GROUNDWATER MODELING IN ENVIRONMENTAL STUDIES

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ABSTRACT

Groundwater modeling is a computer-based methodology for the mathematical analysis of mechanisms and controls of flow and fate and movement of contaminants in groundwater systems. It plays an increasingly dominant role in a wide range of environmental studies. Computer models are essential tools in the determination of the physical and economical effects of proposed water resources protection policy alternatives, and thus in the protection of human and ecological health. Contamination of groundwater by accidental leakage of hazardous chemicals, and the improper disposal of industrial waste has become a widespread and persistent problem. Such a problem admits no easy analysis or solution because it involves the analysis of a complex system of simultaneous flow and transport of contaminants. Groundwater models, when successfully calibrated and properly applied, allow a numerical representation of the complex phenomena in the subsurface environment. Model predictions substantially improve our understanding of the complex interactions among different processes and provide essential information for environmental planning and management.

This paper presents a powerful and user friendly contaminant transport model with particular reference to its application in environmental studies. The salient features of this finite element model include the incorporation of the influence of tidal effects, preservation of the nonlinearities of the governing flow equation for unconfined aquifers and the treatment of natural boundary conditions, and a multiple option Windows-based Graphical User Interface. The model was applied to investigate a typical groundwater contamination problem associated with waste disposal in shallow aquifers. Replacement of the constant head boundary condition with the natural boundary condition provides the freedom of domain selection and promises a more conservative prediction of contaminant movement. This study also concluded that it is necessary to incorporate the effect of tidal fluctuation in order to quantify the mass transport phenomena with special reference to the coastal aquifers where contaminated groundwater might pollute the marine environment.

KEYWORDS

Groundwater, Aquifers, Contamination, Modeling, Environment, Water Quality

INTRODUCTION

We are living in a world which is becoming increasingly technologically oriented. The rapid growth in industrialization, urbanization, and population during this century has forced us to consider whether we are changing the very conditions essential to life on earth. Concern about the environment has developed from man's ever-increasing impact on the earth. Man's impact on the environment is often termed as pollution in its broadest sense. The ecosystem can adapt to man's disruptive activities, but only to a certain point. It is therefore crucial to understand the nature of the ecosystems to be able to understand the consequences of man's impact on his environment. Today, everyone is acutely aware of civil engineering as an indispensable tool for creating and maintaining the quality of human civilization.

How can we diminish the effect of human activity on the environment ? At present, choosing the appropriate action to combat environmental problem is both difficult and complex. The prime task is the integration of two sets of values - environment and economics. The first step is to understand the relation between the activity and the effect - by means of appropriate environmental science - the multidisciplinary field which is concerned with our environment and the interaction between the environment and man (Figure 1). The second step is to control the impact of human activities on the ecosystem - by means of environmental planning and management, a new interdisciplinary field created during the past two decades. Environmental planning and management looks for the answer to the important question of how to select the best ecological and economical methods for solving a specific environmental problem. Figure 2 presents the complete process of environmental planning and management. The compelling motive for environmental planning and management is to establish a balance between development and environment, assuring minimum irreversibility and maximum sustainability. Figure 3 illustrates the relationships between development and environment while the driving forces regulating the relationships between development and environment are shown in Figure 4 (Di Castri, 1987).

Many organisms and processes interact in the ecosystem and, therefore, mapping the effects of human activity on the ecosystem is a very complicated task. The solution to environmental problems can be found only by comprehensive environmental studies that demand integrated efforts from a wide spectrum of engineers and scientists. Principles and quantification are used as the key words in environmental studies. The capability to represent quantitatively the responses of the environment to actions of man is an essential part of environmental planning and management. The procedure requires the application of the principles and knowledge of environmental processes.

Environmental modeling is a widely used tool for environmental studies. It offers a unique opportunity to screen and select the best environmental planning and management alternatives (Figure 2). Ecosystems are very complex systems, thus it is not possible to consider all their processes in a management situation. However, for a given problem, it is possible, with a good grounding in science and engineering and a good knowledge of the ecosystem considered, to make a simplified model of the ecosystem and its processes, to determine and include the relevant variables, and to omit processes of minor importance.

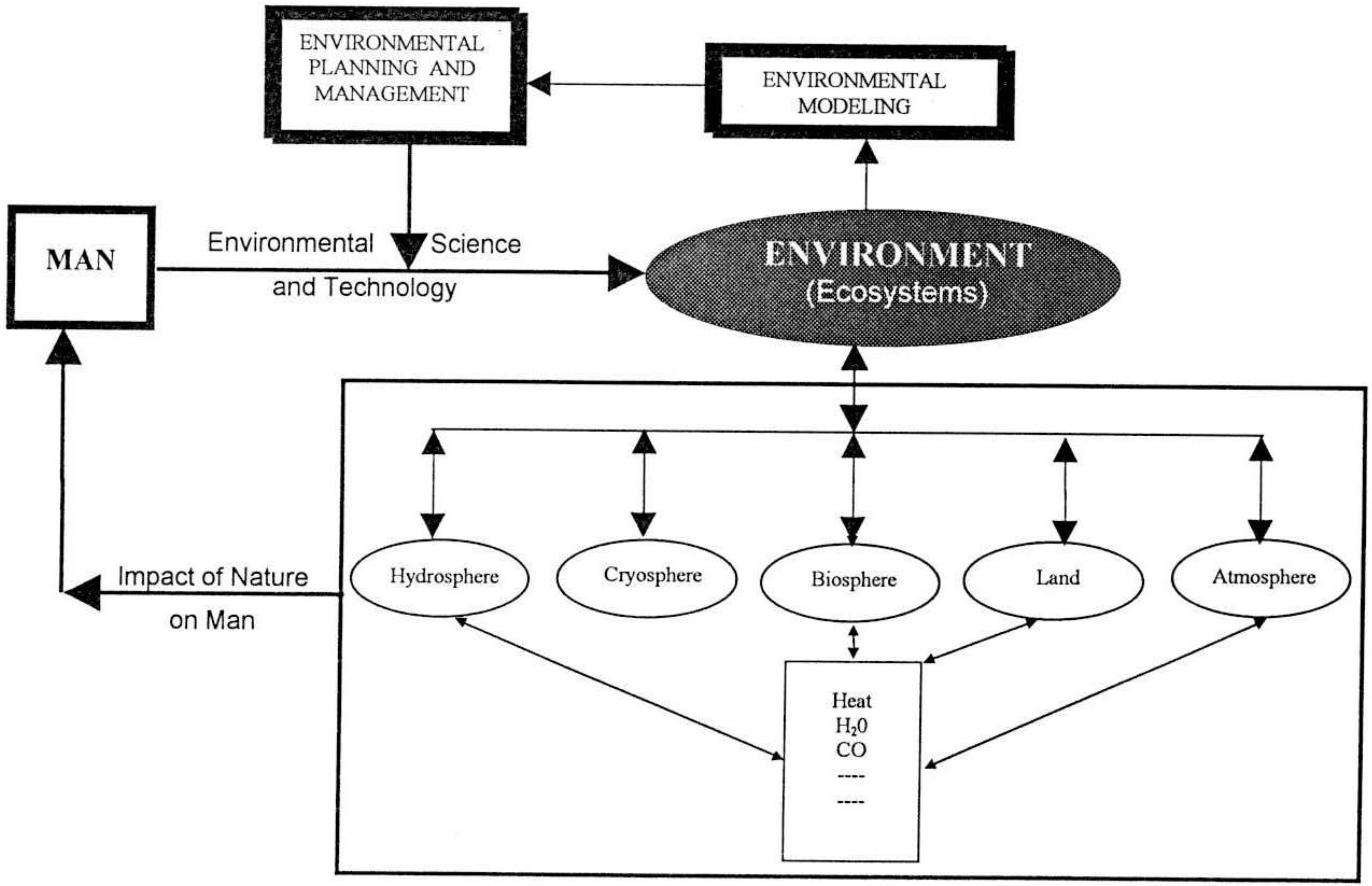

Figure 1. Relations between environmental science, ecology, environmental modeling and environmental planning and management.

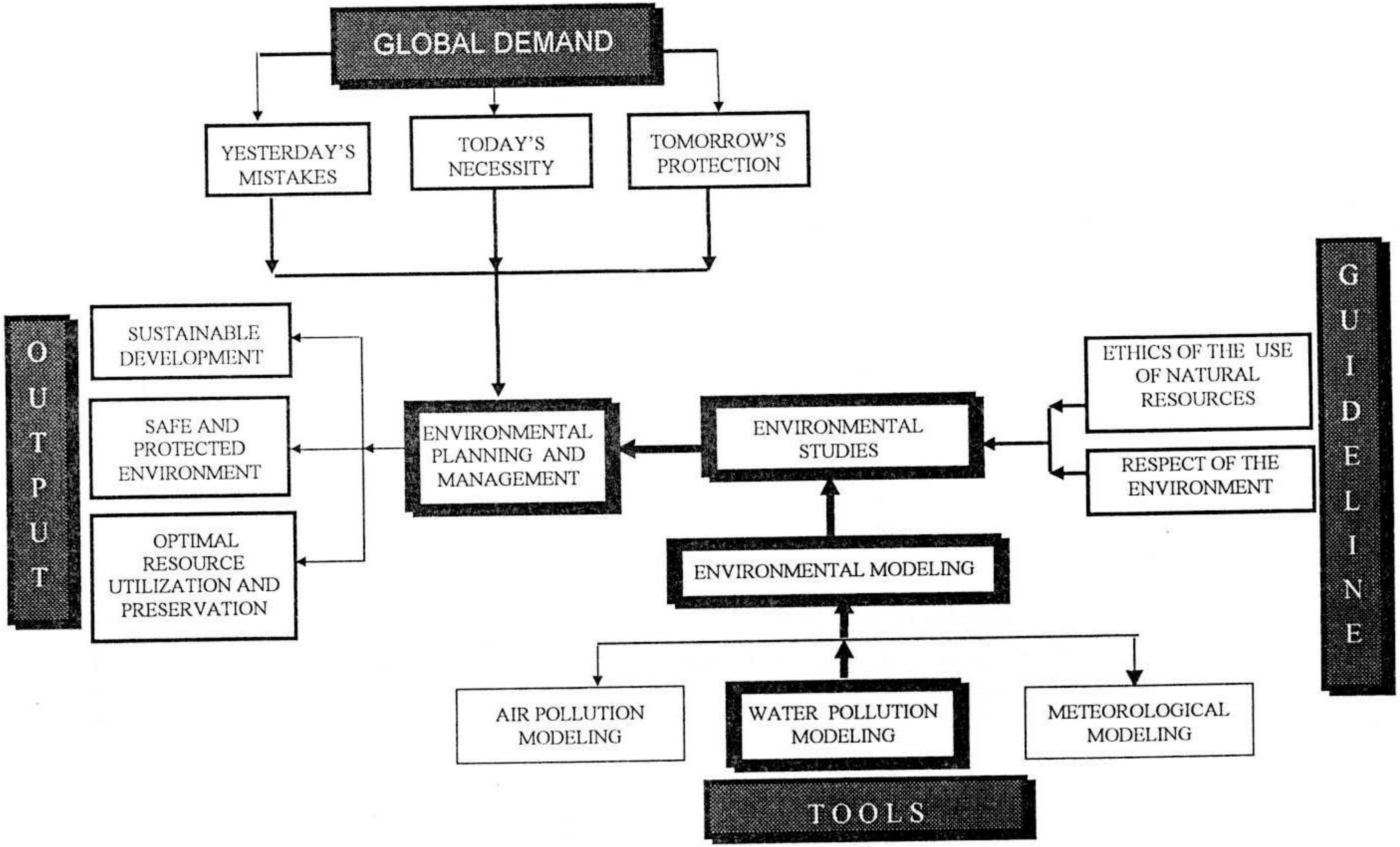

Figure 2. Environmental planning and management process.

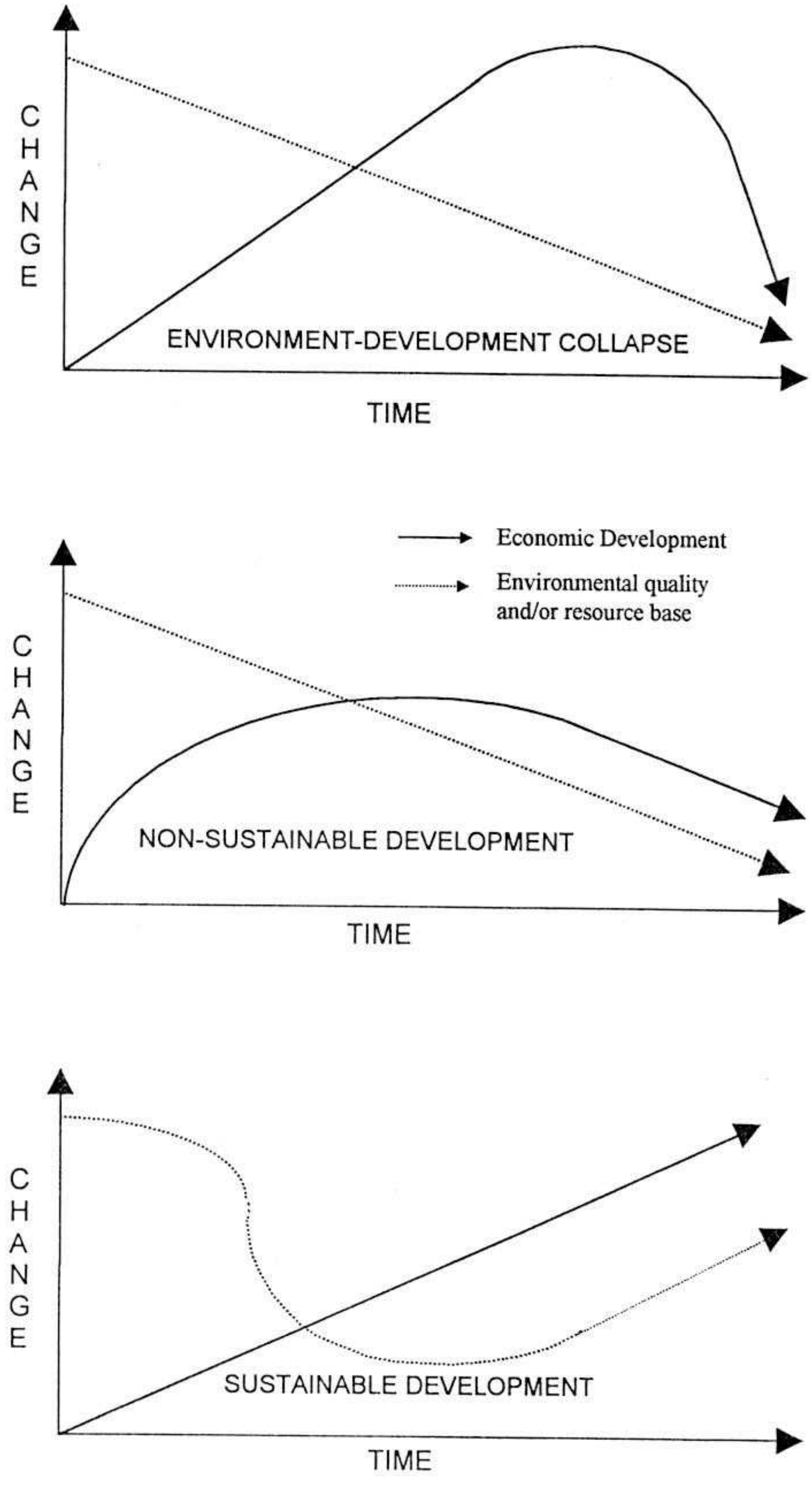

Figure 3. Relationship between development and environment.

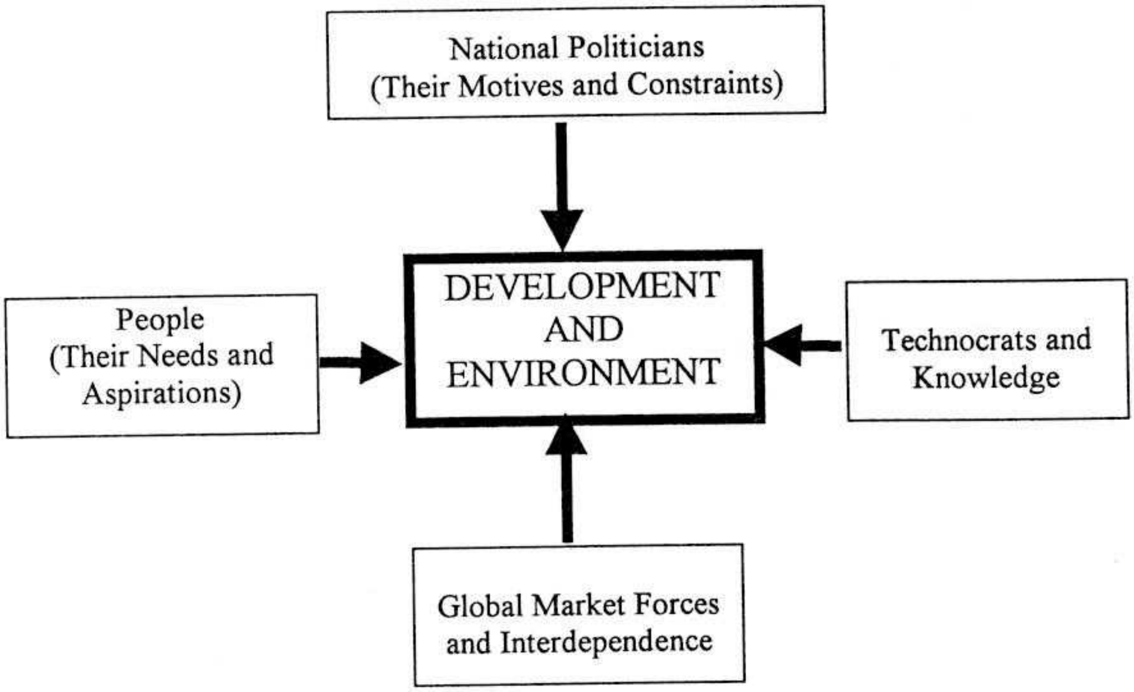

Figure 4. Driving forces regulating the relationship between development and environment.

Such a model will consist of a mathematical description of the processes crucial to the problem, and it is then possible to use the model to evaluate different planning and management alternatives.

The past two decades have seen an unprecedented accumulation of research efforts in environmental modeling. Unfortunately, the very mass of this information explosion has compelled us to concentrate on one particular aspect of environmental modeling that deals with water pollution problems of a diversified nature. The role of water pollution modeling in environmental studies is illustrated in Figure 5.

The purpose of this paper is to present a powerful and user friendly contaminant transport model with particular reference to the important role it plays in environmental studies. The concepts and architecture of the model and its potential applications are discussed in the subsequent sections.

GROUNDWATER MODELING

Groundwater is a subsurface element of the hydrosphere, which is generally understood to encompass all the waters beneath, on, and above the earth's surface. Contamination of groundwater by accidental leakage of hazardous chemicals, and the improper disposal of industrial waste has become a widespread and persistent problem that admits no easy analysis or solution. This is because the introduction of hazardous materials in any hydraulically connected environment results in a complex system of simultaneous flow and transport of contaminants.

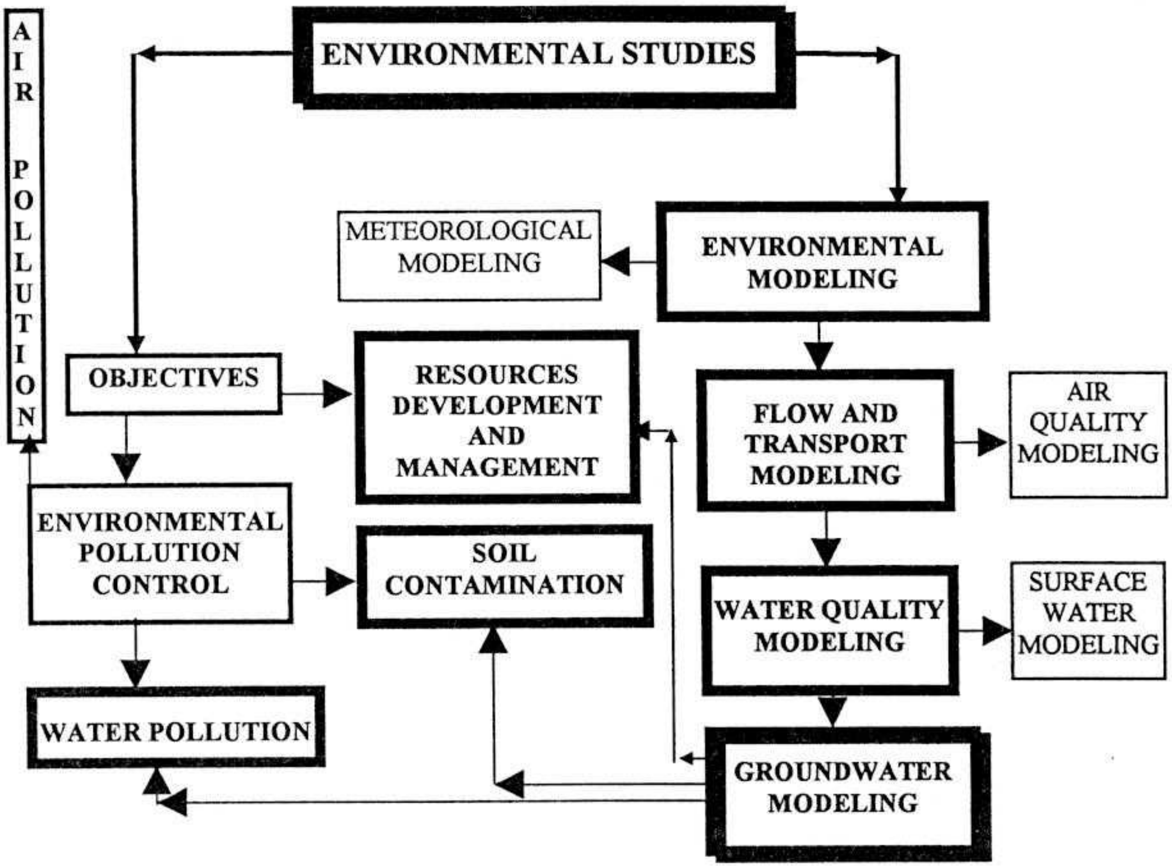

Figure 5. Role of groundwater modeling in environmental studies.

Groundwater modeling is a computer-based simulation approach for the investigation of flow and fate and movement of contaminants in groundwater systems. It is now recognized as an indispensable tool in a wide range of environmental studies. Groundwater models play an increasingly dominant role in evaluation of actual and/or proposed human-induced changes in natural systems. They are essential tools in the determination of the physical and economical effects of proposed water resources protection policy alternatives, and thus in the protection of human and ecological health. Groundwater models, when successfully calibrated and properly applied, allow a numerical representation of the complex phenomena in the subsurface environment. Model predictions substantially improve our scientific understanding of the complex interactions among the different processes. In fact, it is manifest in the groundwater model, which, if correctly designed, will simulate the behavior of the groundwater system under conditions yet to be experienced.

Used with discretion and appreciation of its limitations, the model can become a helpful tool in the management process, enabling the user to explore new horizons of imagination, to compare choices, and to identify pathways toward superior solutions to practical problems.

Mathematical modeling of subsurface flow and transport phenomena is challenging because it demands the integration of so many disciplines. It is dependent upon hydrology and hydromechanics for the description of the movement of water and pollutants, and the mechanisms of mixing. It calls upon climatology, meteorology, and atmospheric physics to specify environmental conditions. Different types of groundwater models are presented in Figure 6. Details of the various types of groundwater models are available in Khondaker et al. (1990) and Batchmat et al. (1980).

THE CONTAMINANT TRANSPORT MODEL - CONTRANS

CONTRANS is a two-dimensional finite element model developed by a group of professionals working with the Environmental Protection Program (EPP) in Water Resources and Environment Division of the Research Institute, King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia. It is a powerful and user friendly model that simulates the natural coupled processes of simultaneous flow and transport of soluble contaminants in the subsurface environment.

The salient features of CONTRANS include:

1. the incorporation of the influence of tidal effects,
2. preservation of the nonlinearities of the governing flow equation for unconfined aquifers and the treatment of natural boundary conditions,
3. a multiple option Windows-based Graphical User Interface, and
4. an embedded mesh generator

The concept and architecture of CONTRANS is presented in Figure 7. Figure 8 illustrates its Windows-based Graphical User Interface. Details of CONTRANS are available in Khondaker et al. (1997) and Al-Suwaiyan et al. (1997).

CONTRANS IN ENVIRONMENTAL STUDIES

In recent years, there has been a growing public concern and increased general awareness of environmental problems. In connection with these problems, engineers and scientists are extensively involved in a range of hydro-environmental and ecological studies arising from various potential contamination sources. Environmental modeling is a modern approach which is widely used in many environmental and ecological studies. Any environmental investigation includes the evaluation of fate and movement of contaminants in the environment.

CONTRANS predicts the spatial and time distribution of soluble contaminants in the subsurface environment. The model predictions are useful for the following purposes:

a) Improving the scientific understanding of the complex natural phenomena of fate and movement of contaminants in the subsurface environment that help analyzing many challenging environmental problems already encountered, as well as other potential problems associated with future development in different sectors.

b) Identification of various sources and the significance of their contribution in environmental pollution.

c) Providing essential information for a wide range of hydro-environmental and ecological studies.

d) Development and application of decision tools for resource development and management

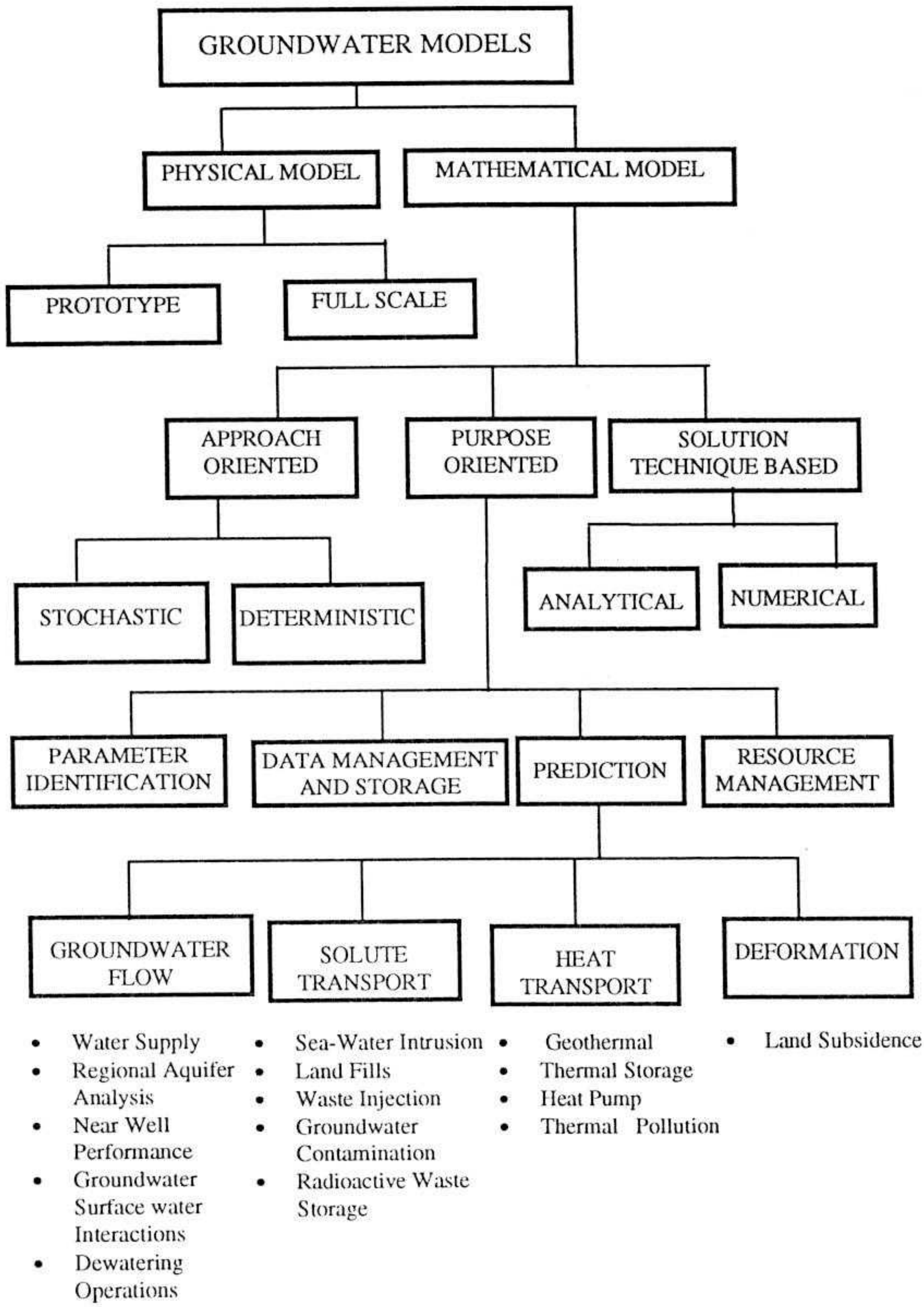

Figure 6. Types of groundwater models and their applications.

e) Development of remediation endpoints for hazardous chemicals in soil and groundwater.

f) Evaluating management alternatives to mitigate environmental pollution problems.

g) Contaminated site assessment and risk analysis.

h) Quantification of contaminant spill in the subsurface environment.

A typical application, presented below, illustrates the important role it plays in groundwater contamination studies. The model was applied to investigate a typical groundwater contamination problem in an unconfined aquifer. In addition to its capability to predict the spatial and time distribution of contaminants, the advantage of using natural boundary condition is also illustrated in this example. Introduction of natural boundary condition allows the user to select a study area of any size.

The hypothetical example represents a common real-world situation of waste disposal in a shallow water table. The input data for the model are shown in Figure 9. Comparisons of simulated contaminant concentration distributions after 125 days under two different boundary conditions are presented in Figure 9. It is evident from Figure 9 that a more conservative prediction of contaminant movement can be obtained by replacing the constant head boundaries with the natural boundary conditions. The effect of natural boundary condition on the spreading behavior of contaminants, however, depends on the size of the study area selected for investigation. Al-Suwaiyan et al. (1997) presented more information on other features of CONTRANS. Khondaker et al. (1997) applied this model to investigate the groundwater contamination problem in a coastal aquifer. The model predictions were used to quantify the mixing behavior of contaminants discharging into the shallow groundwater and delineate the direction of movement and transport of soluble contaminants through the subsurface environment into the marine environment along the coastal boundaries. They evaluated the effects of different types of boundary conditions on the flow dynamics and spreading pattern of soluble contaminants in the subsurface environment. The study of the tidal effects on the flow dynamics confirmed that the behavior of the water table is significantly influenced by the tidal fluctuation along the coastal boundaries. The model predictions showed a decrease in the concentration of the solute with time under the tidal influence for different cases investigated, indicating a loss of solute mass from the study area.

CONCLUSIONS

A brief description of the role of groundwater modeling in environmental studies is presented with particular reference to environmental planning and management. Groundwater simulation models are well recognized as indispensable tools for the investigation of fate and movement of contaminants in the subsurface environment. Groundwater is an integrated part of the ecosystem, and its quality influences a wide range of environmental problems threatening sustainable development - a must to rectify our yesterday's mistakes, today's necessity and tomorrow's protection. Groundwater contamination is also causing structural damage to underground structures. The corrosion and deterioration of substructures depends greatly on the movement of contaminants present in the soil and groundwater. The above discussion concludes that groundwater modeling plays a key role in a wide range of environmental studies.

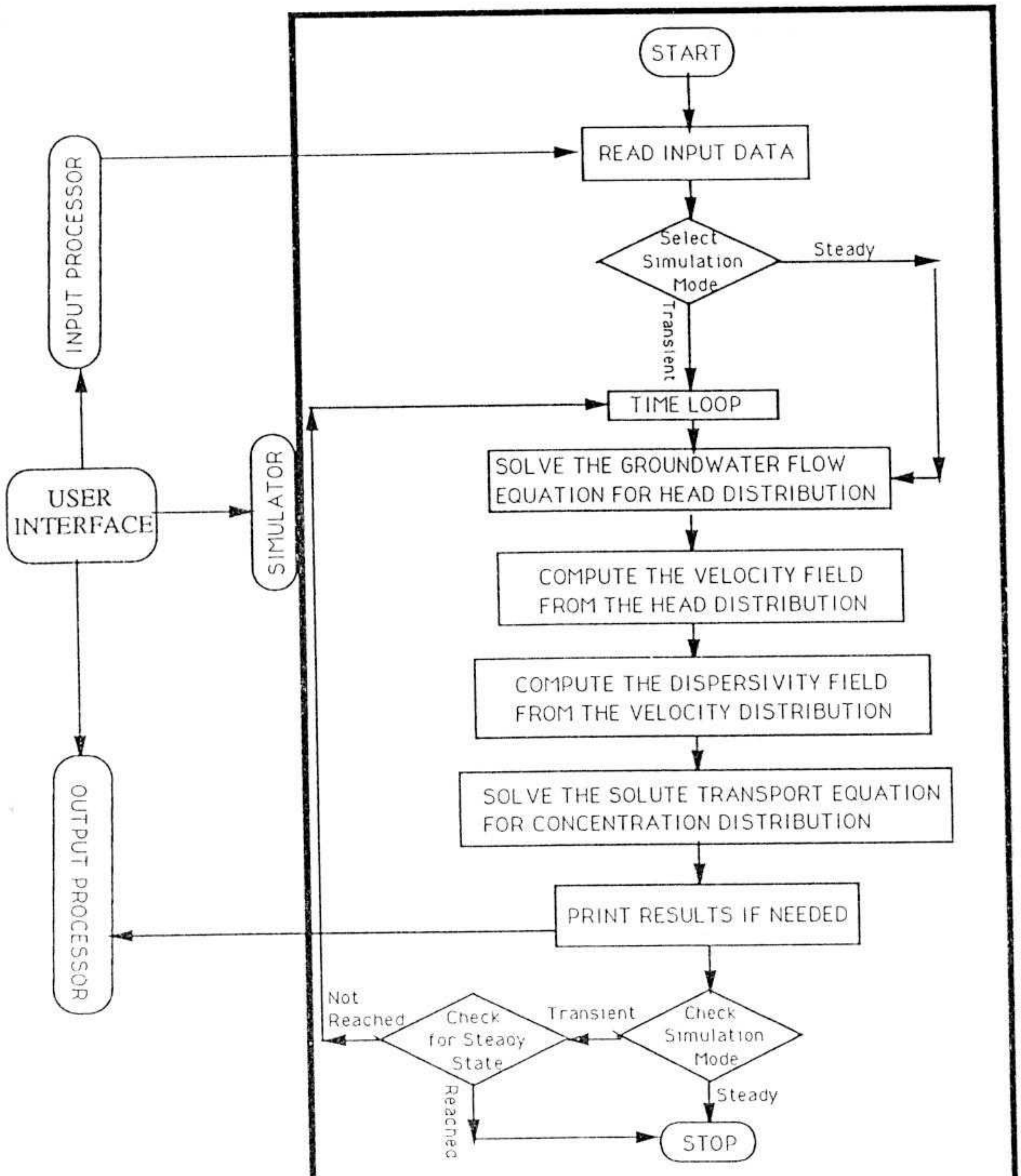

Figure 7. CONTRANS structure.

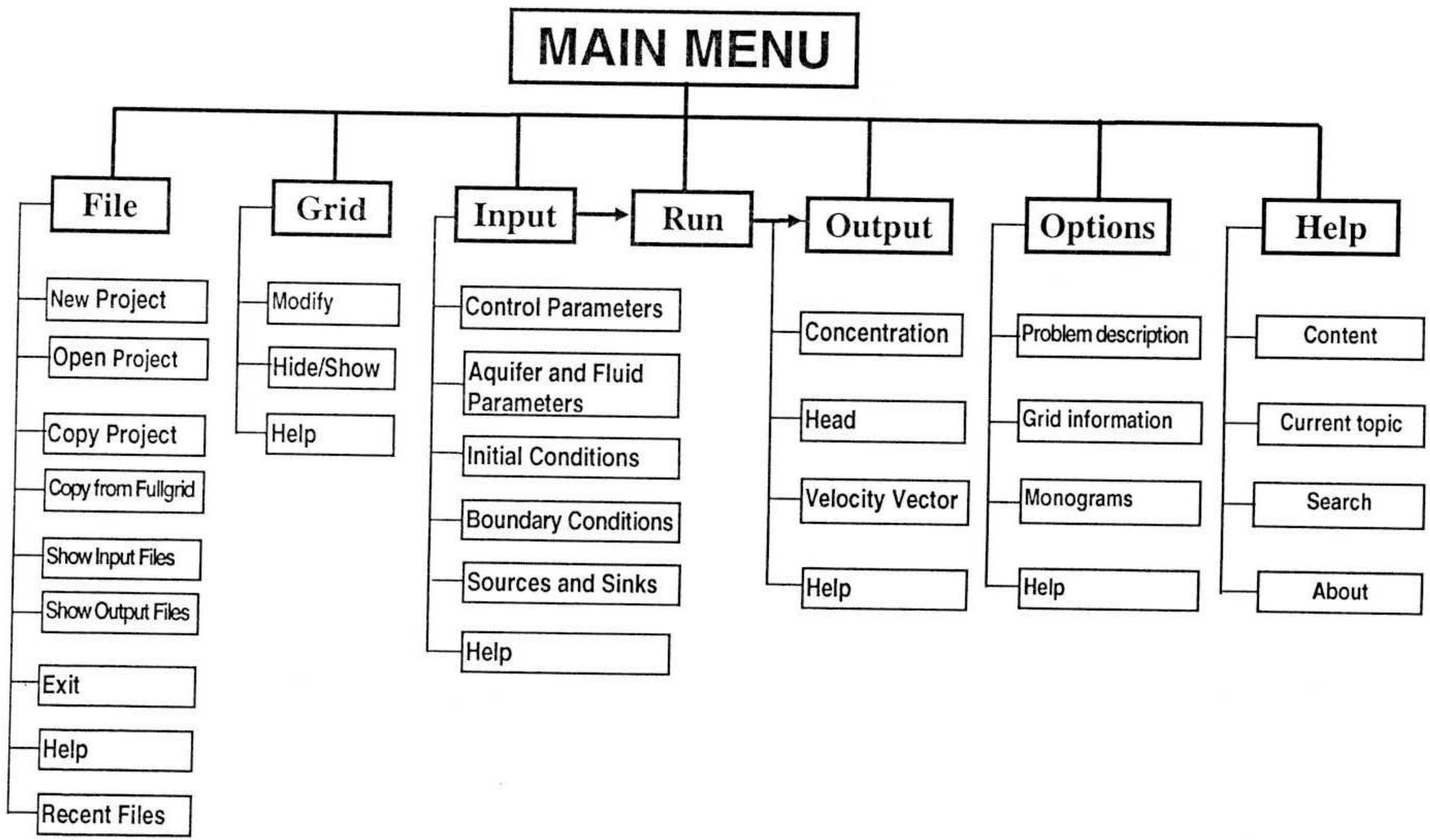

Figure 8 CONTRANS Graphical User Interface.

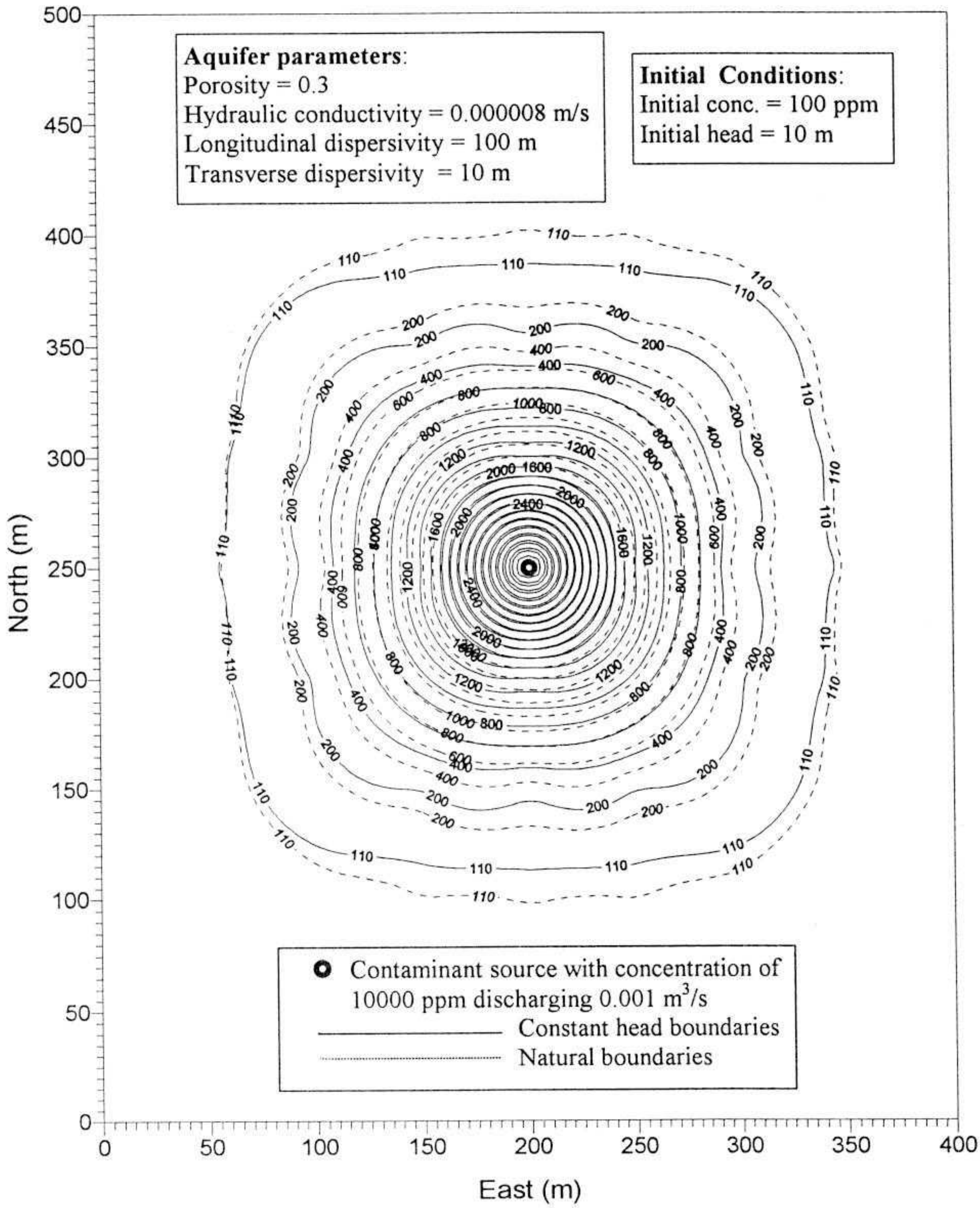

Figure 9 Comparison of simulated concentration distributions obtained after 125 days.

The application of **CONTRANS** to a typical situation of groundwater contamination illustrated several important facts that need to be addressed in modeling subsurface flow and transport phenomena. The study area can be limited to any size by introducing the natural boundary condition. The simple iterative technique used in the treatment of natural boundary condition assures a better continuity along the boundaries. It also promises a more conservative prediction of contaminant spreading compared to that of constant head boundary conditions. It is also necessary to incorporate the effect of tidal fluctuation to quantify the mass transport phenomena with special reference to the coastal aquifers where contaminated groundwater might pollute the marine environment. This study concludes that the model predictions considering all possible combinations of boundary conditions provide essential information for environmental planning and management.

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REFERENCES

Batchmat, Y., Bredehoeft, J., Andrews, B., Holtz, D. and Sebastian, S. (1980), '*Groundwater Management: The Use of Numerical Models*", American Geophysical Union, Washington D.C.

Di Castri, F. (1987), "Global Crises and the Environment", *Study Week on A Modern Approach to the Protection of the Environment*, November 2-7, 1987, pp.7-40.

Khondaker, A.N., Allayla, R.I. and Husain, Tahir (1990), "Groundwater Contamination Studies -The-State-of-The-Art", *Critical Reviews in Environmental Control*, Vol. 20, pp. 231-256.

Khondaker, A. N., Al-Suwaiyan, M.S., Mohammed, N. and Allayla, R.I. (1997), "Tidal Effects of Transport of Contaminants in a Coastal Shallow Aquifer", *The Arabian Journal of Science and Engineering*, Vol. 22(1C).

Al-Suwaiyan, M.S., Khondaker, A. N., Mohammed, N. and Allayla, R.I. (1997), A Two Dimensional Flow and Transport model for Tidaly Influenced Aquifers", accepted in *Journal of King Saud University*, Vol. 10(1).