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Recent Trends in Groundwater Regime Forecasting

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Abstract : *To meet increased demand of groundwater for various purposes there is urgent need for efficient management of aquifers by studying the existing available supplies and possibility of enhancing the recharging potential. Mathematical modelling studies of groundwater system provides systematic approaches for this purpose. This paper discusses in length the broad categories of the models, their specific uses, the type of solution approaches available and the mathematical tools employed for the solution such as finite difference, method of characteristics and finite element methods. Discussion is also made on the calibration of the developed model and its verification using past historical information of the groundwater system under study. A brief description is given regarding various models employed at Central Ground Water Board for predicting the behaviour of ground water systems for different locations in India.*

1. Introduction

The rapid expansion of population, industry and agriculture in recent years, throughout the world, has brought about a steep increase in water demand. All these requirements have to be met mostly from available surface and ground water resources. However, as the number of suitable surface storage sites dwindle, greater stress on use of groundwater appears inevitable to meet the ever-increasing water demand. This calls for an efficient management of existing available supplies and enhancement of recharge potentials by deploying suitable methodology such as artificial and induced recharge.

The use of aquifers has been increasing both as a source of water supply and a medium for storing various hazardous wastes. As the use expands, the knowledge of groundwater system must also expand. The available analytical solutions are restrictive in use as the real systems are quite complex in geometry and matrix characteristics. The stresses imposed also vary widely in space and time and the interlinkages of the aquifer with its surroundings effect it in complex manner. Consequently the analytical solutions of real ground water system are difficult, if not impossible.

In the area of ground water resource planning and management, two new developments in recent years are becoming increasingly more important. These are the application of systems analysis techniques to improve the planning and decision making process and the need for inter-disciplinary team work during such analysis. System analysis has provided a new dimension to man's analytical capabilities, and rapid strides in computer technology have significantly contributed to his computational abilities. These two developments, in combination, now enable planners to develop new and effective management strategies for a popular resource like water, the intensity of demands on which has increased manifold in recent decades and is bound to increase more in the future.

Basically, systems analysis is a problem solving technique where in attempts are made to build a replica of the real world situation with the objective of experimenting with the replica to gain some insight into the real world problem. The system is represented by a series of mathematical expressions in such a way that the resulting relationship describes the phenomenon. This is, what is known as mathematical model building of the system. The parameters that affect the system as well as the factors that influence the parameters, are included in the model. However, since in most cases of groundwater resource planning and management, all the factors affecting the system are not precisely known, the resulting model, therefore, does not exactly describe the real ground water world, but may be fairly close to it for all practical purposes. It may also be pointed out that computers are not essential for system studies but are mandatory if the system to be modelled is complex and multidimensional.

Groundwater models have two related functions in water planning. The first is a means to understand better the mechanism which comprises the ground water system. The second is the use of the model to predict what might happen under various possible future conditions. The prediction, thus, not only allows avoidance of costly experimentation with the real system but also provides means to compare possible alternative actions for most efficient results. The efficiency of the various possible actions can be compared economically, socially, politically or in some combination, in order to provide decision makers with better information base on which to reach decision. Models may also be used for better determination of geohydrologic characteristics and sensitivity analysis. The sensitivity testing provides a way to understand better the real system and evaluate the worth of data collected. However, the most frequent application of ground water models has been to predict aquifer behaviour under different developmental and management options.

2. Groundwater Modelling Principles

Majority of the numerical models of ground water are determinstic in nature and are based on finite difference or finite element approximation of the governing differential equation. They can be broadly put under two categories (i) Direct Models (D.M.) and (ii) Inverse Models (I.M.). Direct Models are those that solve the governing differential equation for the response of the system (e.g. head distribution) given the stress on the system, geohydrologic properties of the aquifer and initial and boundary conditions. Inverse Models, as the name suggests, are those that back out the input information of the Direct Models from known aquifer response data.

The Direct Models have been applied to a wide variety of groundwater problems which include (i) ground water flow in saturated or partially unsaturated materials (ii) land subsidence resulting from groundwater extraction, (iii) flow in coupled groundwater — stream system, (iv) coupling of rainfall-runoff basin models with soil moisture accounting and aquifer flow models, (v) Coupling of economic and hydrologic components, (vi) predicting the transport of contaminants in an aquifer, and (vii) estimating the effects of proposed development schemes for geothermal systems.

The Inverse Models can be broadly grouped into two categories (i) models that use indirect methods to solve the inverse problem, and (ii) models that use direct or algebraic methods for solving the inverse problem. The first category models essentially consist of the following steps : (i) an approximate value of the unknown parameters is assumed, (ii) with assumed parameters, the Direct Model is run to solve for the aquifer response, (iii) the results of step II are compared with actual observed historical data, (iv) if the observed and model responses do not correspond within a prescribed limit, the parameters in step (i) are updated with the help of a suitable adjustment algorithm, (v) steps (ii) to (iv) are repeated until satisfactory value of criterion function, expressing the difference between the observed and the computed values is obtained.

The basic premise of the direct method for solving the inverse problem is that it does not require the iterative solution of the aquifer flow equation which is an essential characteristics of the first category inverse models. The method consists of replacing the partial differential equation of flow by a system of algebraic equations and has two distinct steps, (i) estimation of partial derivatives of the dependent variable from given discrete data by fitting a suitable mathematical surface which possesses the desired properties of the dependent variable surface and, (ii) the solution of the algebraic equations resulting in step (i) to recover the value of the unknown parameters.

It may, however, be mentioned that the Inverse Models, though quite many reported in recent years, are still to find general applicability in the real life situations. Field hydrologists find it yet easier to adjust the model parameters by trial and error than to go for the inverse models to determine the input parameters for later use in the Direct Models. This is because of many uncertainties and non-uniqueness associated with those models. It is the Direct Models that have found general applicability and vast variety of use in ground water problems.

The variety and complexity of mathematical models used in ground water applications have increased dramatically during the last twenty years. This increase has been made possible by significant advances in digital computers, but has also been enhanced by environmental concerns. This proliferation of mathematical models is often bewildering to the hydrologist who is trying to keep up with the research literature. It may, however, be mentioned that though the number of model types is large, only a few basic processes are considered in almost all of them. This is somewhat ironic since the large number of "different" models is the result of various simplifying assumptions used to reduce a general set of equations to some solvable form. Fortunately, if one keeps in mind the fundamental processes being simulated, then different or simplified forms of equations are less confusing.

The major processes that may be considered part of many ground water models are fluid flow, solute transport, heat transport and deformation. Even though only four general processes have been identified, the number of different models that can be conceived is very large. The reason for this is that many of the model variations are application dependent. In addition to application-dependent variations, for convenience, equations describing the same process are often posed in terms of different dependent variables. The wide variety of solution techniques employed in ground water models have also led to the availability of a large number of models. The partial differential equations are usually used to describe the problems in ground water hydrology. Without a solution, however, these equations are of little value. Only a simplified subset of the general equations can be solved by analytical means, and these often describe idealised situations that are limited in application. Numerical solution of the equations using high speed digital computers offers a logical alternative.

The numerical techniques commonly used in ground water applications are variations of two general methods, the finite difference method (including the integrated finite difference method) and the finite element method. Occasionally, specialized techniques such as the method of characteristics are also used. All of these methods approximate the continuous partial differential equations with discrete equations, requiring matrix solutions.

There are two basic ways to solve matrix equations numerically : (i) direct and (ii) iterative. In the direct methods, a sequence of operations is performed only once, and the results obtained are an approximation to the true results. The iterative methods attempt solution by a process of successive approximation.

No particular combination of numerical technique and matrix solution procedure is best for all applications. For most ground water flow problems, the FDM is probably adequate. For sharp front problems the MOC or FEM will probably give better results. For deformation problems, the FEM is better because of its treatment of tensorial parameters. For any given class of problems the choice of the best approach depends on the process being modelled, the accuracy desired, and the effort that can be expanded on obtaining a solution. Often times, however, the hydrologist simply uses a technique that he is familiar with and a computer code that is well documented.

Table 1 presents the pros and cons associated with the different techniques generally employed in ground water model building.

Table 1 : Brief Summary of Important Advantages and Disadvantages of FDM and FEM.

Advantages	Disadvantages
FINITE DIFFERENCE METHOD	
Intuitive basis	Low accuracy for some problems
Easy data input	
Efficient matrix techniques	Regular grids
Program changes easy	
FINITE – ELEMENT METHOD	
Flexible geometry	Mathematical basis is advanced
High accuracy easily included	Difficult data input
Evaluates cross product terms better.	Difficult programming

3. Model Verification

Before a model is used as a predictive tool, it has to pass the test of reliability. This is known as calibration of the model, which is based on history matching technique. The matching procedure is used to refine the initial estimates of aquifer properties, and determine boundaries and boundary conditions so as to arrive at a good match between the observed and simulated responses. The unreliability associated with the mathematical models results from several considerations, important of which are conceptual errors, truncation errors, round off errors and data errors. It is therefore, imperative to test the reliability of the models before they are considered adequate for forecasting and system management. Two techniques are available for model calibration (i) subjective or trial and error, and (ii) automatic history matching. The subjective techniques require repeated running of direct model and comparison of the model response of the natural system at the end of each run by the hydrologist himself. The comparison is subjective and the adjustments of the parameters arbitrary. In this procedure, therefore, the number of 'runs' required to produce a satisfactory match depends on the objectives of the analysis, the complexity of the flow system and length of observed history, as well as the patience of the hydrologist. In order to facilitate model calibration and to quantify better the adequancy of the calibration and predictions, automatic calibrational procedures are now introduced which have resulted into the development of Inverse Model described earlier. Part of the historical response data is used as input to the Inverse Model to obtain the best fit parameters and the boundary specifications. This results in evolution of the system model which is then run with the past aquifer excitation data and the model and system responses of the remaining period of the history are compared. If the two tally, the model is said to be a 'near true' representation of the natural system. Once satisfactorily calibrated, the model can be used to predict the future behaviour of the aquifer system. Of course confidence in any predictive results must be based on (i) a thorough understanding of model limitations, (ii) the accuracy of the match with observed historical behaviour, and (iii) knowledge of data reliability and aquifer characteristics. As a caution it may also be mentioned that aquifer identification problem which is the subject matter of Inverse Models, has a propensity for instability and hence it can be numerically delicate in the presence of any appreciable error in the measurement of system responses. Extreme care is therefore, required in application, analysis and interpretation of results obtained from automatic aquifer identification studies.

Table 2 presents advantages and disadvantages of subjective (Trial and Error) and automatic history matching procedures.

Table 2 : Advantages and Disadvantages of Trial and Error and Automatic History Matching Procedures

Advantages	Disadvantages
Trial and Error	
Well documented programs	Time consuming
Conceptually straight forward	Subjective
Automatic History Matching Procedures	
Less subjective	Programs less well documented
Fewer computer runs	Statistical training necessary
Statistical estimates of confidence	Still a research tool

4. Predictive Digital Models used in Central Ground Water Board

In India, the various centres of technological and hydrological research have been the mainstay for ground water model building activity. The Central Ground Water Board, an apex organisation for surveys, exploration and management of ground water resources of the country has been mainly incharge of development and application of mathematical models in real ground water basins. Efforts are made to make these models general so that with minor modifications, they can be used in other basins also.

The first significant effort made by Central Ground Water Board to develop the modelling technique for management of complex aquifer basins was in 1974, when the Mehsana basin was modelled. Thereafter a number of model studies have been under-taken and completed. Models have been developed and used to study real situations both in hard rock areas and alluvial formations.

Table 3 presents the salient features of the models used in the Central Ground Water Board. In addition, two more model studies in Kasai-Swarna Rekha Basin and Coastal Kerala Area are underway.

Table 3 : Salient Features of Important Direct Models Used in Central Ground Water Board

Area Studied	Aquifer Features	Type of the Model	Purpose of the Model
Mehsana Basin (Gujarat)	Unconfined and semiconfined that merge into one in Upper reaches. Alluvial, non-homogeneous isotropic.	Two dimensional Finite Difference, Transient, Steady State flux backed out and reused in transient model, numerical Scheme and time Centred Crank Nicholson differencing FORTRON IV language.	Forecasting development options, scope & efficiency of artificial recharge.
Ghagar River Basin (Himachal Pradesh, Rajasthan, Haryana and Chandigarh)	Unconfined and semiconfined which merge into one near hills Alluvial, non-homogeneous, isotropic.	Quasi-three dimensional, steady unsteady flow with solute transport, Numerical scheme uses space centred Central difference scheme and time centred Crank Nicholson differencing, FORTRON IV language.	Prediction of aquifer behaviour and change in salinity as a result of various developmental, options. Water supply management for Chandigarh. Evaluation of effects of canal seepage and irrigation return flow. Artificial recharge possibility.
Upper Yamuna Basin (Himachal Pradesh, Haryana, Uttar Pradesh and Delhi).	Unconfined, nonhomogeneous isotropic, stream aquifer interaction incorporated. Alluvial formation, Partially penetrating stream.	Two dimensional Finite Element transient flow, Galerkin procedure, Isoparameteric elements with quadratic sides, Gaussian quadrature for integration in space. Crank-Nicholson for time derivatives.	Forecasting the effect of ground water development on river regeneration and ground water environment.

Area Studied	Aqufier Features	Type of the Model	Purpose of the Model
Vedavati River Basin (Karnataka, Andhra Pradesh).	Semiconfined aquifer in hard rock fracture overlain by aquitard, non-homogeneous, anisotropic	Two dimensional Finite Difference transient with provision for leakage through aquitard, ADI method. A quadratic predictor is used to obtain approximate solution to start ADI algorithm.	Prediction of ground water regime as a consequence of various ground water developmental strategies.
Noyil River Basin (Tamil Nadu, Kerala),	Phreatic and semiconfined aquifer in hard rock formations, non-homogeneous, anisotropic.	Finite Difference, two dimensional, steady transient flow model ADI procedure for solution of algebraic equations.	Prediction of aquifer response to surface water and ground water development in the area.
NION River Basin (Madhya Pradesh).	Semi-confined aquifer in hard rock formation non-homogeneous, anisotropic	Finite Difference, two dimensional, steadytransient model Line Successive Over Relaxation (LSOR) technique used for solution of algebraic equations.	Prediction of aquifer response to surface and ground water development, sensitivity analysis of input data.
Pilot Project for Induced Recharge Study	Phreatic aquifer in alluvial formations, nonhomogeneous isotropic.	Finite Difference, two dimensional transient model, Iterative Alternate Direction Implicit (IADI) technique adopted for solution of algebraic equations.	Prediction of optimum pumpage, induced recharge, long-term effect on ground water regime due to development of surface and groundwater in relation to optimum cropping pattern.
Pilot Project for Artificial Recharge Study.	Phreatic aquifer in alluvial formation, non-homogeneous, Isotropic.	Finite Diference, two dimensional, transient Model. Line Successive Over Relaxation Technique (LSOR) used for solution of algebraic equation.	Forecasting the response of the ground water system to different recharge techniques. Study of efficiency and economics of recharge techniques.

The modelling techniques applied in the Organisation so far, range from the well established finite difference method to highly sophisticated and versatile finite element method. Multiple aquifer systems with provision of leakage between them have also been modelled. The river-aquifer interaction models have been evolved to have a more realistic concept of induced recharge and effects of ground water development on base flows. These models are also being equipped with programme for integrated water use and economic study of various developmental strategies. Efforts are also underway to develop computer based and management and information system for efficient storage and retrieval of data and other related routine informations. The newly created Data Storage & Retrieval Directorate and Mathematical Modelling Directorate shall provide a sound base for development and use of these and other computer based sophisticated techniques in the organisation. A terminal of NEC 1000 Super computer has been installed in the Board to augment its computational capabilities.