TRAINING COURSE

ON

SOFTWARE FOR GROUNDWATER DATA MANAGEMENT

UNDER

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LECTURE NOTES
ON

GROUNDWATER MODELLING SOFTWARES

(UNIT-1)

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OVERVIEW OF GROUNDWATER MODELLING SOFTWARES

1. INTRODUCTION

The amount of water stored in the earth's crust is immense. The volume of water stored in the rocks of the world's land areas may be on the order of 8 billion cubic kilometers, of which half is at depths less than 800 m. This volume is about 35 times the combined storage of all the world's rivers, freshwater lakes, reservoirs and inland seas, and is about one-third the volume of water stored in the arctic and antarctic ice fields, the glaciers of Greenland and the great mountain systems of the world (ASCE, 1987).

Groundwater is one of the important phase of the hydrologic cycle (Fig. 1). It constitutes a significant portion of the entire water supply of the earth as stated earlier. This resource is of paramount importance in those regions where surface water is inadequate or making the the availability of surface water is not economical, or in arid and semi-arid regions. Although, this lecture notes is devoted exclusively to models dealing with various kinds of groundwater problems, many other models exist to deal with the problems emerged from interrelations between groundwater and surface water; groundwater and soil water; and groundwater, soil water and atmosphere. These interrelations and interactions of these systems to the mankind become of paramount importance in comprehensive planning for the maximum utilization of all water resources.

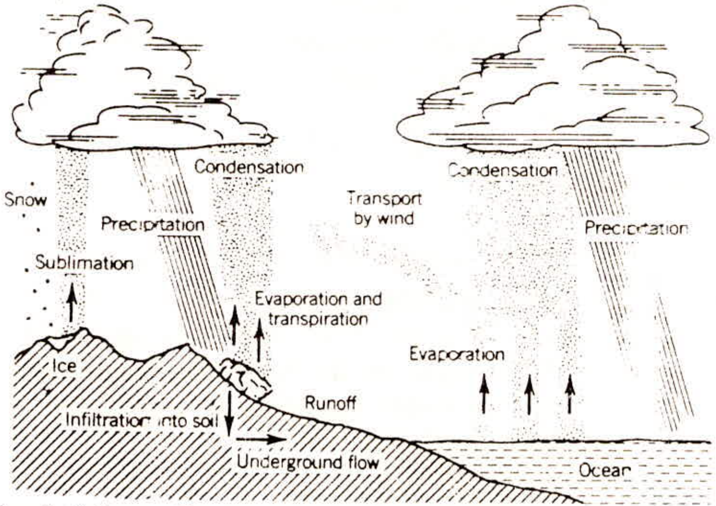

Fig. 1 Schematic representation of the hydrologic cycle (after Domenico and Schwartz,1990)

Historically, many types of models have been used for simulating groundwater distribution and flow conditions in water bearing materials. The first simulation attempts used analog models of physical systems such as sand boxes, electrical conductivity sheets and resistance-capacitance network models. More recently, digital computers have become highly advanced and numerical analysis techniques have been accurately developed to take the full advantage of their capabilities. With these newly available tools, mathematical groundwater basin models and their application in groundwater management has become commonplace. The various techniques are employed to solve localized, regionalized, comprehensive and integrated groundwater basin planning, development and management problems.

Depending upon the intended objectives and nature of the study, groundwater models are formulated. Now a days, many simulation and optimization models are being used to sought the solution for diverse kinds of groundwater problems occurring in different regions of the world. The groundwater models are developed mainly for one of the following groundwater problems:

- Simulation, Prediction, or Forecasting Problems
- Identification or Inverse Problems
- Management Problems
- Monitoring Problems
- Design Problems
- Scheduling Problems

Groundwater basins undergo changes due to climatic cycles and/or man's influence. Most of the changes imposed by men are not planned, but as water becomes more valuable, the need to make changes, knowing the probable results, becomes more important. As in other fields where models are used, the purpose for predicting is not just to predict, but to compare possible alternative actions for most efficient results. The efficiency of the results can be compared economically, socially, financially, politically or in some combination of those aspects. Every model can be used to make predictions which can in turn be used for optimising the alternative actions.

2. MODELLING EQUATIONS

Hydrological processes transform the space and time distribution of water throughout the hydrologic cycle. The motion of water in a hydrologic system is influenced by the physical properties of the system, such as the size and shape of its flow paths, and by the interaction of the water with other media, including air and heat energy. Phase changes of water between liquid, solid and vapour are important in some cases. Many physical laws govern the operation of hydrologic systems.

A consistent mechanism needed for developing hydrologic models is provided by the Reynolds transport theorem, also called the general control volume equation. This theorem is applicable to any extensive property of the system (White, 1986; Chow et al., 1988). The Reynold transport theorem is used to develop the continuity, momentum and energy equations for various hydrologic processes. The governing equations in groundwater are derived using this theorem, and the fluxes to represent the physical, chemical and biological processes occurring within the groundwater system are computed using the appropriate constitutive laws.

2.1 Reynold Transport Theorem

The Reynold transport theorem states that the rate of change of an extensive property of a system is equal to the sum of the rate of change of extensive property within the control volume and the excess of efflux over the influx of the extensive property. Mathematically for the fixed control volume, it can be expressed as:

$$\frac{d(B_{syst})}{dt} = \iiint_{CV} \frac{\partial(\beta\rho)}{\partial t} d\vartheta + \iint_{CS} \beta\rho(\mathbf{v}\,.\,\mathbf{n})\, dA \tag{1}$$

where B_{syst} and β are extensive and intensive properties of the system, respectively; ρ, $d\vartheta$, **v**, dA and **n** represent density of fluid (water in the present context), differential volume, flow velocity, differential area and outward normal unit vector on the control surface, respectively. CV and CS stand for control volume and control surface, respectively.

2.2 Groundwater Balance Equation

The core of the mathematical model that describes the transport of any extensive property, e.g., mass or energy, in a porous medium domain is the balance equation of that quantity. The hydrologic balance or hydraulic equation is a statement of the conservation of matter applied to a groundwater basin. All water entering an area during any given period of time must either go into storage within its boundaries, be consumed, be exported, or flow out, either on the surface or underground, during that period. The hydrologic balance equation used by different modellers may be expressed, in a simplified form, as follows:

$$\frac{dS}{dt} = I(t) - O(t) \tag{2}$$

where S is the storage of the groundwater system under consideration, t is the time, and I(t) and O(t) are the input to and output from the system at any time t, respectively.

The various components in the hydrologic balance may be broadly classified as:

- Surface (Inflow/Outflow)
- Subsurface (Inflow/Outflow)
- Precipitation
- Evapotranspiration
- Imported/Exported water
- Decreased/Increased surface storage
- Decreased/Increased soil moisture storage
- Decreased/Increased groundwater storage

The hydrologic balance for a groundwater basin would include all items of inflow and outflow. In a short term budget; a month, a season, a year, or even several years, substantial differences may occur between natural inflows and outflows. The difference is accounted for in the balance by changes in storage. Budgets for successive short periods of time would show an unsteady state resulting from short-term climatic changes. The longer the time period chosen for the budget, the more nearly the budget will indicate the steady-state conditions of the average climate. Over a long enough period of time changes in storage, changes in storages become insignificant, and the first four items mentioned above express the overall natural balance.

The groundwater balance may be computed for any time interval, but the complexity arises with large areas. This is due to spatial variability and associated uncertainty. The discrepancy of water balance is basically a residuals of the water balance equation and is partly attributed due to associated errors in the computation of various components and the processes/properties which are not taken into consideration.

2.3 Groundwater Flow Equation

Groundwater flow equation is a continuity equation for flow. Fig. 2 shows the definition sketch of a leaky confined aquifer system. The transient groundwater flow equation for two dimensional areal flow of homogeneous compressible fluid through a heterogeneous anisotropic leaky confined aquifer system is expressed as (Bear and Verruijt, 1987; Willis and Yeh, 1987; Keshari and Datta, 1996a):

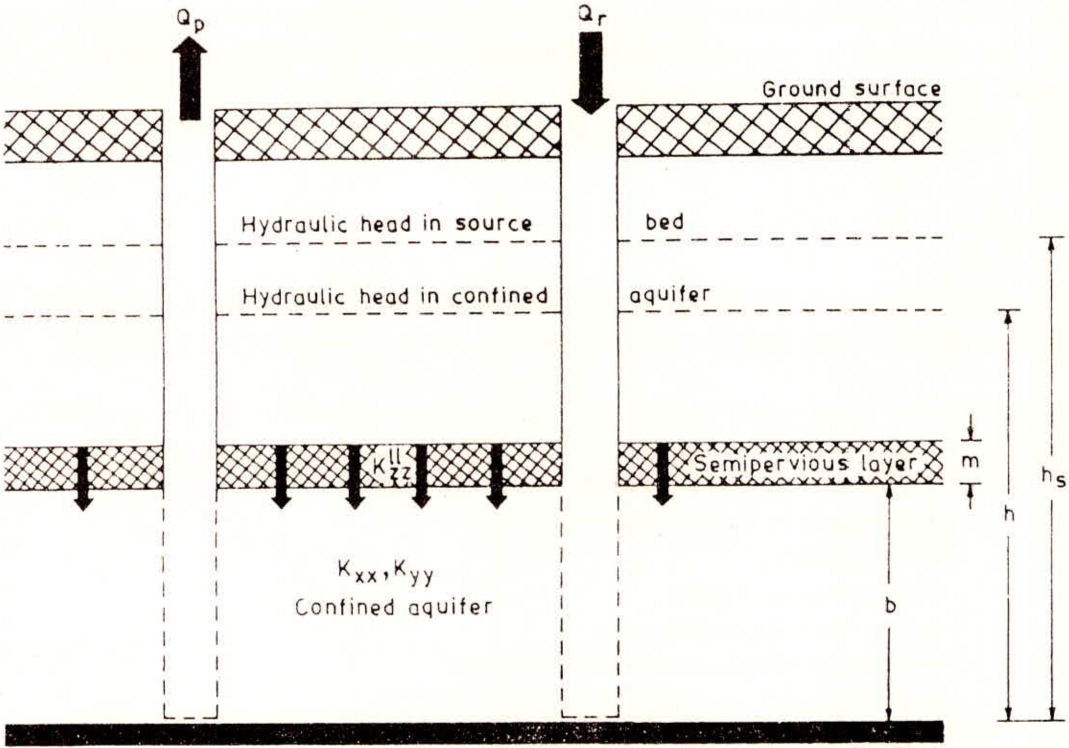

Fig. 2 Definition sketch of a leaky confined aquifer system (after Keshari and Datta, 1996b)

$$\frac{\partial}{\partial x_i}\left(T_{ij}\frac{\partial h}{\partial x_j}\right) = S\frac{\partial h}{\partial t} + \sum_{w\in\Omega_p} q_{pw}\,\delta(x-x_w,\ y-y_w) - \sum_{w\in\Omega_r} q_{rw}\,\delta(x-x_w,\ y-y_w) - \frac{K_{zz}^{l\,l}}{m}(h_s - h); \qquad i,\ j = 1,2 \tag{3}$$

where

T_{ij} = transimissivity tensor
h = hydraulic head
x_i, x_j = cartesian coordinates
S = storage coefficient
t = time
q_{pw} = specific point pumping from the wth pumping well located at (x_w, y_w)
q_{rw} = specific point recharge from the wth recharge well located at (x_w, y_w)
Ω_p = index set of the location of all pumping cells within the system
Ω_r = index set of the location of all recharge cells within the system

$K_{zz}^{l\,l}$ = vertical hydraulic conductivity of the leaky layer
m = thickness of the leaky layer
h_s = hydraulic head in the source bed
$\delta(x-x_w, y-y_w)$ = Dirac delta function

The groundwater flow equation describes the head distribution in the aquifer with respect to space and time. It is a linear partial differential equation. However, for unsaturated flows, the groundwater flow equation becomes nonlinear. The groundwater flow models developed by different modellers are more or less based on Eq. (3). The slight modification in this equation will represent the various processes occurring in the groundwater system under investigation.

2.4 Groundwater Contaminant Transport Equation

There are many processes which govern the transport of a contaminant in a porous media. These processes may be either physical, chemical, biological or a combination of them. The principal processes, which are predominant and most oftenly used by groundwater modellers, are advection (convection), mechanical dispersion (convective dispersion), molecular diffusion, radioactive decay and adsorption. The pumping from groundwater reservoirs, recharge or leakage to the groundwater system, and other hydraulic and hydrogeological settings influence the contaminant transport appreciably. Different processes are incorporated into the model depending upon the intended objectives and nature of the pollutant. Fig. 3 shows the dispersion of a pollutant originating from a point source at a microscopic scale.

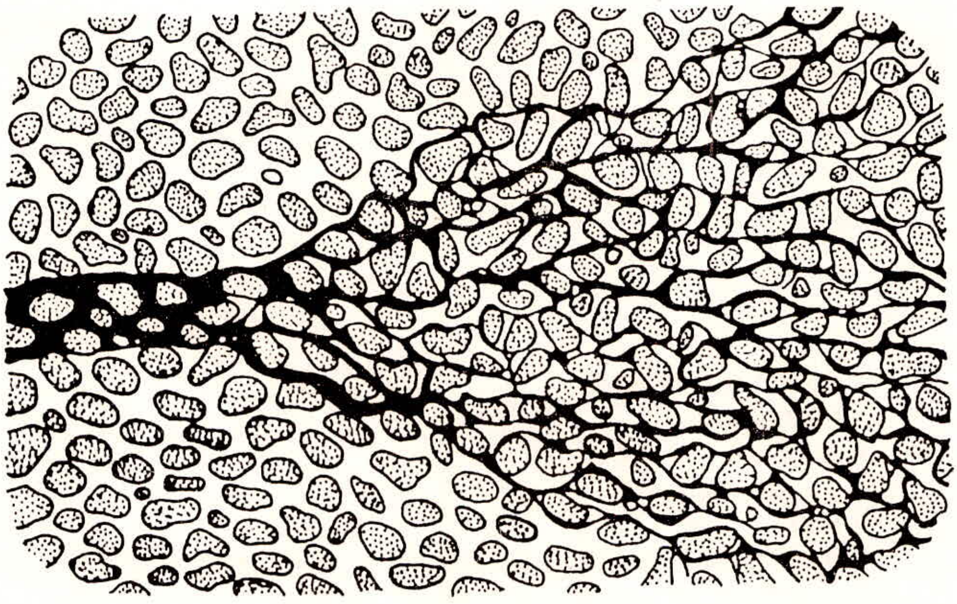

Fig. 3 Dispersion of a pollutant originating from a point source at a microscopic scale (after Keshari, 1994)

The groundwater contaminant transport equation is a continuity equation for the transport of a contaminant. The contaminant transport equation for the two-dimensional areal transport with linear rate of decay and linear equilibrium sorption isotherm of a single dissolved chemical constituent in leaky confined aquifer system is expressed as (Gorelick, 1983; Konikow and Bredehoeft, 1984; Bear and Verruijt, 1987; Keshari and Datta, 1996a):

$$R_d \frac{\partial}{\partial t}(b\,C) = \frac{\partial}{\partial x_i}[\,b\,(D_h)_{ij}\,\frac{\partial C}{\partial x_j}] - \frac{\partial}{\partial x_i}(b\,C V_i)$$

$$- \lambda R_d b\,C - \sum_{w \in \Omega_p} \frac{q_{pw}\,C}{n_{eff}}\,\delta(x - x_w,\ y - y_w) + \sum_{w \in \Omega_r} \frac{q_{rw}\,C_r}{n_{eff}}\,\delta(x - x_w, y - y_w)$$

$$+ K^{l\,l}_{zz}\,\frac{h_s - h)\ C_l}{m\,n_{eff}}; \qquad i,\ j = 1,\ 2 \tag{4}$$

where

R_d = retardation factor
b = saturated aquifer thickness
C = concentration of the dissolved chemical species
$(D_h)_{ij}$ = hydrodynamic dispersion tensor
v_i = average seepage velocity in the direction i
λ = first order kinetic decay rate
n_{eff} = effective aquifer porosity
C_r = contaminant concentration in recharge
C_l = contaminant concentration in leakage

The contaminant transport equation describes the chemical concentration in the aquifer with respect to space and time. It is a nonlinear partial differential equation. Most groundwater quality models are based on this generalized contaminant transport equation. However, many models are in much simplified manner. This transport equation is modified as per the desired objectives, and is included in the transport model. Some quality models differ appreciably from such type of quality models in structure.

3. MODELLING APPROACH

Mathematical models of groundwater basins and aquifers have been used in solving hydrologic problems for many years by using equations of groundwater flow. Each equation is valid for particular boundary and flow conditions, and new equations are being continually developed for other boundary and flow conditions. In addition, some new equations are developed, or more generalized equations are being modified to incorporate various other physical processes to deal with different kinds of groundwater problems encountered in real life situations.

For solving problems in large areas with complex geologic and hydrologic factors, the special mathematical equations are not adequate. Analytical solutions are available only for simplified boundary conditions and flow conditions. For different kinds of groundwater problems, various types of models have been evolved. Such models vary widely from simple to complex and sophisticated. Complex and sophisticated models are generally used to deal with large and complex problems. The models include analytical, semianalytical, physical or scale, analogue and numerical models. With the advent of computers, many numerical models varying in kinds, details, techniques and objectives have been evolved to sought the solution of myriad groundwater problems.

The first groundwater models were analogs of simple groundwater systems. For instance, sand tanks were used to portray groundwater movement in unconfined conditions. More complex groundwater situations could be simulated by analog electrical resistor networks or analog computers. While these analog models were useful, they were also physically and economically restricted to small-scale, idealized groundwater problems. With the widespread availability of digital computers, large-scale groundwater problems are now easily solvable. Early use of digital computers required extensive computer programming to make a groundwater model functional. As groundwater modelling techniques have advanced, many different solution strategies have been developed to solve the systems of mathematical equations. The libraries of successfully applied computer programs are available, and these programmes can be utilized for the modelling purposes.

3.1 Physical Models

Physical models are those which are scaled down from true conditions. These models are usually made of similar materials and having the same basic physical properties. The most obvious example is a sand model of part of an aquifer. The fluid could be water or some other fluid. This kind of model is useful for demonstration, but appears to be best for unsaturated and multiple fluid flow problems. In any event, the reduction in size becomes a problem when the model is too small and large models are more costly. Capillary action, enclosed air and organic growths on small models may be troublesome, and thus, require special treatment and attention.

Of particular interest is the use of such models to predict motion in multifluid problems such as sea water intrusion. Optimising as such cannot generally be done on the model except in very simple cases. Various trials must usually be made and applied as experimental data to optimising techniques. Laboratory facilities are of course required.

3.2 Analog Models

Long before digital computers were available, many physical systems were simulated using physical analogs. The first attempt to simulate groundwater storage and movement is credited to Pavlovskii in 1918. Early use of electrical analog simulation techniques resulted from similarity between Darcy's law and Ohm's law. This similarity has led to several types of electric analog models. These include conductive liquid analogs, conductive solid sheet analogs, resistance-capacitance network analogs and complex analog computer models. The Hele-Shaw model is well known example of an analog model that uses the movement of a viscous fluid between two closely spaced parallel plates to model seepage in an aquifer or embankment.

The advantage of analog techniques is that they force the modeler to physically create the model. This construction process may ultimately provide the modeler with a better feel for the physical system being simulated. The disadvantages are that a real-life analog groundwater model will be bulky to deal with, difficult to modify, and incapable of simulating common situations such as transient multilayer leaky aquifer systems. With the ready availability of digital computers and already developed programs, the use of analog techniques is decreasing.

3.3 Analytical Models

Analytical solutions are available for the groundwater flow and the contaminant transport equations with simple boundary conditions and for the simplified situations in one-dimension. However, analytical solutions of the equations of flow and contaminant transport are not available when boundaries are complex and for most of the real-life situations. Furthermore, most of the users do not have sufficient mathematical background to complete such solutions. However, it should be remembered that analytical approach is the mathematically ideal way to solve these equations. It should be recognised that digital computer programmes are now available to solve ordinary differential equations with a minimum knowledge of programming language.

When boundary conditions are simplified, including the time conditions, the equations either have been solved or can be solved. As a result, there are large numbers of solutions for many different boundary conditions. In a sense, each of these solutions is a model of the particular conditions defined. They have been and will continue to be of great use. Moreover, these solutions are very much useful in validating the numerical groundwater models.

3.4 Semi-Analytical Models

Now a days, solutions of many two-dimensional groundwater problems having a variety of boundary conditions are feasible using semi-analytical methods. These models have increased the potential use of analytical models, and are encouraged for the preliminary analysis. These models can be utilized successfully for small problems and to elucidate many hydrological information.

3.5 Numerical Models

Numerical models are capable of solving large and complex groundwater problems varying widely in size, nature and real-life situations. With the advent of high speed comuters, spatial heterogeneities, anisotropy and uncertainties can be tackled easily. Transient problems in two- and three- dimensions can be solved using numerical techniques. Optimization techniques also can be employed to incorporate various constraints and objectives. With the help of digital computers, numerical methods can be utilized easily to solve various groundwater problems being encountered in day to day life.

Numerical techniques include most of the methods which require a digital computer to do the arithmetic. The finite difference method and finite element method are most commonly used methods for approximating the partial differential equations of the flow and contaminant transport equations. Recently, the boundary element method is also being used. The various schemes are also available to discretize the equations. The resulting algebraic equations can be solved using available numerical methods for the solution of set of algebraic equations.

Most commonly used methods for solving the set of equations are Gauss-Jordan, Gauss-Seidel, Gaussian Elimination methods, and Newton's method, Matrix Inversion, relaxation techniques, etc. For the details on the application of numerical methods in groundwater hydrology, readers may refer Remson et al. (1971), Pinder and Grey (1977), Javandel et al. (1984). Many groundwater models have been developed to deal with the various real-life problems over the globe, and many of them are well documented. Some of the well documented softwares are described briefly in section 4.

Various numerical models are available to predict solute contaminant concentrations in one, two and three dimensions. The models vary in the number of simplifying assumptions that must be made due to the cost of running the model and the level of effort needed. Most numerical models incorporate more information and require more data and expertise to run then simpler analytical models. Anlaytical models are not as rigorous in treating variable aquifer parameters. Regardless of the complexity of the model, however, representative input data must be used to obtain reliable results, and the results of the models must be interpreted with care.

The determination of whether or not to use modeling and the level of effort that should be expended is made on the basis of the objectives of the modeling, the ease with which the subsurface can be conceptualized mathematically, and the availability of data. Field data are collected to characterize the variables that govern the hydrologic and contaminant response of the site in question. Estimates based on literature values or professional judgment are frequently used as well.

The main features of the various numerical methods are:

- The solution is sought for the numerical values of state variables only at specified points in the space and time domains defined for the problem.
- The partial differential equations that represent the physical processes occurring within the system under investigation are replaced by a set of algebraic equations written in terms of the sought discrete values of the state variables at the discrete points in space and time defined for the problem.
- The solution is obtained for a specified set of numerical values of the various model coefficients.
- Since a very large number of equations are involved and needed to be solved simultaneously, a computer code has to be developed in order to obtain a solution using a digital computer.

Fig. 4 shows the solution strategy for the coupled set of flow and transport equations to simulate the contaminant distribution.

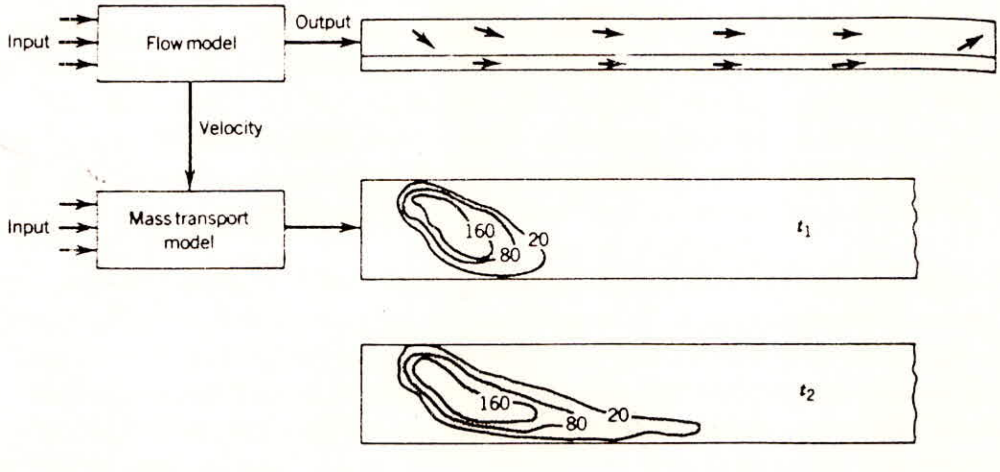

Fig. 4 Solution strategy for the coupled set of flow and transport equations

Another important feature of modelling closely associated with the problem of parameter identification is that of uncertainty. It is uncertain whether the conceptual model indeed represents what happens in the real groundwater system, albeit to the accepted degree of approximation. Furthermore, even when employing some identification technique, one can not be certain about the values of the coefficients to be used in the model. Possible errors in observed data used for parameter identification also contribute to uncertainty in model parameters. As a consequence, one should also expect uncertainty in the values of the state variables predicted by the model. These considerations pave the way to the development of stochastic models in which the information appears in the form of probability distributions, rather than as deterministic ones. A large number of researchers are currently engaged in developing methods that incorporate the uncertainty in both the forecasting and the inverse problems. Fig. 5 shows the classification of hydrologic models according to the way they treat the randomness, and space and time variability of hydrologic phenomena.

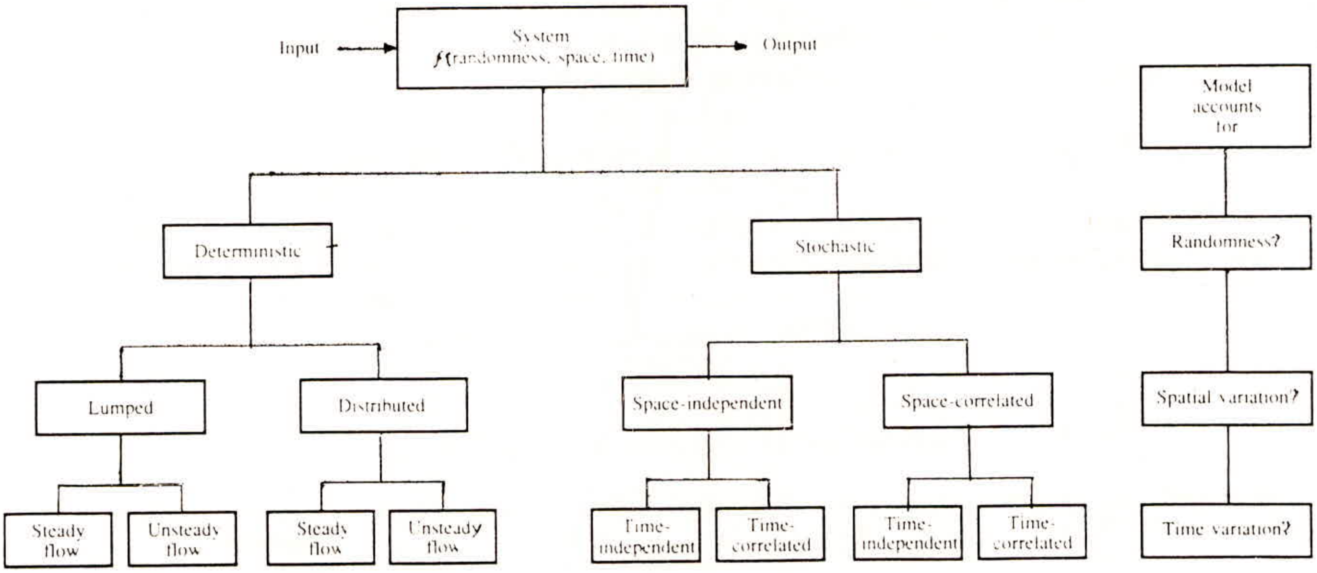

Fig. 5 Classification of hydrologic models based on the treatment of hydrological processes

The current easy accessibility of computerized groundwater models leads to their application early in the over-all groundwater system investigation. In the first stages of their development, groundwater models were used only in basins where the geologic structure was well defined and the hydrology was well understood. Now, mathematical groundwater models are applied often in basins where the aquifer structure and hydrology are only approximately known. In these cases, as in all groundwater modelling situations, the model itself is used as a tool to guide groundwater analysts in their investigations. Once a rudimentary groundwater model has been developed, it quickly points up needs for additional field analysis, data collection, and geologic and hydrologic studies to build an adequate data base. One of the benefits derived from constructing a mathematical model is an improved appreciation of the relative importance of the various elements of hydrologic and geologic data. Hydrogeologic studies provide the geometry and hydraulic characteristic of the groundwater basin. A hydrologic study provides detailed water balance information for verification of a model.

4. SURVEY OF GROUNDWATER MODELS

During the last three decades, many groundwater models were developed. These models differ significantly in their structural sophistication, objectives, computing effort and skill for the use. Spatially the models are one-, two-, or three-dimensional. Temporally, they simulate the groundwater system in either a steady or a transient state. Numerical solutions to these models are accomplished either by Finite Difference Method (FDM) or Finite Element Method (FEM), or more recently by the Boundary Integral Equation Method (BIEM). Linear, nonlinear and dynamic programming techniques are also used in groundwater models. These programming techniques are useful tools in some facets of water resources planning, particularly in the field of optimization.

This lecture notes is confined to the simulation models only. Table 1 gives a survey of the brief discription of the most commonly used groundwater models. Many management models which utilize optimization techniques varying widely from simple to advanced (complicated and sophisticated) techniques have been also developed in the last two decades, and is currently used in many applications. For the optimization models, readers may refer Gorelick et al. (1983), Keshari (1994), Keshari and Datta (1996a).

Table 1. Brief discription of groundwater modelling softwares

Code Name	Developer	Method	Remarks
PLASM (2-D)	T.A. Prickett et al.	FDM	PLASM stands for the Prickett-Lonnquist Aquifer Simulation Model. The Finite difference equations are solved using a form of the Iterative Alternating Direction Implicit (IADI) procedure. It is a flow model.

MODFLOW (3-D) (MODPATH)	USGS	FDM	MODFLOW is a MODular three dimensional finite difference FLOW code. It has been developed by the U.S. Geological Survey (USGS), U.S.A. The code permits the user to select a series of packages (or modules) to be used during a given simulation.
MODINV	J. Doherty	FDM + Optimization	It is developed for the MODFLOW pre-processing, post-processing & parameter optimization. It basically enhances the usefulness of this popular FDM groundwater flow model.
BIO1D (1-D)	GeoTrans, Inc.	FDM	BIO1D is designed to evaluate one-dimensional transport of reactive dissolved specied that undergo adsorption and degradation. The model is ideally suited for deciding which transport processes are important in a given problem.
RNDWALK (2-D)	T.A. Prickett et al.	FDM+RWM	RNDWALK is the RaNDom-WALK model, origianlly developed by the Illinois State Water Survey. It simulates 2-D contaminant transport.

USGS MOC (2-D)	USGS	FDM+MOC	It is the flow and transport code based on the Method Of Characteristics (MOC). It solves contaminant transport in two dimensions. The code was developed by the USGS.
BIOPLUME II (2-D)	Rifai et al.	FDM+MOC	The MOC code has also been extended to treat variable density fluids and to allow parallel computation of an organic plume subject to biodegradation and an oxygen plume.
SWIFT II (3-D)	GeoTrans, Inc.	FDM	The Sandia Waste-Isolation Flow and Transport model (SWIFT II) is a three-dimensional finite difference model for fluid flow, heat, variable density-brine, and trace-level radionuclide transport.
SWIFT III	Reeves & Cranwell	FDM	It is the modified version of SWIFT II. It is a Sandia Waste-Isolation Flow & Transport model for fractured media. It is a fully transient 3-D model. The processes included in the model are fluid flow, heat transport, dominant species miscible displacement and trace species miscible displacement.

HST3D (3-D)	USGS	FDM	HST3D is a Heat- and Solute-Transport code for 3-D simulations. It couples mesh centered finite difference equations for flow, heat, and solute transport including linear equilibrium adsorption and first-order decay. Confined and unconfined aquifers under transient conditions can be represented.
PATH3D (3-D)	Papadopulos et al.	Runge-Kutta	PATH3D uses a fourth-order Runge-Kutta numerical tracking solution that allows a particle to take several small tracking steps while moving across a finite difference block.
PRZM (1-D)	U.S. EPA	Compartment	PRZM stands for the Pesticide Root Zone Model. It is a time-dependent compartment model that simulates chemical movement under unsaturated conditions in the plant root and vadose zones.
SESOIL (1-D)	U.S. EPA	Compartment	SESOIL is a SEasonal compartment model for a SOIL column, the EPA designed to provide multiple-year simulations of water, chemical and sediment transport using a monthly time step.

SUTRA (3-D)	USGS	FDM+FEM	SUTRA stands for the Saturated-Unsaturated TRAnsport. It simulates two-dimensional, density-dependent flow and transport of either a dissolved solute or thermal energy under variably saturated conditions. SUTRA was developed by the U.S. Geological Survey to provide investigators with a tool to evaluate the importance of concentration or temperature on density-dependent flow.

Code Name	**Developer**	**Method**	**Comments**
Aquifer I, II	Pinder	FDM	2-dimensional flow, saturated zone fluid flow.
Aquifem	Wilson et al.	FEM	2-dimensional flow, saturated zone fluid flow.
FLUMP	Neuman	FEM	2-dimensional flow, saturated zone fluid flow.
MICHIGAN	Wingert	FEM	2-dimensional flow, saturated zone fluid flow.
FRESURF	Neuman	FEM	2-dimensional flow, saturated zone fluid flow.
ISOQUAD 2	Pinder and Frind	FEM	2-dimensional flow, saturated zone fluid flow.
SAMIR	Armisen et al.	FEM	2-dimensional flow, saturated zone fluid flow.
HOREC	Luckner and Schestakov	FDM	2-dimensional flow, saturated zone fluid flow.

SOPH	Vandenberg	FDM	2-dimensional flow, saturated zone fluid flow.
INTERA HCTM	INTERA Environmental Consultants, Houston, USA	FEM	3-dimensional flow, saturated zone fluid flow.
DAVIS FE	Gupta et al.	FEM	3-dimensional flow, saturated zone fluid flow.
WALES Eng	France	FEM	3-dimensional flow, saturated zone fluid flow.
USGS (3 D)	Trescott	FDM	3-dimensional flow, saturated zone fluid flow.
HANDFORD VII	Kipp et al.	FDM	3-dimensional flow, saturated zone fluid flow.
COOLEY	Coley	FEM	3-dimensional flow, saturated zone fluid flow.

OAK RIDGE I	Reeves and Duguid	FEM	2-dimensional (flow vertical plane), saturated-unsaturated zone fluid flow.
OAK RIDGE II	Yeh and Ward	FEM	2-dimensional (flow vertical plane), saturated-unsaturated zone fluid flow.
NEUMAN FE	Neuman	FEM	2-dimensional (flow vertical plane), saturated-unsaturated zone fluid flow.
COLORADO	Brutsaert	FDM	3-dimensional flow, saturated-unsaturated zone fluid flow.
SEGOLFE	Segol	FEM	3-dimensional flow, saturated-unsaturated zone fluid flow.
PRINCETON	Van Genuchten and Pinder	FEM	3-dimensional flow, saturated-unsaturated zone fluid flow.

HANFORD PCP	Friedrichs	PCP	2-dimensional advection transport of conservative substance - horizontal, saturated zone contaminant transport.
FLOP	Van Den Akker	PCP	2-dimensional advection transport of conservative substance - horizontal, saturated zone contaminant transport.
FRONT	Vandenberg	MCH	2-dimensional advection transport of conservative substance - horizontal, saturated zone contaminant transport.
INTERA CTM	INTERAL Environmental Consul. Inc. Houston, USA	MCH	3-dimensional advection and dispersion transport of conservative substance, saturated zone contaminant transport.
SEGOL	Segol	FEM	3-dimensional advection and dispersion transport of conservative substance, saturated zone contaminant transport.
USGS MC	Konikow & Bredehoeft	FDM+MCH	2-dimensional adection and dispersion transport of conservative substances - horizontal, saturated zone contaminant transport.
ISOQUAD	Pinder & Frind	FEM	2-dimensional advection and dispersion transport of conservative substances-horizontal, saturated zone contaminant transport.
MC	Llamas	MC	2-dimensional advection and dispersion transport of conservative substances - vertical, saturated zone contaminant transport.

MMT-DPRW	Ahlstrom and Foote	RW	2-dimensional advection and dispersion transport of conservative, saturated zone contaminant transport.
SCHWARTZ	Schwartz	FDM-MCH	2-dimensional advection and dispersion transport of conservative substance - horizontal, saturated zone contaminant transport.
REFQS	Scheaffer	FEM	2-dimensional advection and dispersion transport of conservative substances - horizontal, saturated zone contaminant transport.
FEM	Kovarik et al.	FEM	3-dimensional advection and dispersion transport of conservative substances, saturated zone contaminant transport.

FET	Duguid, Reeves	FEM	2-dimensional advection and dispersion transport of reactive substances - vertical, saturated-unsaturated zone contaminant transport.
FEMWASTE	Yeh, Ward	FEM	2-dimensional advection and dispersion transport of reactive substances - vertical, saturated-unsaturated zone contaminant transport.
WATEQF	USGS	water quality model	It models thermodynamic speciation of inorganic ions and complex species in solution for a given water analysis.

PHREEQE	USGS	water quality model	It models geochemical reactions based on an ion-pairing aqueous model. It can calculate pH, redox potential and mass transfer as a function of reaction progress.
BALANCE	USGS	water quality model	It defines and quantifies chemical reactions between groundwater and minerals using chemical compositions of water samples from two points along a flow path.
RESSQ	Javandel et al.	semianalytical method	It is a semianalytical flow code.

5. ADOPTING A MODEL

In order to use a groundwater model for future predictions, evidence must be developed to demonstrate its ability to simulate plausibly the historic past. This process is called model verification. If the groundwater model is a good simulation of the prototype, then the model should be able to reproduce historic system conditions.

The general procedure in verification is to estimate the range of values of both groundwater flow and solute transport parameters and then test the model, using first the best guess values of the basin parameters to obtain system response to external stresses over time. The result is computed values of the system state variables. Then a comparison is made between the computed values and the known histories of the basin. If a good job has been done in developing the data, a fairly close match may result in the initial run. However, some adjustment of the parameters of storativity, transmissivity, net deep percolation, or other parameters is required. A tremendous insight into the dynamics of the system is achieved during the verification process.

A calibrated and verified groundwater model can be used for future predictions or solutions of the encountered problems. It allows a comprehensive and rational evaluation of alternative management plans by studying system responses of the groundwater systems to various inputs. To make a complete economic evaluation of these plans, a system submodel using optimization techniques such as linear, nonlinear and dynamic programming can be built into the model. As a result, a management plan selected by modelling analysis would be most economic and also meet system constraints.

The groundwater investigator must avoid assuming the computer model output is infallible. Before applying the model to solving a problem, the investigator should always consider carefully the accuracy of data and the degree of the model verification obtained. The well documented groundwater modelling softwares can be easily applied using data readily obtainable in the field or from the existing computerized water-data systems, such as WATSTORE, STORET, HYMOS, etc.

Keeping all the modelling aspects under consideration, it can be stated here that the selection of the appropriate model to be used in any particular case depends mainly on:

- Data Availability
- Model Availability
- Computer Facilities Available
- CPU Time Requirement
- Computing Cost
- Model Accuracy
- Desired Accuracy
- Model Realism
- User's Willingness
- User's Skill
- Intended Objectives of the Study/Investigation
- Ease in Implementation & Use

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