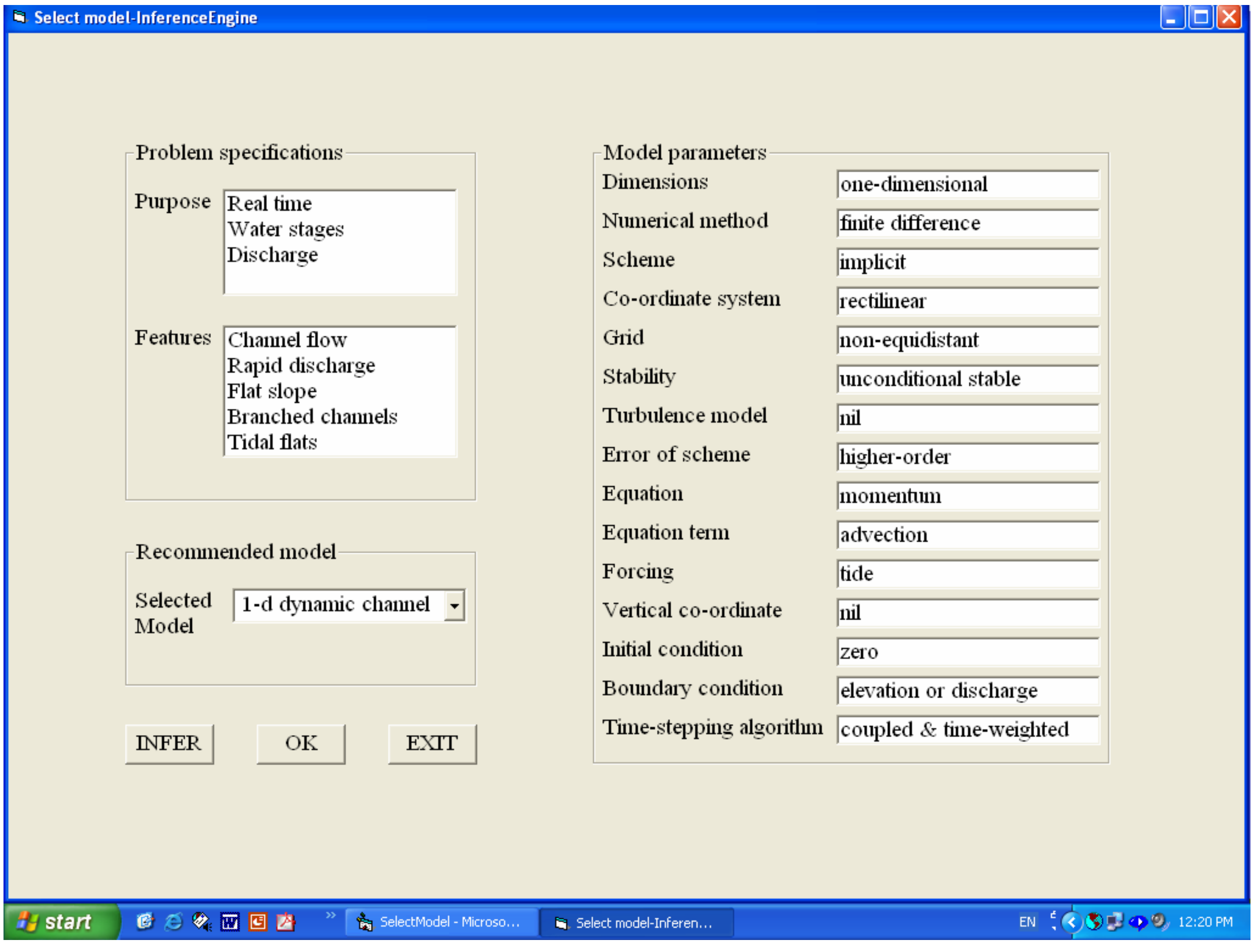

Figure 8. Sample screen of model selection for the application example