

Environmental Modelling & Software, Vol. 18, No. 2, 2003, pp. 99-108

Manipulation of Numerical Coastal Flow and Water Quality Models

K.W. Chau

Department of Civil & Structural Engineering, Hong Kong Polytechnic University, Hunghom, Kowloon, Hong Kong

Abstract

Nowadays, numerical flow and water quality models are widely applied to solve coastal engineering problems. The outcomes of the algorithmic execution often deviate from the anticipation, particularly when the model is set up initially. This necessitates the modeler to perform the manipulation procedure, which comprises feed back and modification. As such, it is desirable that expert system technology be integrated into the modeling system to furnish assistance for the novice user who lacks the requisite knowledge to establish the model and assess the results. In this paper, a prototype expert system on manipulation of numerical coastal flow and water quality models is developed and implemented by employing an expert system shell, Visual Rule Studio, as an Active Designer under Microsoft Visual Basic environment. Through the successful development of this prototype system, it is shown that the expert system technology can be coupled into numerical modeling for mimicking the manipulation process. It assists the user to formulate a suitable strategy for striking a balance between accuracy and effectiveness and to tune the model to accomplish satisfactory modeling of real phenomena. It is able to bridge the existing gap between numerical modelers and practitioners in this field.

Introduction

With the recent advent in microcomputer technology, numerical models are widely employed in coastal engineering research and application. Over the years, a myriad of models has become available for engineering or environmental problems. Typical examples are mathematical models of tidal flow and of a particular water quality phenomenon (Chau and Jiang, 2001; Chau and Jiang, 2002; Chau and Jin, 1995; Chau and Jin, 1998; Chau and Lee, 1991; Chau et al., 1996). Modern modeling software system in coastal engineering is usually quite comprehensive and covers a diversity of modules on various coastal processes including, namely, hydrodynamics, wind-wave, water quality, sediment, transport-dispersion, and so on. Numerical modeling can be delineated as a process that transforms knowledge regarding physical phenomena into numerical formats, simulates for the behaviors, and translates the numerical results back to apprehensible formats (Abbott, 1993). In other words, it is an interaction between knowledge and information in the form of knowledge to information and then back to knowledge again. It is through the process that our understandings on the phenomena are enhanced. Whilst the former step is concerned with the selection of a suitable model and its associated model parameters, the latter deals with post-processing of the model outputs.

The manipulation of numerical modeling can be regarded as an intermingled process of the two aforementioned steps, comprising usually both feed back as well as modification. The transformation from knowledge to information is considered completed once sufficient confidence of correctness is acquired on the selection of numerical model together with its parameters. However, in most situations, particularly for novice model user, there is a necessity for the choice to be rectified and adjusted several times prior to accomplishing satisfactory model results. In general, the process on manipulation of modeling is time-consuming, which depends highly on the experience of the modeler. Extensive and detailed expertise knowledge are required before one can distinguish the special features and limitations of these individual numerical models and then select the befitting model to apply in a particular circumstance. It is apparently easier for a well-experienced modeler, who may use the heuristic knowledge unconsciously, to undertake the manipulation procedure of modeling. Thus, it is highly desirable to incorporate more heuristic knowledge in the modeling package, with a view to furnishing help for a novice user who is not a well-experienced expert in this problem domain of coastal engineering.

The notion of “generations” of modeling to describe this trend of development was introduced by Abbott (1989). The third generation modeling, being a system to solve specific domain problems, can only be apprehended by the modeler and special users well trained over a long period. It has incorporated very few features to facilitate other users and for other problems. Typical examples are some sophisticated 2-dimensional or 3-dimensional finite difference numerical models on tidal flow and on a particular water quality phenomenon (Chau and Jin, 1995; Chau and Jin, 1998). In the fourth generation of numerical modeling system, there have been some developments in the post-processing and user-friendly interface, and in the fifth generation of modeling system artificial intelligence technology is integrated to furnish assistance for non-experienced user. At present, successful applications of expert system technology have been reported in the selection of numerical model in coastal engineering (Chau and Yang, 1993; Chau and Chen, 2001). Yet they only refer to a one-dimensional modeling system for river network or river planning due to the simplicity of knowledge and selection procedure. The integration of expert system with two-dimensional or three-dimensional modeling is more complex. Moreover, literature on the incorporation of expert system technology into the model manipulation is scarce to date.

As such, the key objective of this study is to integrate expert system technology, together with some pre-processing and post-processing tools, into traditional models for model manipulation. This paper presents the development and implementation of a prototype expert system on manipulation of numerical coastal flow and water quality models by employing an expert system shell, Visual Rule Studio, as an ActiveX Designer under Microsoft Visual Basic environment. The architecture and main components of the system are depicted. Through establishing the requisite knowledge base as well as utilizing a proper reasoning inference engine, the system has strong potential in facilitating the non-experienced user in both model selection and manipulation.

Selection and Manipulation of Numerical Model

The selection of a numerical model is composed of the following steps, namely, physical representation of problems, discretization of equations, imposition of proper boundary conditions,

selection of suitable coefficients of turbulence, adoption of problem solving algorithm, and model execution. The numerical technique can be based on finite element method, finite difference method, boundary element method and Eulerian-Lagrangian method. The time-stepping algorithm can be implicit, explicit or characteristic-based. The shape function can be of first order, second order or higher order. The spatial dimensions can be simplified into 1-dimensional, 2-dimensional depth-averaged, 2-dimensional layered, or 3-dimensional.

The manipulation procedure normally begins from the trial selection of an initial model and ends with the satisfactory simulation to a specific real phenomenon, through iterative modifications until fulfilling the user's specified threshold of correctness. The intermediate procedure between the beginning and the end comprises the determination of the direction to improve the simulation by changing certain model parameters. This task to find the correct direction of manipulation is the most significant step in the manipulation of numerical modeling. It is found that modeling experts themselves are often used to maintain certain basic choice of modeling unaltered in the manipulation. For instance, recently, three-dimensional models were the norm and engineers often employed the popular Ocean Model of Princeton University (POM) (Mellor, 1996) to simulate coastal dynamics. Whilst the co-ordinate system, grid setting, temporal and spatial numerical scheme were all maintained, only turbulence coefficients in vertical and horizontal directions were maneuvered (Chau and Jiang, 2001). Another example is in the dispersion-transport modeling. After Eulerian-Lagrangian Model (Cheng et al., 1984) has been reported to raise the accuracy of modeling, the numerical schemes in many models were kept the same, and only the dispersion coefficient was changed. These examples reflect that the human intelligence uses existing knowledge to reduce the number of choices in order to raise the effectiveness of manipulation of modeling. They also illustrate that, in the manipulation procedure, modelers tend to modify at most one or two parameters simultaneously so as not to get loss in the manipulation direction.

Apparently, the direction and effectiveness of manipulation are two main factors to control the manipulation procedure. A balance between modeling accuracy and effectiveness should be stricken in the manipulation of numerical modeling. This is because computer is used and the memory and speed of computer is often limited. The level of result satisfaction depends highly on the user's requirement of the balance between modeling accuracy and effectiveness. For engineering problem, the accuracy is very important, however, for research problem to understand the rough process of phenomenon mechanism, the accuracy become not so important as the effectiveness. Different strategies for these two manipulation directions are employed under different demands of the user. Figure 1 shows certain methods to change the parameters to enhance modeling effectiveness.

System Architecture

Since a variety of modules with different functions are involved, it is difficult to incorporate them into traditional standalone expert system shells. As such, the expert system shell, Visual Rule Studio (Rule Machine Corporation, 1998), which runs as an ActiveX Designer under the windows-based programming language environment Microsoft Visual Basic 6.0, is employed. Visual Rule Studio is a hybrid expert system shell that couples the advantage of both production rules and objected programming paradigm. All the usual control objects of the common interface

under Windows 98 or 2000 environments such as command button, picture box, etc., are furnished. The major reasons in adopting this programming environment are the user-friendliness of the interface and its ability to execute external programs written in other traditional languages such as FORTRAN, PASCAL or C. Knowledge rules are written in the Production Rule Language format. In addition to the usual components in a typical expert system, namely, knowledge base, inference engine, context, user interface, knowledge acquisition facility and explanation module, it also incorporates external modules including numerical processor, databases and toolbox. The architecture of the integrated system is shown in Figure 2. The domain knowledge entailed in the development of this expert system has been encoded mainly from literature review and interviews with expert numerical modelers. Figure 3 shows a typical screen of the system displaying part of the selection tree of the model parameters.

Two containers mainly represent the interface in this system. One container is used to store the information, to dialog, to ask question and to acquire answers in the interaction with the user. The purpose is to capture the user's demand for accuracy or effectiveness and physical conditions of the simulating environment. This container provides the information to let the system make inference from the knowledge base. The user can specify his/her preference to accuracy or effectiveness, and a set of suggested parameters would be listed in the interface for modification. Figure 4 shows an example screen of the user interface for the selection of the model and its associated parameters. Keyboard is primarily employed to enter numerical input data while mouse device is used to choose the user preference amongst available options and to confirm any recommendation made by the system. This prototype system has many graphics-oriented interface features such as interactive graphics, window management and explanation facilities. The same graphical user interfaces as those used in windows operating system are used for message transfer and hence input, handling and interpretation of data and information have been greatly simplified. Another container is a report table, which is a port between selection and manipulation components of the modeling system. The report table lists the parameters selected in the modeling and tells the system processor to run the simulation with these parameters. Output results obtained by executing various numerical models are interpreted through the aid of post-processing graphic expedients.

A key part of a numerical modeling system is the numerical processor, which can be run to produce the digital simulation of real phenomena. Being a fifth generation of modeling system, certain new features or interface are designed to demonstrate the new technology integration. It is designed as a form of ActiveX Control (in Visual Basic developing language). This numerical processor is an OCX program, which is a type of ActiveX file type with an extension .OCX, ready to run with a lot of properties and a lot of methods of action such as initialization, run, stop, pause, record, comparison, warning, etc. The selection of the modeling parameters then becomes to set the properties and methods of this numerical processor. The properties are grouped into the following types: dimensions, grid, scheme, turbulence, boundary conditions, and some others. This grouping facilitates the query and reasoning processes in searching the knowledge base. The methods include retrieving the data file, comparing with field observations, monitoring the results under restrictions, displaying animation results, etc. This design facilitates the integration of expert system technology. Only the properties and methods of the processor are exposed to changes on modeling selection or manipulation. In this way, there are obvious advantages in the development of modeling system because different modules are developed independently. Figure

5 demonstrates the interface of the properties and methods of the numerical processor of modeling.

In order to ensure the consistency of numerical simulations and real phenomena, ample availability of real data are entailed. In this system, the database stores information on current, tidal elevation, water depth, temperature, salinity, dissolved oxygen, biological oxygen demand, phosphorus, nitrogen, algae, and their variations with time and locations. In addition, description statement can be written in the forms of rules and included into the knowledge base. Automatic checking and warning prompts are designed to effect the verification between modeling results and real observation data. The database chosen is Microsoft Access, which is selected due to several reasons including its popularity as a user-friendly relational database within industry, reasonable cost, and Visual Basic support by means of Visual Basic for Applications.

The major role of the toolbox in the system, designed as a separate module, is to perform comparison between simulation result and real data. Moreover, it provides assistance for both pre-processing and post-processing in the procedure of manipulation. The toolbox can be used to monitor the manipulation procedure by highlighting warning prompts to the user if the modeling results exceed the pre-set limiting values.

Operation of the System

The set of parameters specified for numerical modeling is depicted under the form of a decision tree. The mechanism begins when the system searches the decision tree and asks the user to give specifications. The model selection procedure is basically similar to the usual steps in performing numerical modeling manually. The selection of a model together with its associated parameters depends on the following factors, namely, main purpose of the modeling, physical conditions of the problem, modeling experience of the user, and user's apprehension of modeling results. This process can be regarded as a matching process to relate model parameters to the specified conditions. As such, the use of expert system technology is mainly focussed on the establishment of their relationships, through a knowledge base and a befitting reasoning inference mechanism. The process proceeds until all the branches have been properly filled and the solution has been found.

Heuristic rules on the direction and effectiveness of manipulation are extracted and encoded in the form of knowledge rules. The knowledge base incorporates the entire set of production rules relating the user's specifications and the choice of parameters. Comparison and evaluation of the performance of different models and hence their relative advantages, applicability as well as limitations are thoroughly explored on the basis of this repository of domain knowledge. By questioning the user to pinpoint the relative significance of accuracy and effectiveness, the system can search the knowledge base and suggest the best option. The role of the expert system is limited to an intelligent assistant to guide the decision making process, yet does not automatically balance accuracy and effectiveness. Since the selection decision in this system is mainly driven by the factor of confidence, a thorough knowledge base is required for the system to derive a good balance. The encoded knowledge rules can provide substantial assistance to novice model user.

During the manipulation process, some parameters are kept unchanged whilst some parameters are modified. Besides, certain recommended combinations of parameters are adhered to in accordance with heuristic rules stored in the knowledge base. Under the terms of expert system technology, model templates are prepared under the form of a model frame. The frame comprises a number of slots representing model parameters. Whilst changes are not allowed on certain slots, some others can be altered to suit the specific conditions. The procedure is mainly to determine appropriate slots such that the modeling results coincide properly with real phenomena. Under this system, the modifiable parameters are represented as a parameter tree. All available choices of that specific parameter are shown as branches of the parameter in the tree. The tree, which has a full skeleton during the process of modeling selection, is managed by production rules in the knowledge base. When the user specifies his/her demand of accuracy or effectiveness, certain branches are cut off. At the completion of the manipulation procedure, both the tree skeleton as well as the branches become fixed, representing satisfactory modeling simulation. Figure 6 shows the example of the tree formation in the manipulation procedure.

The purpose of the manipulation procedure is to obtain satisfactory simulation of real phenomenon. There is a comparison procedure between the simulation results and the real observational data. Of course, there are many fuzzy processes in estimating whether or not the modeling results meet the demand of the user about modeling accuracy or effectiveness. In fact, the improvement in estimating the modeling results is based upon technology of pattern recognition. The normalized mean square error (NMSE) between the principal model results and the corresponding field measurement data is employed as the performance indicator. This indicator represents the sum of squared errors normalized by the number of patterns over all output data and the estimated variance of the data.

The inference engine drives the decision tree to explore the most feasible solution that matches properly the problem specifications. When the initial choice of model together with specifications of preference on model accuracy or effectiveness are made, the mixed chaining strategy is employed to recommend the manipulation direction. The inference process is mainly driven by antecedent clauses in rule statements with the highest factors of confidence. Forward chaining is used to search from user's responses to the query and to update the decision tree. Backward chaining is employed to determine the requisite parameters and then the question for the user. Once the user has replied on the question, the answer is fed back to the system and the inference engine drives the decision process forward until accomplishment of the solution. As more specifications to the problems are gradually input, the inference engine computes the new confidence factors for all branches of the decision tree through searching the knowledge base. Figure 7 shows an example of the inference direction from the user's specifications through the inference engine. The inference engine directs the searching and matching so as to result in enhancing confidence factors of parameter selection.

The confidence factor undertakes an imperative role in controlling the inference process and the selection of parameters. In the process, the system evaluates the probable largest increase in the confidence of selection by matching from the knowledge base. The corresponding question gets the priority to be asked next. This is achieved through the rule base, which relates the user's specifications and the parameter selection by matching the highest confidence factor. Confidence factors of conclusion subsequent to firing of a rule are determined using a product space

calculation. It is given a final confidence that is calculated from the individual confidence factor of the premises and the confidence specified in the knowledge base for the conclusion. The improbable branches of choice with confidence factor less than 20 are cut away from the decision tree. The user can also enter their exact numerical values during the query process. The system can transform the numerical values into the corresponding fuzzy description by a fuzzy member curve, which computes the pertinent confidence of membership prior to searching the rule base for conclusions.

Application Case Studies

The usefulness and applicability of any numerical model 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 real prototype problems in Hong Kong coastal waters. The major goals for manipulation are placed on enhancements in accuracy and effectiveness. The application case studies involve the establishment of several numerical models on coastal flow and water quality in Hong Kong, which encapsulate a few strategically chosen locations such as Pearl River Estuary (Chau and Jiang, 2001; Chau and Jiang, 2002), Shing Mun River (Chau and Lee, 1991), and Tolo Harbour (Chau and Jin, 1995; Chau et al., 1996; Chau and Jin, 1998). Each of these water bodies is subject to a distinct environmental problem. The areas around the Pearl River Estuary, which is the largest river system in the South China, have been prospering during the past decade in such a dramatic rate that almost all the resources of the estuary are involved. This results in a worsening and deteriorating water quality as evidenced by the increasing occurrence of algal blooms recently. Figure 8 shows an example screen showing an interactive graphical display of the topography at the Pearl River Estuary. Shing Mun River is one of the most representative river channels in Hong Kong. The water quality of Tolo Harbour, which is an almost land-locked embayment with merely a narrow outlet channel, has declined drastically in recent years. It exhibits high algal growth and is in particular highly eutrophic. The details and modeling results for these areas, which can be found in the above references, are not reiterated here. This prototype system is applied to these modeling case studies so as to evaluate the outcomes of employing a variety of methods to manipulate either accuracy or effectiveness.

The comparison of the NMSE in percentage term, for the two cases with and without applying the specified method respectively, is used as a yardstick for enhancement in accuracy. In each comparison, in order to study the effect of a design parameter on the modeling result, only its value is varied whilst all other variables are kept unchanged. Table 1 shows examples of comparison in enhancement of accuracy from the case studies. Replacement of a cubic order error scheme by a first order error scheme has the effect of changing the NSME from 0.721 to 0.692, which represents a 4% accuracy enhancement. Similarly, a fully three-dimensional finite difference model has been run instead of a depth-averaged two-dimensional staggered grid finite difference model, resulting in enhancement of accuracy by 10%. In another trial, the reduction of the time step size from 10 minutes to 5 minutes is found to have led to 6% enhancement. The refinement in horizontal grid spacing size from 500m to 200m can accomplish accuracy enhancement of 5%, also on the basis of the change in the NSME.

Apart from the accuracy enhancement, the effect and direction on enhancement in effectiveness have also been investigated and evaluated in the application case studies. The comparison of the entailed computing processing unit (CPU) time, in percentage term running on a pentium for the two cases with and without applying the specified method respectively, is employed as the yardstick for enhancement in effectiveness. Table 2 shows examples of comparison in enhancement of effectiveness from the case studies. Similar to the above study on accuracy, only one design parameter is modified whilst all others are maintained constant. The use of a conditionally stable explicit finite difference model instead of an implicit finite difference model is found to be able to shorten the CPU execution time from 7.61 hour to 6.09 hour and hence to enhance the effectiveness by 20%. Replacement of a depth-averaged two-dimensional finite difference model with a four-point operators Preissmann one-dimensional implicit finite difference model has the effect of enhancing effectiveness by 50%. The use of only four most significant tidal constituents instead of forty-two tidal constituents as the open boundary condition can speed up the computation by 8%, also on the basis of the change in the CPU time. Similarly, a model has been run assuming constant density and salinity with respect to time instead of its counterpart of varying density as well as salinity, resulting in enhancement of computational speed by 12%. In another trial, instead of nine water quality variables, the adoption of only biological oxygen demand and dissolved oxygen representing the two most significant water quality variables is found to have led to 10% enhancement in computational effectiveness.

Conclusions

This paper delineates a prototype expert system on manipulation of numerical coastal flow and water quality models. The manipulation procedure of numerical modeling is an indispensable process for effective simulation to obtain satisfactory results. By applying the recent advent in artificial intelligence, it is shown that the integration of the heuristic knowledge about what is the correct manipulation direction and how to raise the manipulation effectiveness as a knowledge base into numerical modeling can provide significant assistance to novice model user. The integration furnishes an intelligent as well as user-friendly modeling system in this specific problem domain. The use of the hybrid expert system shell, Visual Rule Studio, which runs together with Microsoft Visual basic 6.0, is found to be very effective in producing the system under the popular Windows environment. Besides, the system is able to bridge the existing gap between numerical modelers and practitioners in this field. It is apparent that there is strong potential to develop in this direction, though it is very difficult to glean experience of various expert modelers in the world. In the time being, this system incorporates only a few well-known numerical models. Through frequent usage and feedback from the users as well as validation of personal conclusions and experience in the previous literature, expertise knowledge on more extensive types of numerical models can be expanded for further enrichment of this prototype system. For this purpose, the extant architecture of the expert system has been designed such that new knowledge can be added easily into the knowledge base.

Acknowledgments

The work described in this paper was substantially supported by a grant from the Research Grant Council of the Hong Kong Special Administrative Region (Project No. PolyU5084/97E).

References

1. Abbott, M.B. (1989), Review of recent developments in coastal modelling, in Falconer, R.A., Goodwin, P., and Matthew, R.G.S., Hydraulic and Environmental Modelling of Coastal, Estuarine and River Waters, Avebury Technical, Aldershot, pp. 3-39.
2. Abbott, M.B. (1993), The electronic encapsulation of knowledge in hydraulics, hydrology and water resources, Advances in Water Resources Vol. 16, No. 1, pp. 21-39.
3. Chau, K.W. and Chen, W. (2001), A fifth generation numerical modeling system in coastal zone, Applied Mathematical Modelling, Vol. 25, No. 10, pp. 887-900.
4. Chau, K.W. and Jiang, Y.W. (2001), 3D numerical model for Pearl River Estuary, Journal of Hydraulic Engineering, ASCE, Vol. 127, No. 1, pp. 72-82.
5. Chau, K.W. and Jiang, Y.W. (2002), Three-dimensional pollutant transport model for the Pearl River Estuary, Water Research, Vol. 36, No. 8, pp. 2029-2039.
6. Chau, K.W. and Jin, H.S. (1995), Numerical solution of two-layer, two-dimensional tidal flow in a boundary fitted orthogonal curvilinear coordinate system, International Journal for Numerical Methods in Fluids, Vol. 21, No. 11, pp. 1087-1107.
7. Chau, K.W. and Jin, H.S. (1998), Eutrophication model for a coastal bay in Hong Kong, Journal of Environmental Engineering, ASCE, Vol. 124, No. 7, pp. 628-638.
8. Chau, K.W., Jin, H.S. and Sin, Y.S. (1996), A finite difference model of 2-d tidal flow in Tolo Harbour, Hong Kong, Applied Mathematical Modelling, Vol. 20, No. 4, pp. 321-328.
9. Chau, K.W. and Lee, J.H.W. (1991), Mathematical modelling of Shing Mun River network, Advances in Water Resources, Vol. 14, No. 3, pp. 106-112.
10. Chau, K.W. and Yang, W.W. (1993), Development of an integrated expert system for fluvial hydrodynamics, Advances in Engineering Software, Vol. 17, No. 3, pp. 165-172.
11. Cheng, R.T., Casuilliv, V. and Milford, S.N. (1984), Eulerian-Lagrangian solution of the convection-dispersion equation in natural coordinates, Water Resources Research, Vol. 20, No. 7, pp. 944-952.
12. Mellor, G.L. (1996), User's guide for a three-dimensional, primitive equation, numerical model, Princeton University Rep. Princeton University, Princeton, NJ
13. Rule Machine Corporation (1998), User's Guide for Visual Rule Studio

Table 1. Examples of comparison of accuracy enhancement from case studies

<i>Method</i>	<i>NMSE for 1st scheme</i>	<i>NMSE for 2nd scheme</i>	<i>Improvement in accuracy</i>
use cubic order scheme instead of first order scheme	0.721	0.692	4%
use 3-d finite difference method instead of 2-d staggered grid finite difference method	0.649	0.584	10%
decrease time step size from 10 minutes to 5 minutes	0.69	0.649	6%
decrease horizontal grid spacing from 500 m to 200 m	0.649	0.617	5%

Table 2. Examples of comparison of effectiveness enhancement from case studies

<i>Method</i>	<i>CPU for 1st scheme (hr)</i>	<i>CPU for 2nd scheme (hr)</i>	<i>Improvement in effectiveness</i>
use explicit time scheme instead of implicit time scheme	7.61	6.09	20%
use Preissmann 1-d finite difference method instead of 2-d finite difference method	15.22	7.61	50%
incorporate 4 significant tidal constituents only instead of 42 tidal constituents	15.22	14.00	8%
use constant density and salinity instead of varying density and salinity	21.89	19.26	12%
consider 2 significant water quality variables instead of 9 water quality variables	21.89	19.70	10%

Figure Captions

Figure 1. Certain methods to enhance modeling effectiveness

Figure 2. Architecture of the prototype expert system on manipulation of numerical flow and water quality models

Figure 3. Screen showing part of the selection tree of model parameters

Figure 4. Example screen of the user interface for selection of model and its associated parameters

Figure 5. Interface of properties and methods of numerical processor

Figure 6. Example of tree formation of model parameters

Figure 7. An example of the inference direction from the user's specifications through the inference engine

Figure 8. Example screen showing an interactive graphical display of the topography at the Pearl River Estuary

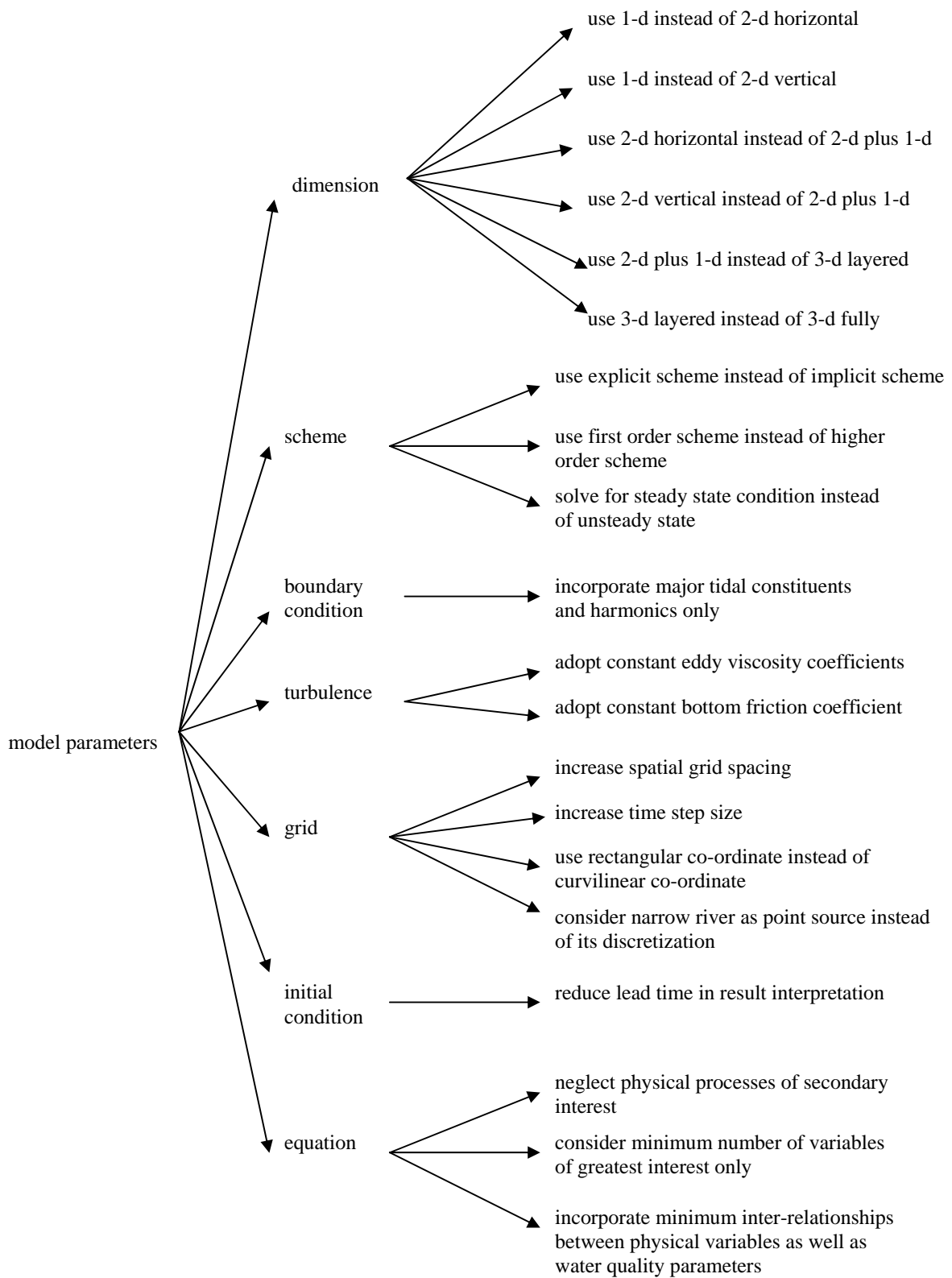


Figure 1

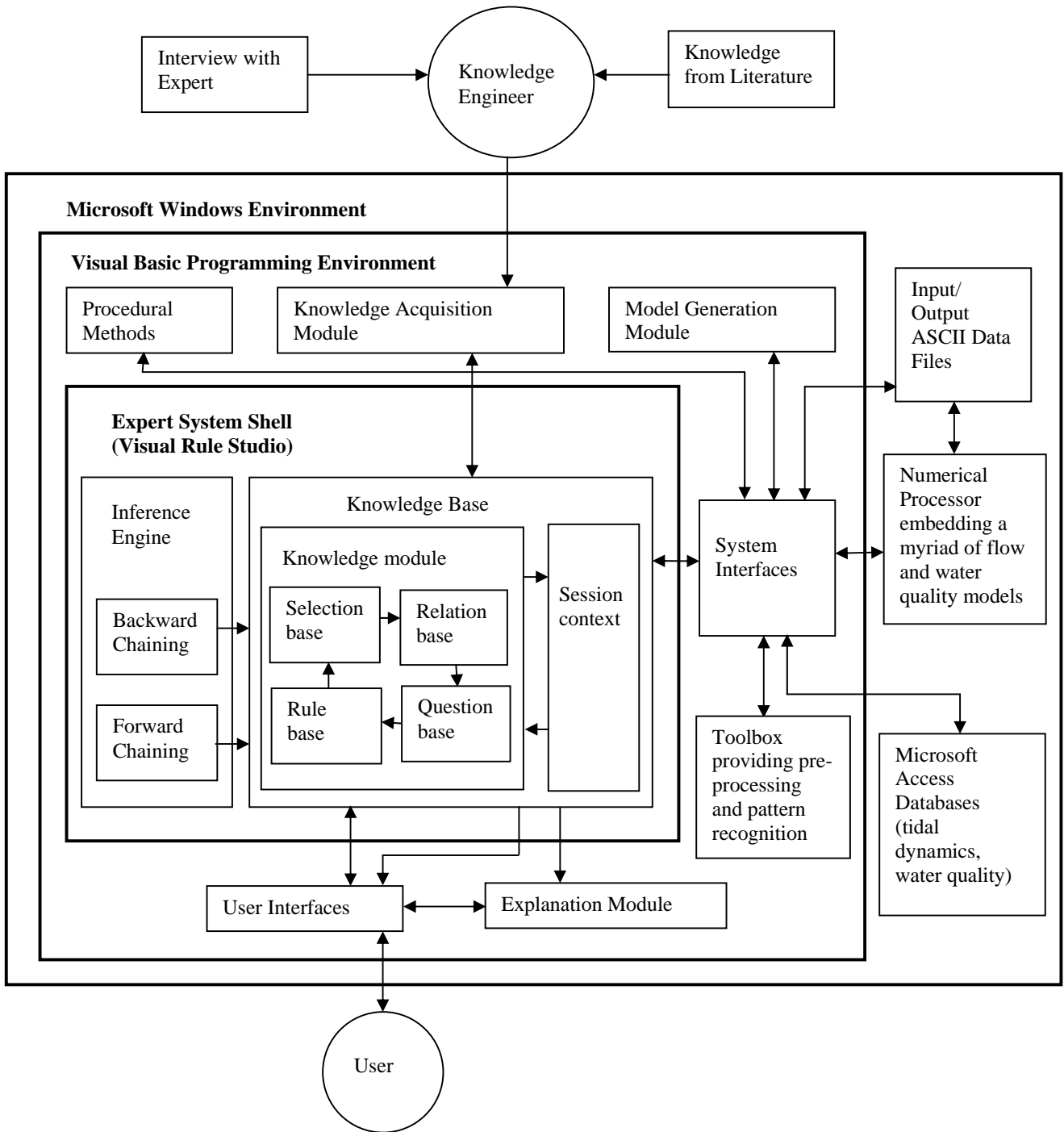


Figure 2

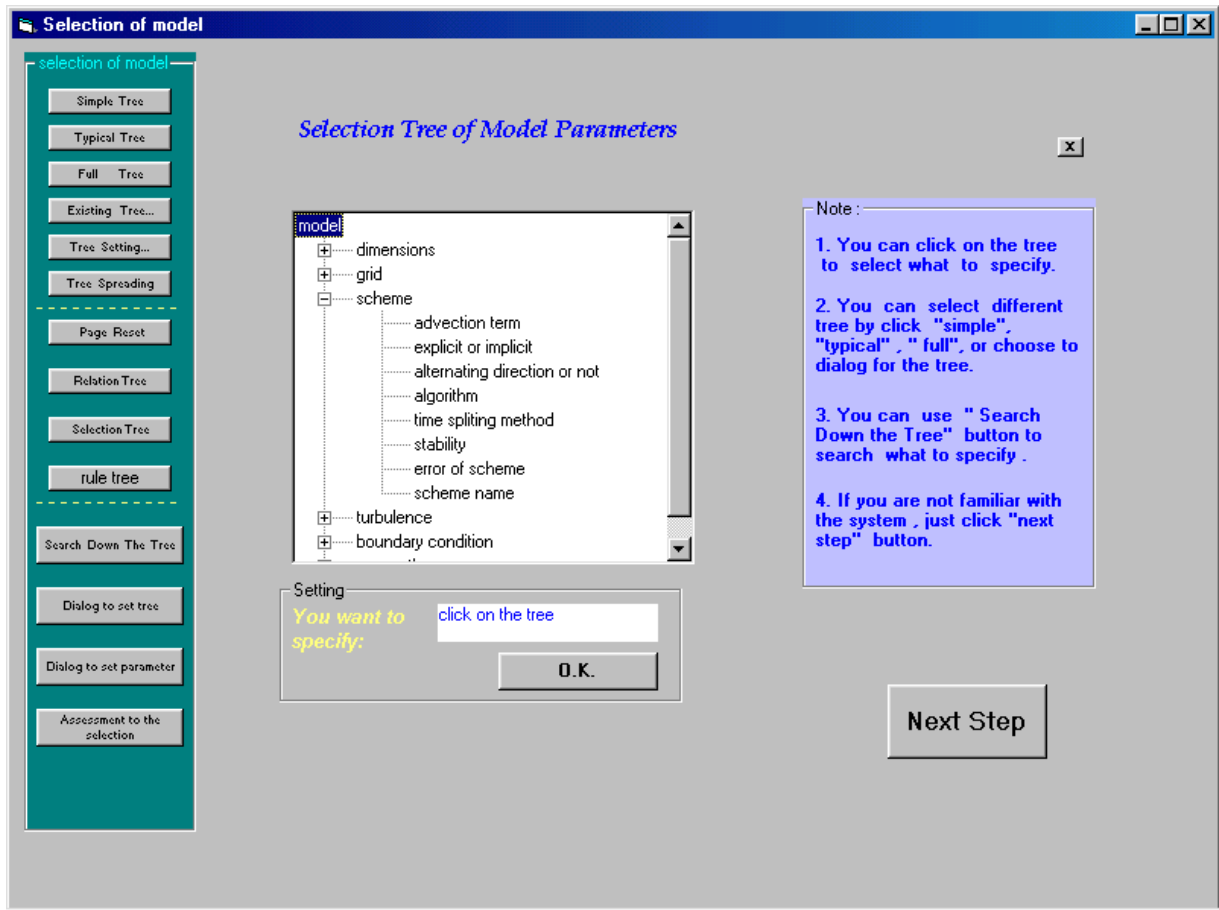


Figure 3

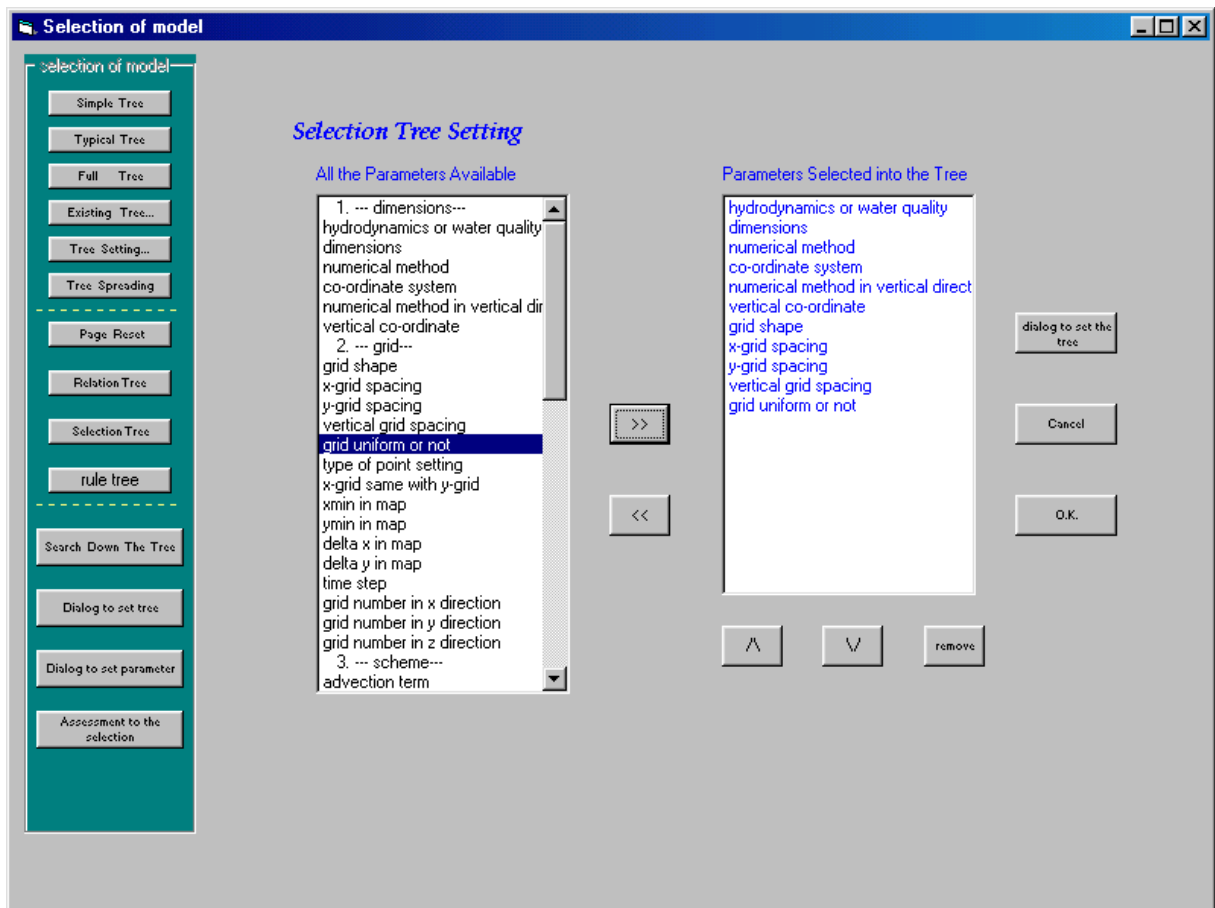


Figure 4

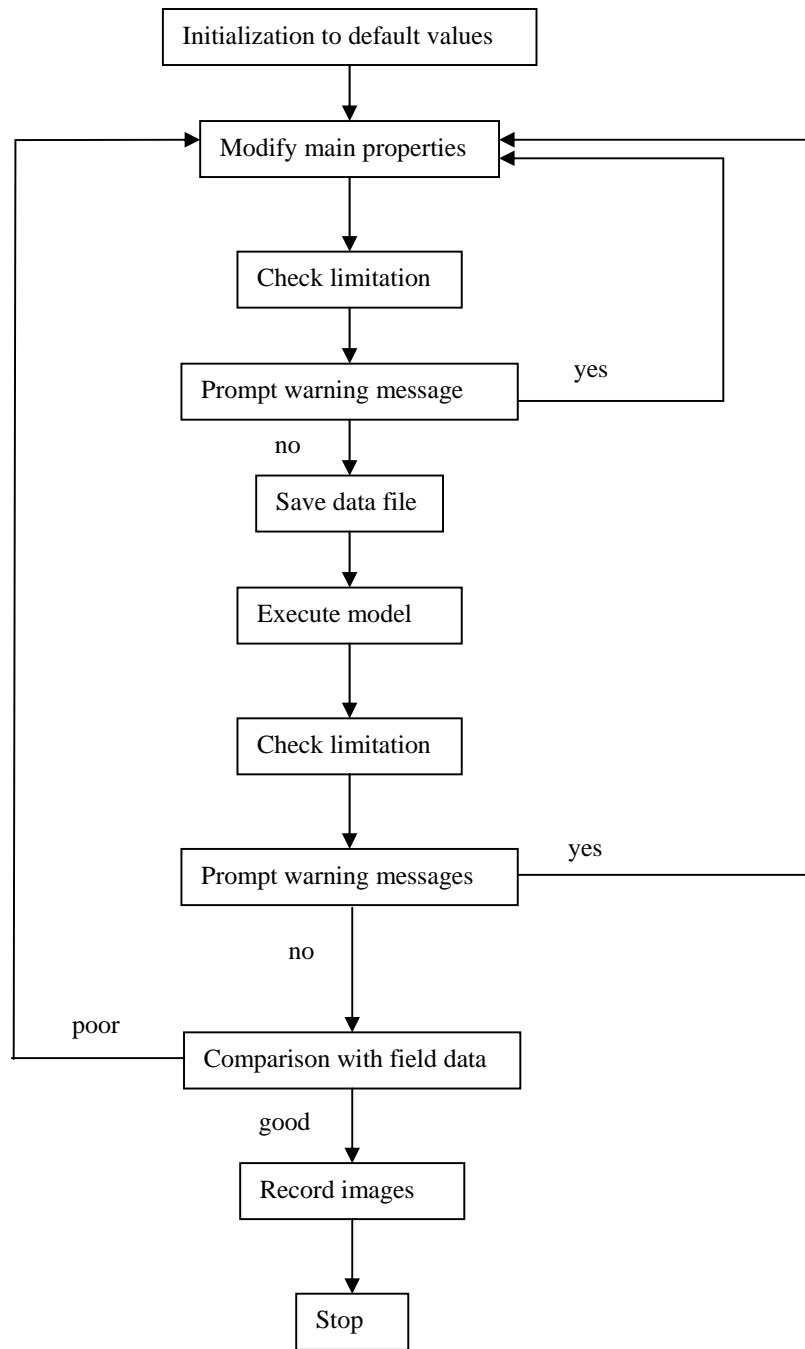


Figure 5

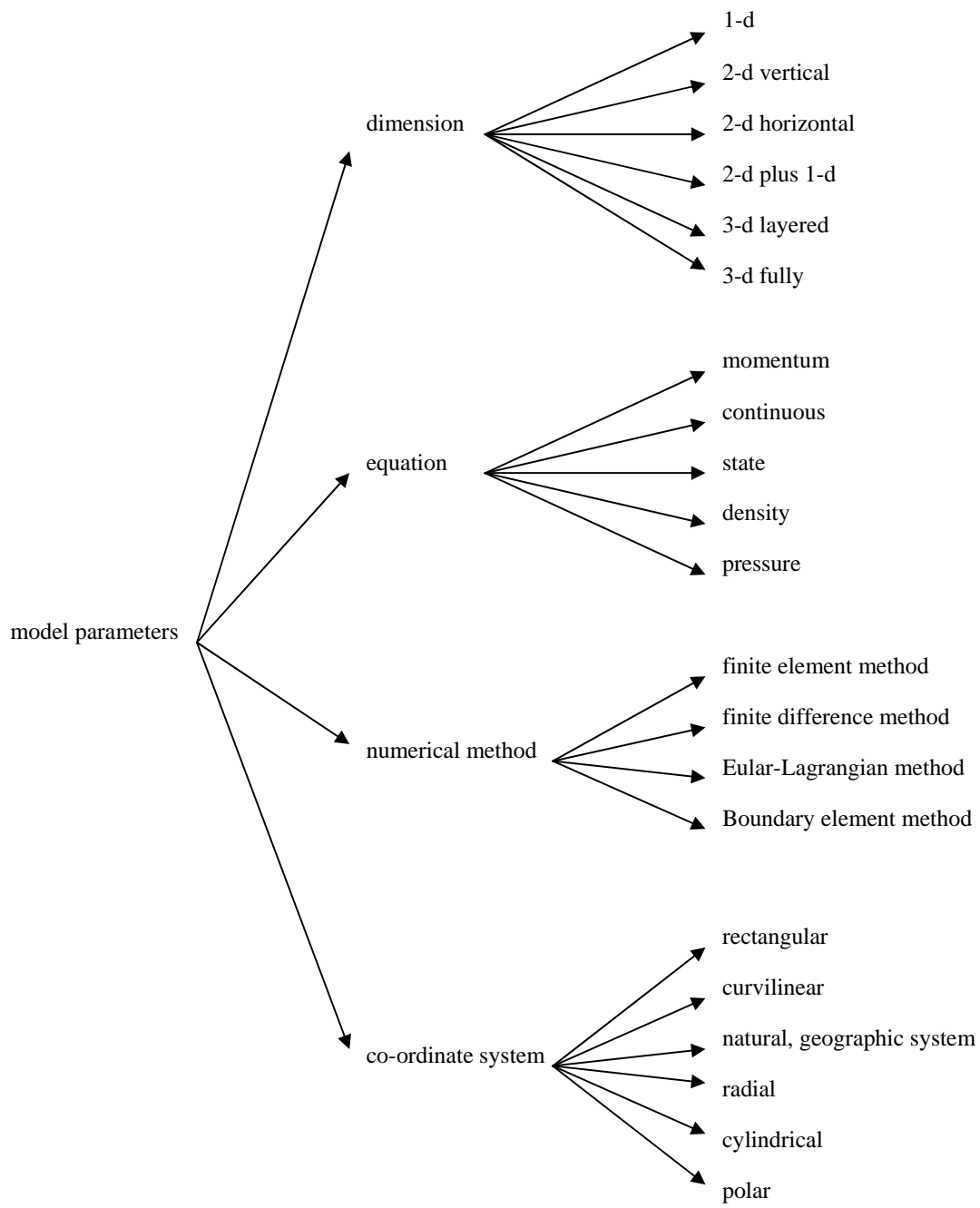


Figure 6

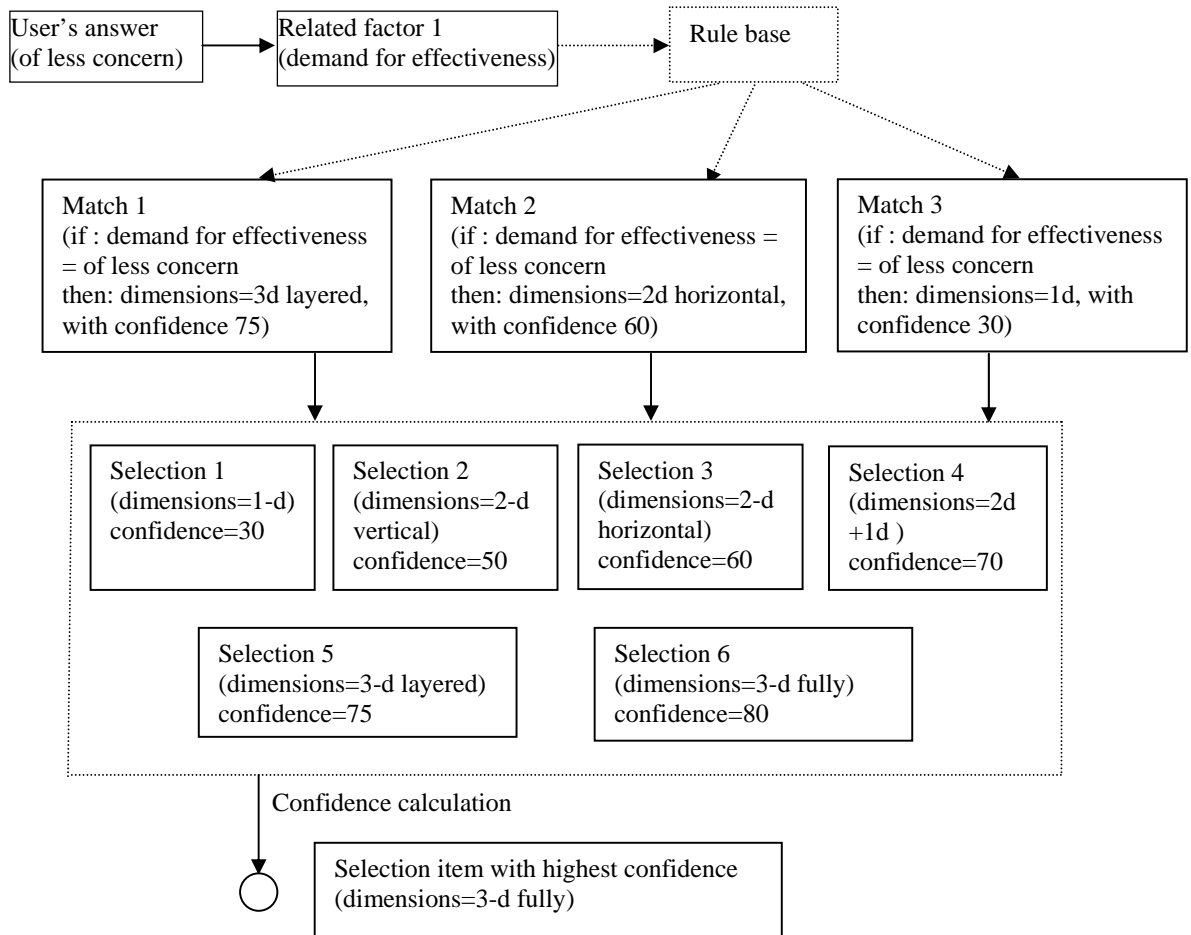


Figure 7

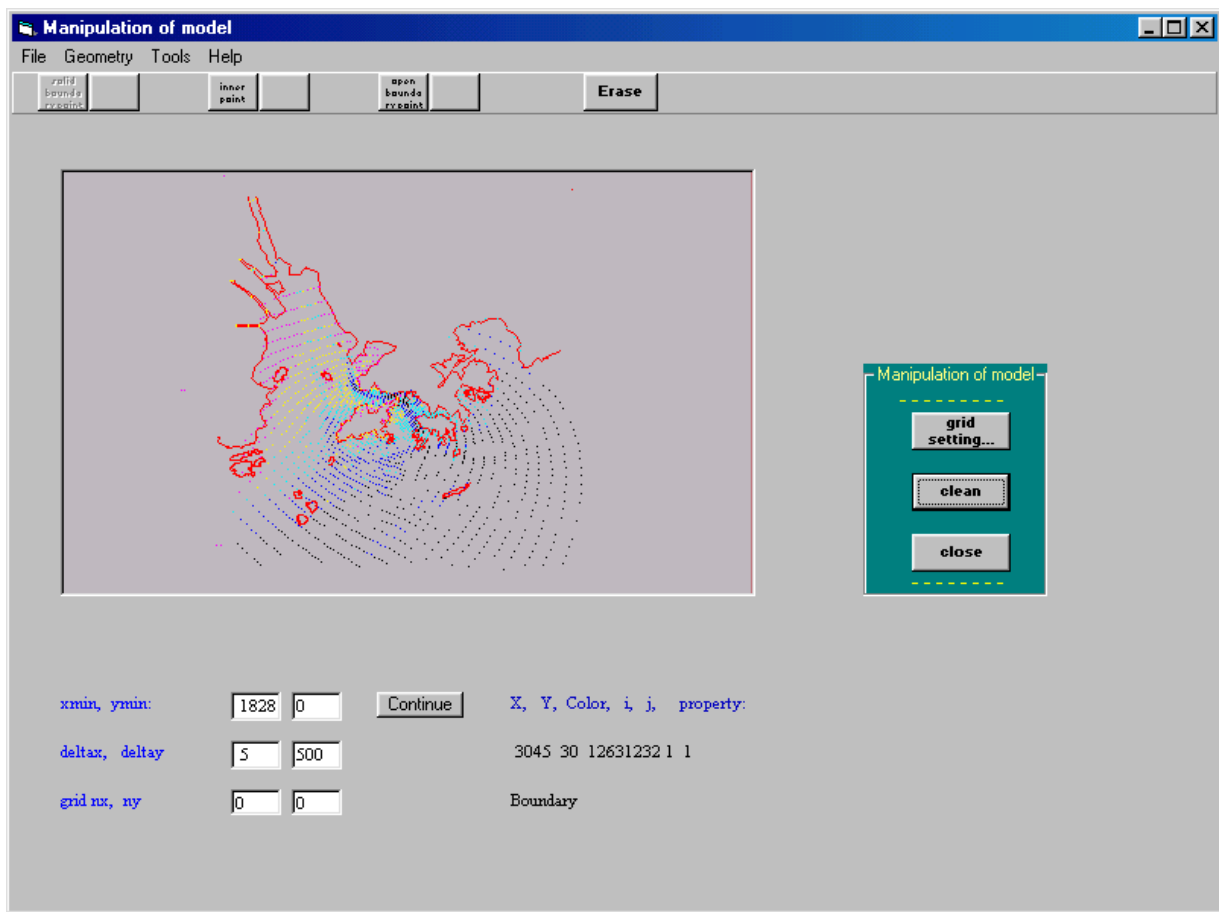


Figure 8