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Concepts and Modeling of Groundwater System

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Abstract

Groundwater is of fundamental importance in water resources planning, development and management. Groundwater flow has many applications, among which are agricultural developments, domestic use such as supply of drinking water, irrigation, and a variety of water quality applications. As the usage of groundwater expands, our knowledge of groundwater systems must also expand. Numerical groundwater modelling is a tool that can aid in studying groundwater problems and can help increase our understanding of groundwater systems. The purpose of this article is to highlight major groundwater issues, concepts of groundwater modelling, and commonly used groundwater modelling software.

Keywords: *Groundwater, Aquifer, Model, Calibration, MODFLOW, ArcGIS.*

1. Introduction

Groundwater lies almost everywhere below the earth's surface. It is an important source of drinking water supply and irrigation and caters to more than 45% of the total irrigation in the country. More than 90% of the world’s total supply of drinkable water is groundwater. The contribution of ground water irrigation to achieve self-sufficiency in food grains production in the past three decades is phenomenal. In the coming years, the ground water utilization is likely to increase manifold for expansion of irrigated agriculture and to achieve targets of food production. Although the groundwater is annually replenishable resource, its availability is non-uniform in space and time. Hence, precise estimation of ground water resource and irrigation potential is a prerequisite for planning its development.

When rain falls to the ground, the water does not stop moving. Some of it flows along the surface in streams or lakes, some of it is used by plants, some evaporates and returns to the atmosphere, and some sinks into the ground. Imagine pouring a glass of water onto a pile of sand. Where does the water go? The water moves into the spaces between the particles of sand. Groundwater is water that is found underground in cracks and spaces in soil, sand and rocks. The area where water fills these spaces is called the saturated zone. The top of this zone is called the water table, the top of the water is the table. The water table may be only a meter below the ground’s surface or it may be hundreds of meters down.

Groundwater can be found almost everywhere. The water table may be deep or shallow; and may rise or fall depending on many factors. Heavy rains or melting snow may cause the water table to rise, or an extended period of dry weather may cause the water table to fall. Groundwater is stored in and moves slowly through layers of soil, sand and rocks called aquifers. The speed, at which groundwater flows, depends on the size of the spaces in the soil or rock and how well the spaces are connected. Aquifers typically consist of gravel, sand, sandstone or fractured rock, like limestone. These materials are permeable because they have large connected spaces that allow water to flow through.

Water in aquifers is brought to the surface naturally through a spring or can be discharged into lakes and streams. This water can also be extracted through a well drilled into the aquifer. A well is a pipe in the ground that fills with groundwater. This water then can be brought to the surface by a pump. Shallow wells may go dry if the water table falls below the bottom of the well. Some wells called artesian wells do not need a pump because of natural pressures that force the water up and out of the well.

Groundwater supplies are replenished or recharged by rain and snow melt. In some areas of the world, people face serious water shortages because groundwater is used faster than it is naturally replenished. In other areas groundwater is polluted by human activities. In areas where material above the aquifer is permeable, pollutants can sink into the groundwater. Groundwater can be polluted by landfills, septic tanks, leaky underground gas tanks and from overuse of fertilizers and pesticides. If groundwater becomes polluted, it will no longer be safe to drink. It is important for all of us to learn to protect our groundwater.

2. Groundwater Issues

Certain problems have beset the use of groundwater around the world. Just as river waters have been over-used and polluted in many parts of the world, so too have aquifers. The big difference is that aquifers are out of sight. The other major problem is that water management agencies, when calculating the "sustainable yield" of aquifer and river water, have often counted the same water twice, once in the aquifer, and once in its connected river. This problem, although understood for centuries, has persisted. Following are the major issues related to development and management of groundwater resources.

2.1 Overdraft

Groundwater is a highly useful and often abundant resource. However, over-use, or overdraft, can cause major problems to human users and to the environment. The most evident problem (as far as human groundwater use is concerned) is a lowering of the water table beyond the reach of existing wells. As a consequence, wells must be drilled deeper to reach the groundwater; in some places, the water table has dropped hundreds of metres because of extensive well pumping. In the Punjab region of India, for example, groundwater levels have dropped 10 meters since 1979, and the rate of depletion is accelerating. A lowered water table may, in turn, cause other problems such as groundwater-related subsidence and saltwater intrusion.

2.2 Subsidence

Subsidence occurs when too much water is pumped out from underground, deflating the space below the surface, and thus causing the ground to collapse. The result can look like craters on plots of land. This occurs because, in its natural equilibrium state, the hydraulic pressure of groundwater in the pore spaces of the aquifer and the aquitard supports some of the weight of the overlying sediments. When groundwater is removed from aquifers by excessive pumping, pore pressures in the aquifer drop and compression of the aquifer may occur. This compression may be partially recoverable if pressures rebound, but much of it is not. When the aquifer gets compressed, it may cause land subsidence, a drop in the ground surface.

2.3 Waterlogging

Waterlogging refers to the saturation of soil with water. Soil may be regarded as waterlogged when the water table of the groundwater is too high to conveniently permit an anticipated activity, like agriculture. In agriculture, various crops need air (specifically, oxygen) to a greater or lesser depth in the soil. Waterlogging of the soil stops air getting in. How shallow the water table to be classified as waterlogged, varies with the purpose in view. A crop's demand for freedom from waterlogging may vary between seasons of the year, as with the growing of rice. In irrigated agricultural land, waterlogging is often accompanied by soil salinity as waterlogged soils prevent leaching of the salts imported by the irrigation water.

2.4 Saltwater intrusion

Saltwater intrusion is the movement of saline water into freshwater aquifers, which can lead to contamination of drinking water sources and other consequences. Saltwater intrusion occurs naturally to some degree in most coastal aquifers, owing to the hydraulic connection between groundwater and seawater. Because saltwater has a higher mineral content than freshwater, it is denser and has a higher water pressure. As a result, saltwater can push inland beneath the freshwater. Certain human activities, especially groundwater pumping from coastal freshwater wells, have increased saltwater intrusion in many coastal areas. Water extraction drops the level of fresh groundwater, reducing its water pressure and allowing saltwater to flow further inland. Other contributors to saltwater intrusion include navigation channels or agricultural and drainage channels, which provide conduits for saltwater to move inland. Saltwater intrusion can also be worsened by extreme events like hurricane storm surges.

2.5 Pollution

Water pollution of groundwater, from pollutants released to the ground that can work their way down into groundwater, can create a contaminant plume within an aquifer. Movement of water and dispersion within the aquifer spreads the pollutant over a wider area, its advancing boundary often called a plume edge, which can then intersect with groundwater wells and springs, making the water supplies unsafe for humans and wildlife. Different mechanism have influence on the transport of pollutants, e.g. diffusion, adsorption, decay in the groundwater. The interaction of groundwater contamination with surface waters is analyzed by use of hydrology transport models.

The stratigraphy of the area plays an important role in the transport of these pollutants. An area can have layers of sandy soil, fractured bedrock, clay, or hard pan. Areas of karst topography on limestone bedrock are sometimes vulnerable to surface pollution from groundwater.

Earthquake faults can also be entry routes for downward contaminant entry. Water table conditions are of great importance for drinking water supplies, agricultural irrigation, waste disposal (including nuclear waste), wildlife habitat, and other ecological issues.

3. Applications of Groundwater Models

The use of groundwater models is prevalent in the field of environmental science. Models have been applied to investigate a wide variety of hydrogeologic conditions. More recently, groundwater models are being applied to predict the transport of contaminants for risk evaluation.

In general, models are conceptual descriptions or approximations that describe physical systems using mathematical equations; they are not exact descriptions of physical systems or processes. By mathematically representing a simplified version of a hydrogeological system, reasonable alternative scenarios can be predicted, tested, and compared. The applicability or usefulness of a model depends on how closely the mathematical equations approximate the physical system being modeled. In order to evaluate the applicability or usefulness of a model, it is necessary to have a thorough understanding of the physical system and the assumptions embedded in the derivation of the mathematical equations.

Groundwater models describe the groundwater flow and transport processes using mathematical equations based on certain simplifying assumptions. These assumptions typically involve the direction of flow, geometry of the aquifer, the heterogeneity or anisotropy of sediments or bedrock within the aquifer, the contaminant transport mechanisms and chemical reactions. Because of the simplifying assumptions embedded in the mathematical equations and the many uncertainties in the values of data required by the model, a model must be viewed as an approximation and not an exact duplication of field conditions. Groundwater models, however, even as approximations, are a useful investigation tool that groundwater hydrologists may use for a number of applications.

Application of groundwater models include water balance (in terms of water quantity), gaining knowledge about the quantitative aspects of the unsaturated zone, simulating of water flow and chemical migration in the saturated zone including river-groundwater relations, assessing the impact of changes of the groundwater regime on the environment, setting up/optimising monitoring networks, and setting up groundwater protection zones.

The modelling studies in India have so far been confined to academic and research organisations. The practising professionals mostly still prefer to employ lumped models for planning of groundwater development and recharge. Such models completely ignore the distributed character of the groundwater regime. Thus, they are based upon rather conservative concepts like safe yields and are incapable of accounting for the stream-aquifer interaction and the dependence of lateral recharge on the water table pattern. Consequently, permissible mining (i.e. withdrawals in excess of vertical recharge) and perennial yield can not be arrived at. The objectives of modelling studies in India have been mainly (i) groundwater recharge, (ii) dynamic behaviour of the water table, (iii) stream-aquifer interaction, and (iv) sea-water intrusion etc. It is important to understand general aspects of both groundwater flow and transport models so that application or evaluation of these models may be performed correctly.

4. Model Development

A groundwater model application can be considered to be two distinct processes (Figure 1). The first process is model development resulting in a software product, and the second process is application of that product for a specific purpose. Groundwater models are most efficiently developed in a logical sequence.

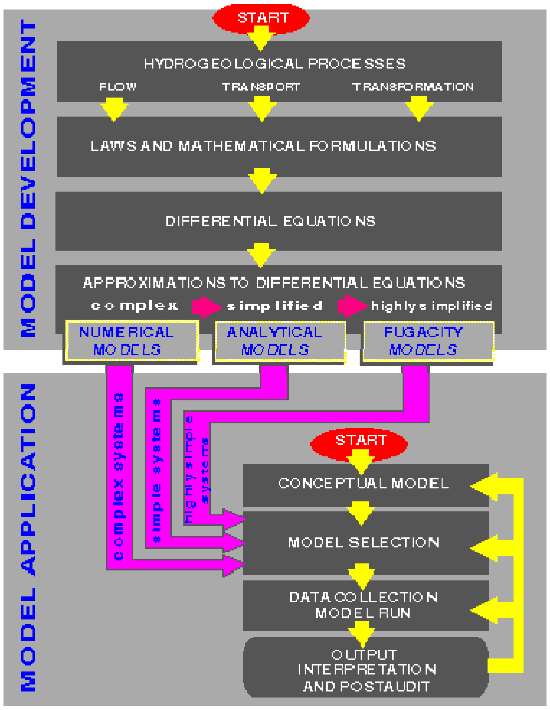

Fig. 1 Development Process of a Model

4.1 Model Objectives

Model objectives should be defined which explain the purpose of using a groundwater model. The modelling objectives will profoundly impact the modelling effort required.

4.2 Hydrogeological Characterization

Proper characterization of the hydrogeological conditions at a site is necessary in order to understand the importance of relevant flow or solute transport processes. Without proper site characterization, it is not possible to select an appropriate model or develop a reliably calibrated model.

4.3 Model Conceptualization

Model conceptualization is the process in which data describing field conditions are assembled in a systematic way to describe groundwater flow and contaminant transport processes at a site. The model conceptualization aids in determining the modelling approach and which model software to use.

4.4 Modelling Software Selection

After hydrogeological characterization of the site has been completed and the conceptual model developed, a computer model software is selected. The selected model should be capable of simulating conditions encountered at a site. For example, analytical models can be used where field data show that groundwater flow or transport processes are relatively simple. Similarly, one-dimensional/ two-dimensional/ three-dimensional groundwater flow and transport models should be selected based upon the hydrogeological characterization and model conceptualization.

4.5 Model Design (Input Parameters)

Model design includes all parameters that are used to develop a calibrated model. The input parameters include model grid size and spacing, layer elevations, boundary conditions, hydraulic conductivity/transmissivity, recharge, any additional model input, transient or steady state modelling, dispersion coefficients, degradation rate coefficients etc.

4.6 Model Calibration

Model calibration consists of changing values of model input parameters in an attempt to match field conditions within some acceptable criteria. Model calibration requires that field conditions at a site be properly characterized. Lack of proper site characterization may result in a model calibrated to a set of conditions that are not representative of actual field conditions.

4.7 Sensitivity Analysis

A sensitivity analysis is the process of varying model input parameters over a reasonable range (range of uncertainty in value of model parameter) and observing the relative change in model response. Typically, the observed change in hydraulic head, flow rate or contaminant transport are noted. Data for which the model is relatively sensitive would require future characterization, as opposed to data for which the model is relatively insensitive.

4.8 Model Verification

A calibrated model uses selected values of hydrogeologic parameters, sources and sinks and boundary conditions to match historical field conditions. The process of model verification may result in further calibration or refinement of the model. After the model has successfully reproduced measured changes in field conditions, it is ready for predictive simulations.

4.9 Predictive Simulations

A model may be used to predict some future groundwater flow or contaminant transport condition. The model may also be used to evaluate different remediation alternatives. However, errors and uncertainties in a groundwater flow analysis and solute transport analysis make any model prediction no better than an approximation. For this reason, all model predictions should be expressed as a range of possible outcomes that reflect the assumptions involved and uncertainty in model input data and parameter values.

4.10 Performance Monitoring Plan

Groundwater models are used to predict the migration pathway and concentrations of contaminants in groundwater. Errors in the predictive model, even though small, can result in gross errors in solutions projected forwarded in time. Performance monitoring is required to compare future field conditions with model predictions.

5. Groundwater Flow Equation

Groundwater modelling begins with a conceptual understanding of the physical problem. The next step in modelling is translating the physical system into mathematical terms. In general, the results are the familiar groundwater flow equation and transport equations. The governing flow equation for three-dimensional saturated flow in saturated porous media is:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-Q=S_s\frac{\partial h}{\partial t} \qquad (1)$$

where,

K_{xx}, K_{yy}, K_{zz} = hydraulic conductivity along the x,y,z axes which are assumed to be parallel to the major axes of hydraulic conductivity;
H = piezometric head;
Q = volumetric flux per unit volume representing source/sink terms;
S_s = specific storage coefficient defined as the volume of water released from storage per unit change in head per unit volume of porous material.

The transport of solutes in the saturated zone is governed by the advection-dispersion equation which for a porous medium with uniform porosity distribution is formulated as follows:

$$\frac{\partial c}{\partial t}=-\frac{\partial}{\partial x_i}\left(cv_i\right)+\frac{\partial}{\partial x_i}\left(D_{ij}\frac{\partial c}{\partial x_j}\right)+R_c \qquad i,j=1,2,3 \qquad (2)$$

where,

c = concentration of the solute;
R_c = sources or sinks;
D_{ij} = dispersion coefficient tensor;
v_i = velocity tensor.

An understanding of these equations and their associated boundary and initial conditions is necessary before a modelling problem can be formulated. Basic processes, that are considered, include groundwater flow, solute transport and heat transport. Most groundwater modelling studies are conducted using either deterministic models, based on precise description of cause-and-effect or input-response relationships or stochastic models reflecting the probabilistic nature of a groundwater system.

The governing equations for groundwater systems are usually solved either analytically or numerically. Analytical models contain analytical solution of the field equations, continuously in space and time. In numerical models, a discrete solution is obtained in both the space and time domains by using numerical approximations of the governing partial differential equation. Various numerical solution techniques are used in groundwater models. Among the most used approaches in groundwater modelling, three techniques can be distinguished: Finite Difference Method, Finite Element Method, and Analytical Element Method. All techniques have their own advantages and disadvantages with respect to availability, costs, user friendliness, applicability, and required knowledge of the user.

The input data for a groundwater model include natural and artificial stress, and parameters, dimensions, and physico-chemical properties of all aquifers considered in the model. A finer level of detail of the numerical approximation (solution) greatly increases the data requirements. Input data for aquifers are common values such as transmissivities, aquitard resistances, abstraction rates, groundwater recharges, surface water levels etc. The most common output data are groundwater levels, fluxes, velocities and changes in these parameters due to stress put into the model.

6. Groundwater Modelling Software

Salient features of the frequently used groundwater models and supporting software have been presented below. The most widely used numerical groundwater flow model is MODFLOW which is a three-dimensional model, originally developed by the U.S. Geological Survey (McDonald and Harbaugh, 1988).

6.1 MODFLOW

MODFLOW is the USGS's three-dimensional (3D) finite-difference groundwater model. MODFLOW is considered an international standard for simulating and predicting groundwater conditions and groundwater/surface-water interactions. Originally developed and released solely as a groundwater-flow simulation code when first published in 1984, MODFLOW's modular structure has provided a robust framework for integration of additional simulation capabilities that build on and enhance its original scope. The family of MODFLOW-related programs now includes capabilities to simulate coupled groundwater/surface-water systems, solute transport, variable-density flow (including saltwater), aquifer-system compaction and land subsidence, parameter estimation, and groundwater management.

The current core version of MODFLOW is MODFLOW-2005 v.1.11.00. MODFLOW-2005 is the standard version of MODFLOW supported by the USGS Office of Groundwater and is the most stable and well-tested version of the code. There are few other USGS software most commonly used as USGS MODFLOW utitilities. *GW_Chart* is a graphing application for MODFLOW, ZONEBUDGET, and other codes. GW_Chart also converts binary cell-by-cell flow files to text files. *ModelMuse* is a GUI for MODFLOW-2005, MODFLOW-LGR, MODFLOW-NWT, MT3DMS, PHAST, MODPATH, and ZONEBUDGET. *Model Viewer* is a program for 3D visualization of groundwater-model results. *ZONEBUDGET* is a program for computing subregional water budgets for MODFLOW.

6.2 FEFLOW

FEFLOW is an acronym of Finite Element subsurface FLOW simulation system and solves the governing flow, mass and heat transport equations in porous and fractured media by a multidimensional finite element method for complex geometric and parametric situations including variable fluid density, variable saturation, free surface(s), multispecies reaction kinetics, non-isothermal flow and multidiffusive effects.

FEFLOW is a professional software package for modelling fluid flow, groundwater age and transport of dissolved constituents and/or heat transport processes in the subsurface. FEFLOW contains pre- and post processing functionality and an efficient simulation engine. A user-friendly graphical interface provides easy access to the extensive modelling options. FEFLOW - in contrast to some of the competing products - is not a graphical front end for a separately developed simulation kernel. It is a completely integrated system from simulation engine to graphical user interface. It includes a public programming interface for user code.

FEFLOW is developed by DHI-WASY GmbH, the German branch of the DHI group. DHI-WASY's areas of expertise encompass groundwater hydrology, surface water hydrology and geographic information systems. In these fields, DHI-WASY provides software, training and consulting services. FEFLOW is used by leading research institutes, universities, consulting firms and government organizations all over the world. Its scope of application ranges from simple local-scale to complex large-scale simulations.

6.3 SUTRA

SUTRA is a computer program which simulates fluid movement and transport of either energy or dissolved substances in a subsurface environment. SUTRA employs a two-dimensional or three-dimensional hybrid finite-element and integrated finite-difference method to approximate the governing equations that describe the two interdependent processes that are simulated: (1) fluid density-dependent saturated or unsaturated ground water flow and either (2a) transport of a solute in the ground water, in which the solute may be subject to equilibrium adsorption on the porous matrix, and both first-order and zero-order production or decay, or (2b) transport of thermal energy in the ground water and solid matrix of the aquifer.

6.4 MT3DMS

MT3DMS is a latest version of the Modular 3-D Transport model, where MS denotes the Multi-Species structure for accommodating add-on reaction packages. MT3DMS has a comprehensive set of options and capabilities for simulating advection, dispersion/diffusion, and chemical reactions of contaminants in groundwater flow systems under general hydrogeological conditions.

6.5 SEAWAT

SEAWAT is a generic MODFLOW/MT3DMS-based computer program designed to simulate three-dimensional variable-density groundwater flow coupled with multi-species solute and heat transport. The program has been used for a wide variety of groundwater studies including those focused on brine migration in continental aquifers as well as those focused on saltwater intrusion in coastal aquifers. SEAWAT uses the familiar structure of MODFLOW and MT3DMS. Thus, most of the commonly used pre and post-processors can be used to create SEAWAT datasets and visualize results. The MODFLOW concepts of "packages" and "processes" are retained in SEAWAT, which allows the program to work with many of the MODFLOW-related software programs, such as MODPATH, ZONEBUDGET, and parameter estimation programs. SEAWAT is a public domain computer program. The source code and software are distributed free of charge by the U.S. Geological Survey (USGS). SEAWAT Version 4 is a replacement for SEAWAT-2000.

6.6 MIKE SHE

MIKE SHE is an integrated hydrological modelling system for building and simulating surface water flow and groundwater flow. MIKE SHE can simulate the entire land phase of the hydrologic cycle and allows components to be used independently and customized to local needs. MIKE SHE emerged from System Hydrologique European (SHE) as developed and extensively applied since 1977 onwards by a consortium of three European organizations: the Institute of Hydrology (United Kingdom), SOGREAH (France) and DHI Water-Environment-Health (Denmark). Since then, DHI has continuously invested resources into research and development of MIKE SHE.

MIKE SHE delivers truly integrated modelling of groundwater, surface water, recharge and evapotranspiration. MIKE SHE includes all important aspects of hydrology when a project requires a fully integrated model. MIKE SHE can be used for the analysis, planning and management of a wide range of water resources and environmental problems related to surface water and groundwater, especially surface-water impact from groundwater withdrawal, conjunctive use of groundwater and surface water, wetland management and restoration, river basin management and planning, impact studies for changes in land use and climate. The program is offered in both 32-bit and 64-bit versions for Microsoft Windows operating systems.

6.7 Visual MODFLOW

Visual MODFLOW Flex (VMOD Flex) is a graphical interface for MODFLOW. The program also combines proprietary extensions, such as MODFLOW-SURFACT, MT3DMS (mass-transport 3D multi-species) and a 3D model explorer. Visual MODFLOW supports MODFLOW-2000, MODFLOW-2005, MODFLOW-NWT, MODFLOW-LGR, MODFLOW-SURFACT, and SEAWAT. The software is used primarily by hydrogeologists to simulate groundwater flow and contaminant transport. The program, developed by Schlumberger Water Services, is one of the first commercial graphical interfaces for MODFLOW.

6.8 Groundwater Vistas

Groundwater Vistas 6 (GV) is a pre- and post-processor for MODFLOW models. GV is a state of the art software package for 3-D groundwater flow and contaminant transport modelling, calibration and optimization using the MODFLOW suite of codes. GV also couples a powerful model design system with comprehensive graphical analysis tools. Developed by the author of ModelCad^{TM}, GV is a model-independent graphical design system for MODFLOW MODPATH (both steady-state and transient versions), MT3DMS, MODFLOWT, MODFLOW-SURFACT, MODFLOW2000, GFLOW, RT3D, PATH3D, SEAWAT and PEST.

The Advanced version of Groundwater Vistas 6 adds Monte Carlo uncertainty analysis, SWIFT support, Recharge/ET memory compression for large transient models, support for the HUF Package in MODFLOW2000/2005 and PEST SVD Assist capabilities. The Professional version of Groundwater Vistas 6 includes everything in the Advanced version plus GW3D for 3D Visualization. The Premium version of Groundwater Vistas 6 is everything included in the Professional version plus the sophisticated SAMG Solver.

6.9 GMS

GMS (Groundwater Modelling System) is a complete program for building and simulating groundwater models. It features 2D and 3D geostatistics, stratigraphic modelling and a unique conceptual model approach. GMS provides tools for every phase of a groundwater simulation including site characterization, model development, calibration, post-processing, and visualization. GMS supports both finite-difference and finite-element models in 2D and 3D including MODFLOW 2000, MODPATH, MT3DMS/RT3D, SEAM3D, FEMWATER, PEST, UTEXAS, MODAEM and SEEP2D. The program's modular design enables the user to select modules in custom combinations, allowing the user to choose only those groundwater modelling capabilities that are required.

6.10 PMWIN

Processing Modflow^{TM} (PMWIN) is a comprehensive integrated groundwater modelling system. It includes the following components.

- Intuitive graphical user interface to greatly simplify and clarify data input and result visualization processes that work with result files of practically unlimited file size (way greater than 2 GB).

- 3D finite-difference groundwater model MODFLOW. Supports multiple versions, including MODFLOW-96, MODFLOW-2000, MODFLOW-2005, and MODFLOW-NWT.

- Solute transport models MT3DMS (v5.3), MT3D, RT3D (v2.5), and MT3D99 (MT3D99 is sold separately by SSP&A.)

- Multicomponent reactive transport model PHT3D (v2.17) that incorporates MT3DMS (v5.3) for the simulation of three-dimensional advective-dispersive multi-component transport and the geochemical model PHREEQC-2 (v2.14) for the quantification of reactive processes.

- Variable-density groundwater flow and multi-species solute and heat transport model SEAWAT (v4.0).

- Nonlinear parameter estimation package PEST (v12.0). Supports advanced features such as regularization, truncated singular value decomposition (SVD), and powerful SVD-Assisted Parameter Estimation.

- Particle-tracking Model PMPATH which uses a semi-analytical particle-tracking scheme similar to MODPATH to calculate the groundwater paths and travel times. Through the interactive graphical modelling environment of PMPATH, the user can place particles and perform particle tracking with just a few mouse clicks.

- Water Budget calculator for computing sub-regional water budget and inter-region water budget. It can optionally creates time-series of water budget for transient models.

- Field Generator to generate heterogeneously-distributed parameter fields for stochastic simulation.

- Field Interpolators to interpolate from point-wise data to model cells by using interpolation methods such as Kirging, Inverse distance, etc.

6.11 ArcGIS

GIS is a powerful tool for developing solutions for water resources such as assessing water quality and managing water resources on a local or regional scale. ArcGIS is an integrated collection of GIS software products for building a complete GIS. Hydrologists use GIS technology to integrate various data and applications into one, manageable system. The suite of tools contained in Arc Hydro facilitate the creation, manipulation, and display of hydro features and objects within the ArcGIS environment. ArcGIS Spatial Analyst includes a variety of tools for Hydrologic Analysis. The groundwater tools can be used to perform simple 2D advection–dispersion modelling of groundwater flow and constituents in groundwater.

6.12 Surfer

Surfer is a full-function 3D visualization, contouring and surface modelling package that runs under Microsoft Windows. Surfer is used extensively for terrain modelling, bathymetric modelling, landscape visualization, surface analysis, contour mapping, watershed and 3D surface mapping, gridding, volumetrics, and much more.

Surfer’s sophisticated interpolation engine transforms XYZ data into publication-quality maps. Surfer provides gridding methods and control over gridding parameters, including customized variograms. One can also use grid files obtained from other sources, such as USGS DEM files or ESRI grid files. Display grid as outstanding contour, 3D surface, 3D wireframe, watershed, vector, image, shaded relief, and post maps. Add base maps and combine map types to create the most informative display possible.

6.13 Hydro GeoAnalyst

Hydro GeoAnalyst is a groundwater, borehole, hydrogeologic interpretation and data management software that integrates a complete range of easy-to-use analysis and reporting tools, with a powerful yet flexible SQL Server database technology. Hydro GeoAnalyst is an all-in-one desktop concept that provides one-click access to many powerful features e.g. data transfer system, query editor, GIS map manager, 2D cross-section editor, 3D-explorer, template manager, report editor, and much more.

6.14 RockWorks

RockWorks is a comprehensive program that offers visualization and modelling of spatial data and subsurface data. RockWorks offers numerous options for analyzing the subsurface data, and accepts many different data types, such as stratigraphy, lithology, quantitative data, color intervals, fracture data and hydrology and aquifer data. In addition to its impressive collection of existing capabilities, the latest RockWorks version has numerous new features, including dozens of Google™ Earth display tools (the "EarthApps"); coordinate and unit support for data, models, and graphics; enhanced cross section drawing tools; and much more.

6.15 ArcHydro Groundwater

Arc Hydro Groundwater is a data model and set of tools to help better manage groundwater and subsurface data within ArcGIS. The Arc Hydro Groundwater data model is a geodatabase design for representing multidimensional groundwater data. The data model supports representations of different types of groundwater data including representation of data from aquifer maps and well databases, data from geologic maps, 3D representations of borehole and hydrostratigraphy, temporal information, and data from simulation models. The data model is based on the Arc Hydro framework which is shared by the surface water and groundwater data models. Users can add groundwater and surface water components to the framework as necessary, or develop their own components. This new componentized approach enables tailoring the geodatabase design to meet specific project needs.

The Arc Hydro Groundwater tools enable to take advantage of the ArcGIS platform to archive, manage, and visualize groundwater information. Use Arc Hydro Groundwater to create water level, water quality and flow direction maps, create, archive and visualize MODFLOW models, and create and visualize both 2D and 3D geologic models. Additionally, one can georeference subsurface data including boreholes, sketch cross sections, and geovolumes, and store, georeference, and create GIS maps of MODFLOW model input and solution data.

6.16 PEST

PEST is a nonlinear parameter estimation package. It can be used to estimate parameters for just about any existing computer model, whether or not a user has access to the model's source code. PEST is able to "take control" of a model, running it as many times as it needs to while adjusting its parameters until the discrepancies between selected model outputs and a complementary set of field or laboratory measurements is reduced to a minimum in the weighted least squares sense.

PEST communicates with a model through the model's own input and output files. Thus PEST adapts to the model, the model does not need to be adapted to PEST. It implements a particularly robust variant of the Gauss-Marquardt-Levenberg method of nonlinear parameter estimation. Furthermore, through adjustment of a number of control variables, a user is able to "tune" PEST's implementation of the method to suit the model for which parameters are sought.

Considering the large variability and the quick development of groundwater models, a new, more sophisticated model can often replace a previously applied model. Additionally, the reconsideration of the conceptual model and the regeneration of the mesh may need a new allocation of the parameters. Therefore, it is important that model data (information) are stored independently from a given model, with a preference for GIS-based databases. Considerable development in the field of user-friendly GIS and data base servers makes the set-up and the modification of models easier and more time-effective.

7. Concluding Remarks

Mathematical models are tools, which are frequently used in studying groundwater systems. In general, mathematical models are used to simulate (or to predict) the groundwater flow and in some cases the solute and/or heat transport. In order to avoid model misuse, it is important to know and understand the limitations and possible sources of error in numerical models. To avoid applying an otherwise valid model to an inappropriate field situation, it is not only important to understand the field behavior but also to understand all of the assumptions that form the basis of the model.

Predictive simulations must be viewed as estimates, dependent upon the quality and uncertainty of the input data. Models may be used as predictive tools, however field monitoring must be incorporated to verify model predictions. The best method of eliminating or reducing modelling errors is to apply good hydrogeological judgement and to question the model simulation results. If the results do not make physical sense, find out why.

References

[1] Anderson, M.P. and W.W. Woessner, 1992, Applied Groundwater Modelling. Academic Press, Inc., San Diego, CA., 381 p.

[2] American Society for Testing and Materials, 1993, Standard Guide for Application of a Ground-Water Flow Model to a Site-Specific Problem. ASTM Standard D 5447-93, West Conshohocken, PA, 6 p.

[3] American Society for Testing and Materials, 1995, Standard Guide for Subsurface Flow and Transport Modelling. ASTM Standard D 5880-95, West Conshohocken, PA, 6 p.

[4] Bear, J., and A. Verruijt, 1987, Modelling Groundwater Flow and Pollution. D. Reidel Publishing Company, 414 p.

[5] Franke, O.L., Bennett, G.D., Reilly, T.E., Laney, R.L., Buxton, H.T., and Sun, R.J., 1991, Concepts and Modelling in Ground-Water Hydrology -- A Self-Paced Training Course. U.S. Geological Survey Open-File Report 90-707.

[6] Kashyap, Deepak, 1989, Mathematical Modelling for Groundwater Management – Status in India. Indo-French Seminar on Management of Water Resources, 22-24 September, 1989, Festival of France-1989, Jaipur, pp. IV-59 to IV-75.

[7] Kinzelbach, W., 1986, Groundwater Modelling: An Introduction with Sample Programs in BASIC. Elsevier, New York, 333 p.

[8] Kumar, C. P., 1992, Groundwater Modelling – In. Hydrological Developments in India Since Independence. A

Contribution to Hydrological Sciences, National Institute of Hydrology, Roorkee, pp. 235-261.

[9] Kumar, C. P., 2001, Common Ground Water Modelling Errors and Remediation. Journal of Indian Water Resources Society, Volume 21, Number 4, October 2001, pp. 149-156.

[10] McDonald, M.G. and A.W. Harbaugh, 1988, A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model, USGS TWRI Chapter 6-A1, 586 p.

[11] Mercer, James W. and Charles R. Faust, 1980, Ground-Water Modelling: An Overview, Ground Water, Vol. 18, No. 2, March-April 1980, pp. 108-115.

[12] Pinder, G.F., and J.D. Bredehoeft, 1968, Application of the Digital Computer for Aquifer Evaluation, Water Resources Research, Vol. 4, pp. 1069-1093.

[13] Wang, H.F. and M.P. Anderson, 1982, Introduction to Groundwater Modelling. W.H. Freeman and Company, San Francisco, CA, 237 p.

[14] Website - USGS Ground-Water Software:
http://water.usgs.gov/nrp/gwsoftware/

[15]Website – Wikipedia: Groundwater, Waterlogging, Saltwater Intrusion
http://en.wikipedia.org/wiki/Groundwater
http://en.wikipedia.org/wiki/Waterlogging_(agriculture)
http://en.wikipedia.org/wiki/Saltwater_intrusion

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