Groundwater Models: How the Science Can Empower the Management?

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Abstract

Protection, restoration and development of groundwater supplies and remediation of contaminated aquifers are the driving issues in groundwater resource management. These issues are further triggered on and driven by the population expansion and increasing demands. To transform the 'vicious circles' of groundwater availabilities into 'virtuous circles' of demands, understanding of the aquifer behavior in response to imposed stresses and/or strains is essentially required. If groundwater management strategies are directed towards balancing the exploitations in demand side with the fortune of supply side, the goals of groundwater management can be achieved when the tools used for solution of the management problems are derived considering mechanisms of supply-distribution-availability of the resource in the system. Groundwater modeling is one of the management tools being used in the hydro-geological sciences for the assessment of the resource potential and prediction of future impact under different stresses/constraints. Construction of a groundwater model follows a set of assumptions describing the system's composition, the transport processes that take place in it, the mechanisms that govern them, and the relevant medium properties. There are numerous computer codes of groundwater models available worldwide dealing variety of problems related to; flow and contaminants transport modeling, rates and location of pumping, artificial recharge, changes in water quality etc. Each model has its own merits and limitations and hence no model is unique to a given groundwater system. Management of a system means making decisions aiming at accomplishing the system's goal without violating specified technical and non-technical constrains imposed on it. A complete groundwater management model is the combination of groundwater simulation models and the optimization methods. A management approach has its own mathematical logic and constraints complemented by the simulation models. It is simulation models, which actually impart groundwater sciences to the management to evaluate potentiality and the fate of the resource for different options and constrained cases. Thus, to meet the increasing demands of water for variety of uses when the supply-side becomes a limiting case or being dragged by the pollution threats, the uses of groundwater models to the management problems are bound to increase and new modeling techniques with inclusion of more real world complexities with improved predictive capacity are bound to dominate the decision process.

Introduction

Groundwater is an important, dependable and major source of drinking water besides agricultural and other uses. It is becoming increasingly important and popular resource, particularly in tropical countries, because of relative ease to access and flexiblility in tapping. It is believed that it can be drawn on demand and also more risk free from pollution than surface sources of water, making it far more attractive to many groups of users. Groundwater moves through aquifers from area of recharge to area of discharge normally at slow rates. These slow flow rates and long residence times, consequent upon large aquifer storage volume, are some distinct features of groundwater systems, which have given rise to its reliability. In South Asia –a region, which has varied problems involving population dynamics and their allied demands and activities, illiteracy, diversity in culture and religions, water use patterns, extremes in rainfall variations, natural disasters and hazards coupled with poor economy; although has one of the world's largest untapped groundwater aquifers–the Ganga-Brahmaputra-Meghna basin–but still holds the problems and challenges to promote sustainable and equitable development of this resource. Development and management of groundwater resources in a sustainable way pose many challenges including threats. Some of the important concerns are: depleting groundwater levels, failure of wells, ever increasing cost of tapping of aquifers, public health problem due to occurrence of carcinogenic elements (e.g., arsenic and fluoride), pollution threat from surface water bodies and leaching, seawater ingress into the freshwater aquifers etc. These added problems beside hydrological and hydro-geological severities including socio-economic forces pose many untoward complexities and challenges in the management of supply-side to meet the requirements in the demand side. Groundwater management is just not making water available for different uses but to evolve a sustainable scheme that would be safe from pollution, ecological imbalances and economic uncertainty besides protecting and restoring the aquifer storage. Irrespective of its economical value, the groundwater resources management has to deal with balancing the exploitation (in terms of quantity, quality, and its interaction with surface water bodies) with increasing demands of water and land uses. These are possible when the hydrological and hydro-geological processes of aquifers for diverse initial and boundary conditions are reasonably understood and integrated appropriately in the chain of development and management objectives.

If the management of groundwater resources is directed towards balancing the supply-side and the demand-side, then for addressing the key issues of the groundwater supply-management, one needs to understand; (i) aquifer systems and their susceptibilities to negative impacts when it is under abstraction stress, and (ii) interaction between surface water and groundwater, such as, abstraction effects and recharge reduction effects. On the groundwater demand-management side, key issues are: (i) social development goals influenced by water use, especially where agricultural irrigation and food production are of primary concern, (ii) regulatory interventions (such as water rights or permits) and economic tools (such as abstraction tariffs, etc.), and (iii) regulatory provisions to ensure government capacity to enforce and user capacity to comply. These complex issues can't be resolved unless their insights are properly understood.

The management of any system means making decisions aimed at achieving the system's goals without violating specified technical and non-technical constraints imposed on it. The hydro-geological processes of the aquifer system govern the technical rules in the groundwater management. Models, which are constructed conceptualizing the physical realism of the hydro-geological processes, are utilized to explore groundwater management alternatives. Prediction, forecasting, and fate evaluation of an aquifer system against some imposed forcing functions involves integration of hydrological and hydro-geological processes with the aquifer properties both on time and space generating huge computational burden, which can not be handled by verbal and simplified approaches. The groundwater modeling is the most preferred alternative. Groundwater modeling is one of the tools of the management that has been used in the hydro-geological sciences for the assessment of the resource potential and prediction of future impact under different circumstances. The predictive capacity of a groundwater model makes it the most useful and powerful tool for planning, design, implementation and management of the groundwater resources.

Prior to advent of the numerical methods and computers, which have tremendously eased the computational scope, groundwater studies were confined, to analytical researches focused mainly towards solving simple boundary problems with limited real life complexities, to field investigations for assessing the aquifer potential, etc. Modeling of aquifer responses and multi-allocations management problem of groundwater resources was a rarity. Intensive field investigations and data acquisition together with advanced instrumentations have facilitated further understanding of the physical processes of groundwater storage and movement including science of heterogeneous aquifer systems. Needless to mention that this has encouraged development of generalized computer codes. Socio-economic and socio-cultural development besides food security and increasing environmental concerns driven by the population growth, are other factors, which are multiplying the complexities of management and development of the groundwater resources. Neither the availability of groundwater resources is plenty (but limited) nor there are much scope left to increase the overall quantity. Replenishable quantity forms the main guiding factor to the availability side, while the demand-side factors are rising both on number and magnitude. The multi-dimensional demands side by side the increasing environmental concerns along with the limitations of availability call for development of advanced to most advanced approaches of management satisfying the conditions of technicalities.

The paper presents a state-of-art of groundwater modeling along with an overview of groundwater flow and contaminant transport modeling including their roles in management of groundwater resources. It is also intended to focus some key issues of supply and management of groundwater resources, which are real concern in the planning and policy decisions, and may pose challenge to the researchers in future years. The scope of the paper is restricted to the groundwater system in porous media.

Groundwater System

A groundwater system comprises of the surface water, the geological media containing the water (such as, aquifer), flow boundaries and sources (such as, recharge), and sinks (such as, withdrawals). Aquifers are rocks or sediment that act as storage reservoirs for groundwater and typically characterized by high porosity and permeability. An aquiclude is rock or sediment that represents a barrier to groundwater flow. Infiltrated water into open aquifers from top represents recharge. Pumping, evapo-transpiration and loss through boundaries represent withdrawal. Open aquifers contain a saturated zone where pore spaces are filled with water. The water table is the top of the saturated zone. Water enters closed (artesian) aquifers from a recharge area..

Let us consider a control volume of a lumped groundwater system as shown in Fig.1. At a given period of time, let all the components of sources and sinks (Fig.1) be in position. If the system truly represents the water balance over a period of time (say, Δt), then the difference of inflow to the system and outflow from the system should equal to the accumulated storage in the system over that time. This accumulated storage of groundwater would be available in the control volume at the end of the time period, Δt. If the process continues for a finite time, t (= n Δt, where n = an integer), the accumulated storage at the end of time, nΔt, would be the resulting effect of inflows and outflows in the control volume, and the water level corresponding to this resulting effect would give shape to the groundwater level. If the control volume represents a groundwater basin, and the time period size is taken relatively large, then the computed accumulated storage of recharge months (monsoon period) gives the lumped assessment of the groundwater availability in that basin. In regular coordinate systems and for control volume of regular size with infinitely small dimension, if the processes are linked to the aquifer properties and mechanism then, what one obtains, is the groundwater flow equation. The groundwater balance equation for the control volume as shown in Fig. 1 for a time period, Δt, can be written as:

$$\left(R_i + R_c + R_{ir} + R_t + R_{is} + I_b\right)\Delta t = \left(E_t + G_w + R_{es} + O_b\right)\Delta t + \Delta S \qquad (1)$$

All the components of equation (1) can be estimated using independent methods, or, one of the unknown components can be estimated if all other components are known.

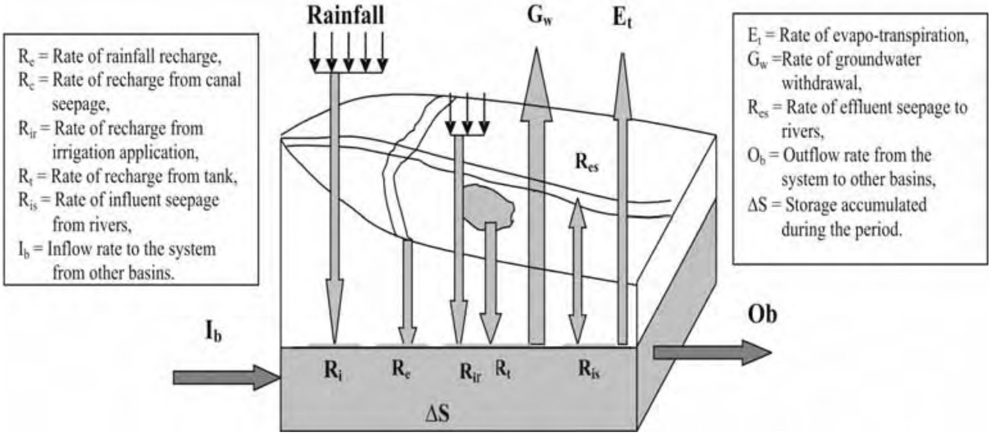

Figure 1. Schematic of a control volume of lumped groundwater system

Groundwater Models

In general, models are conceptual descriptions or approximations of physical systems or processes, which are translated into well-posed mathematical equations. The mathematical representation converts the physical system into the conceptual framework of computation through mathematical variables that helps in performing the job of simulation and scenarios development for the imposed stresses and/or strains without physically intervening into the system. Model is, thus, quantitative representation of the relationships among the entities or processes in a system. Models are used to bring quantitative data and qualitative information together in a predictive framework. A groundwater model may be defined as a simplified version of a groundwater system that approximately simulates the relevant excitation-response relations of the system. Since real-world systems are very complex, there is a need for simplification in policy planning and management decisions. The simplification is introduced as a set of assumptions, which expresses the nature of the system, their features and behaviors that are relevant to the problem under investigation. These assumptions together with other factors would relate to the geometry of the investigated domain, the various heterogeneities, the nature of the porous medium, the properties of the fluid involved, and the type of flow regime under investigation etc. Being a simplified version of real-world system, and hence no model is unique to a given system. Different sets of simplifying assumptions result in different models. However, a model is generally constructed for a particular aquifer by specifying the area to be analyzed, conditions at the boundaries of the area, and parameter values within the aquifer, and they are constructed by mathematical equations, which describe the physical laws that groundwater must obey. The usefulness and accuracy of computing the values of a model depends on how closely the mathematical equations approximate the physical system being modeled and what competence level of understanding one has about the physical system and the assumptions embedded in the derivation of the mathematical model.

The major processes associated with groundwater problems are fluid flow, solute transport, heat transport and deformation. Accordingly, different models associated with these processes are used for different purposes. Groundwater flow models are used for the management of groundwater resources. Solute transport models are used for the study of groundwater quality problems including seawater intrusion. Heat transport models are used to study geothermal problems. Deformation models are used to study the subsidence of groundwater as a result of excessive pumping. However, when we talk about groundwater resource management, we often refer the groundwater flow and solute transport models. A groundwater model can have two distinct components: (i) groundwater flow component, and (ii) groundwater contaminant transport and reactive reactions component. Groundwater flow and contaminant transport modeling together play an important role in the characterization of groundwater bodies and the management of groundwater. A groundwater flow modeling is pre-requisite for developing a contaminant transport model of an area of interest. A groundwater flow model can provide a quantitative assessment of groundwater resources along with the following components: (i) estimating groundwater recharge, discharge, and storage at spatial scale; (ii) assessing the cumulative effects on existing and proposed water resources uses and developments; and (iii) evaluating the cumulative impact on water resources of various water management options. A groundwater contaminant transport model, however, assists in predicting the transportation or movement of dissolved constituents including their chemical reactions in groundwater and soil matrices.

Elements of Groundwater Model Development

Elements of a groundwater model can be divided into two distinct processes: (i) model development, and (ii) model application (Fig. 2). The model development deals with process description and mathematical formulations of the processes, and bringing them into the computational mode by developing computer code, i.e., software part. The model application is the use of the computer code for a specific purpose. Fig.2 illustrates elements of a groundwater model development. A groundwater model development process requires understanding and skill of two broad components: (a) conceptualization, and (b) mathematical formulations. The contents of conceptualization deal with set of assumptions that verbally describe the system's composition, the transport processes that take place in it, the mechanisms that govern them, and the relevant medium properties. The conceptualization is one of the most important steps in the modeling process. Oversimplification may lead to a model that lacks the required information, while under-simplification may result in a costly model, or in the lack of data required for model calibration and model parameter estimation or both. The step next to the conceptual representation is the mathematical modeling. The complete statement

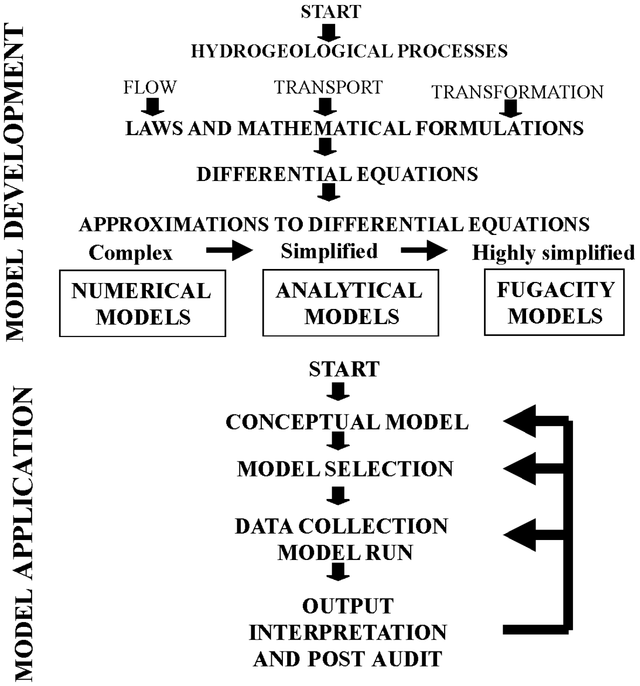

Figure 2. Development process of a groundwater model

of a mathematical model consists of: (i) a definition of the geometry and its boundaries, (ii) an equation (or equations) expressing the water balance, (iii) flux equations that relate the fluxes, (iv) constitutive equations that define the behavior of the fluids and solids involved, (v) an equation (or equations) that expresses initial conditions, (vi) an equation (or equations) that defines boundary conditions describing interaction with its surrounding environment. The solution to the mathematical equations yield the required predictions of the real-world system's behavior in response to various sources and/or sinks. The mathematical model contains the same information as the conceptual one, but expressed as a set of equations which are amenable to analytical and numerical solutions. All the mathematical equations are expressed in terms of the dependent variables, and the number of equations included in the model must be equal to the number of dependent variables.

Groundwater Modeling

Modeling is not just about entering data into existing modeling packages and reporting results. Development of the groundwater model for a real world and its application requires thorough understanding of the groundwater system for refinement of the conceptualized elements to maximize knowledge about current state of groundwater body and the possible future impacts of proposed development. Groundwater models are used as tool for the assessment of the resource potential and prediction of future impact under different circumstances/stresses. Predictive capacity of a model makes it the most useful tool for planning, design, implementation and management of the groundwater resources. Groundwater modeling provides the framework to decide and predict the fate of decision variables of the hydro-geological processes in response to the stresses and/or sinks acting on the system.

The very first step in the modeling process is the construction of a conceptual model. Selecting the appropriate conceptual model for a given problem is one of the most important steps in the modeling process. The selection of an appropriate conceptual model and its degree of simplification depends on:

- Objective of the management problem,
- Available resources
- Available field data
- Users and beneficiaries attitude to the use of water,
- Legal and regulatory framework applicable to the situations.

The next step in the modeling process is to express or to bring the conceptual model in the form of a computational framework. Existing software packages or mathematical equations can be used as computation tools. Fig. 3 illustrates a simple diagram of a model application process (Bear *et al.*, 1992).

A successful model application requires appropriate site characterization and expert insight into the modeling process. No model can be used for predicting the behavior of a system unless the numerical values of its parameters have been determined by some identification procedure. Because of the simplifying assumptions embedded in the mathematical equations and the many uncertainties

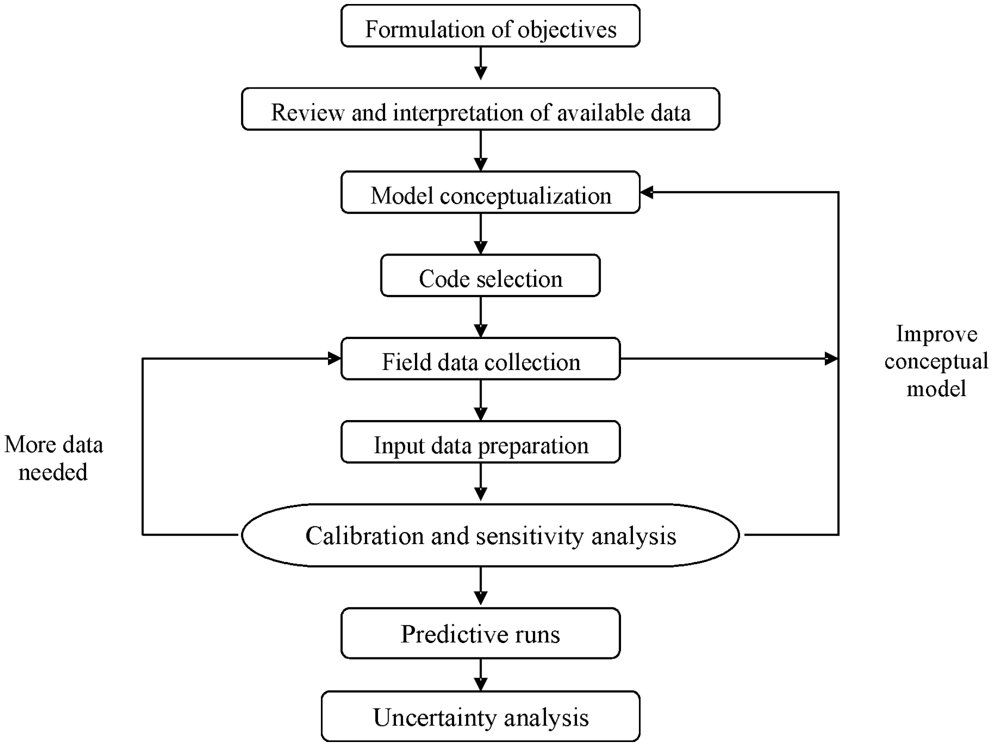

Figure 3. Model application process *(Source: Bear et al., 1992)*

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.

Modeling Equations

Groundwater flow and solute transport are governed by the principles of conservation of momentum and mass. Mathematically, these conservation principles, together with empirical laws can be expressed as a set of partial differential equations. Subject to initial and boundary conditions as well as appropriate source functions, the equations can be solved analytically or numerically to interpret observations or predict certain phenomena.

The modeling equations basically originate from water balance or mass balance of flow and contaminant transport in porous medium domains. A number of simplifying assumptions are usually made before any of these equations are written. The well-known Darcy's law can be derived from simplified assumptions of momentum balance equation.

Groundwater Flow Equation

The generalized groundwater flow equation for a 3-Dimensional saturated flow in porous medium is written as (Bear, 1972; Bear, 1979):

$$S_o \frac{\partial \phi}{\partial t} = \nabla * \{K * \nabla \phi\} + Q \tag{2}$$

where S_o is the specific storativity of porous medium, ϕ is the piezometric head, K is the hydraulic conductivity tensor, Q is the volumetric flux per unit volume representing source/sink term, and ∇ is the vector operation in the xyz plane.

The specific storativity, S_o, is defined as the volume of water added to storage in a unit volume of porous medium, per unit rise of piezometer head. Hence, left hand side of equation (2) expresses the volume of water added to storage in the porous medium domain, per unit volume of porous medium per unit time. The divergence of flux vector, q (= - K *Ñf) expresses the excess of outflow over the inflow per unit area, per unit time. In equation (2), the operators are in the three dimensional space. The variable to be solved is *f (x,y,z, t)*. Thus, equation (2) states that the excess of inflow over outflow of water in a unit volume of porous medium, per unit time, at a point, is equal to the rate at which water volume is stored.

The generalized groundwater flow equation for a 2-dimensional saturated flow in confined aquifer is written as (Bear, 1972; Bear, 1979):

$$S \frac{\partial \phi}{\partial t} = \nabla * \{T * \nabla \phi\} - P(x,y,t) + R(x,y,t) \tag{3}$$

where S is the aquifer storativity, ϕ is the piezometric head, T is the aquifer transmissivity tensor, *Ñ* is the vector operation in the xy plane, *P(x,y,t)* is the rate of pumping (per unit area of aquifer), and *R(x,y,t)* is the rate of recharge (per unit area of aquifer).

The storativity, S, is defined as the volume of water added to storage in a unit area of aquifer, per unit rise of piezometer head. Hence, left hand side of equation (3) expresses the volume of water added to storage in the aquifer, per unit volume of porous medium per unit time. The divergence of flux vector, q (= - T *Ñf) expresses the excess of outflow over the inflow per unit area,per unit time. In equation (3), the operators are in the two dimensional horizontal coordinates, and the variable to be solved is *f (x,y, t)*. Thus, equation (3) states that the excess of inflow over outflow of water in a unit area of an aquifer, per unit time, at a point, is equal to the rate at which water volume is stored.

The governing equation for 3-dimensional density–dependent miscible flow uses for a coastal aquifer may be written as (Guo and Langevin, 2002):

$$\frac{\partial(\rho\ n)}{\partial t} = \bar{\rho}\, Q - \nabla * (\rho\ q) \tag{4}$$

in which ρ is the variable fluid density; ‘ρ is the density of water entering from a source or leaving through a sink; n is the porosity; Q is the volumetric flow per unit volume of aquifer representing sources/sinks; q is the specific discharge vector, with its component given by:

$$q_x = \frac{K_x}{\mu} \frac{\partial \phi}{\partial x} \qquad q_y = \frac{K_y}{\mu} \frac{\partial \phi}{\partial y} \qquad q_z = \frac{K_z}{\mu} \left[\frac{\partial \phi}{\partial z} + \rho\ g \right] \tag{5}$$

μ being the dynamic viscosity; g being the acceleration due to gravity; K being the hydraulic conductivity tensor.

Contaminant Transport Equation

The generalized contaminant transport equation for a 3-dimensional saturated flow in porous medium is written as (Bear, 1972; Bear and Bachmat, 1984; Bear and Verrrujit, 1987):

$$\frac{\partial\{nC\}}{\partial t} = -\nabla * \left\{Cq + nJ^* + nJ\right\} + R_c + \sum_{k=1}^{N} R_k \tag{6}$$

where C is the concentration of considered contaminant, n is the porosity of porous medium, q is the specific discharge of water (= volume of water passing through a unit area of porous medium per unit time), J^* is the diffusive flux of contaminant per unit area of fluid in micro-scale, J is the diffusive flux of contaminant per unit area of fluid in macro-scale, R_c is strength of contaminant source (added quantity per unit volume of porous medium per unit time), and R_k is the chemical reaction term.

The transport equation is linked to the flow equation, as:

$$q = -K * \nabla\phi \tag{7}$$

The left hand side of equation (6) expresses the mass of the contaminant added to storage per unit volume of porous medium per unit time, while the first term on the right hand side of equation (6) expresses the excess of the contaminant's inflow over outflow, per unit volume of porous medium, per unit time. The second and third terms on the right side of equation (6) express respectively the added mass of various sources and the chemical reaction component. The total flux is made up of an advective flux with fluid, a diffusive flux, and a dispersive flux. The diffusive and dispersive fluxex appearing in equation (6) are expressed in terms of the concentration, C, as:

$$J^* = -D_m * \nabla C \quad ; \qquad J = -D * \nabla C \tag{8}$$

where D_m is the coefficient of molecular diffusion in a porous medium, and D is the coefficient of dispersion.

The governing equation for 3-dimensional variable density transport equation can be expressed in the same way as equation (6) but the density can be written by an empirical equation as a function of concentration suggested by Baxter and Wallace (1916):

$$\rho = \rho_f + EC \tag{9}$$

in which, E is a dimensionless constant, approximately value of 0.7143 for salt concentrations ranging from zero for freshwater to 35 kg/m^3 for seawater and ρ_f is the fluid density of freshwater.

Model Coefficients and their Estimation

In describing movement from microscopic level to macroscopic level, various coefficients of transport and storage are introduced. The permeability of porous medium, aquifer transmissivity, aquifer storativity, and porous medium dispersivity are examples of model coefficients. Permeability and dispersivity are examples of coefficients that express the macroscopic effects of microscopic configuration of the solid-fluid interfaces of a porous medium. The coefficients of aquifer storativity and transmissivity are introduced by the further averaging of the three-dimensional macroscopic model over the thickness of an aquifer in order to obtain a two-dimensional model. All these coefficients are coefficients of the models, and their interpretation and actual values may differ from one model to the next. The activity of identifying these model coefficients is often referred to as the identification problem.

The values of the coefficients for a considered model are obtained by investigating the available data of real-world aquifer system on: (i) initial conditions of the system; (ii) excitations of the system, as in the form of pumping and artificial recharge and changes in boundary conditions; and (iii) observations of the response of the system, as in the form of temporal and spatial distributions of water levels and solute concentrations. Various techniques exist for determining the "best" or "optimal" values of the coefficients. Some techniques use the basic trial-and-error method, while others employ more sophisticated optimization methods. In some methods, a priori estimates of the coefficients, as well as information about lower and upper bounds, are introduced. Beside these, another unique method, called inverse problem, is also used to determine the model coefficients.

Methods of Solution

Once a well-posed model for a given problem has been constructed, including the numerical values of all the model coefficients, it must be solved for any given set of excitations (i.e., initial and boundary conditions, sources and sinks). The preferable method of solution is the analytical one, however, for most cases of practical interest, this method of solution is not possible due to the irregularity of the domain's shape, the heterogeneity of the domain with respect to various coefficients, and various non-linearities. Instead, numerical models are employed.

As a numerical model is derived from the mathematical equations and interpretations, it need not necessarily be considered as the numerical method, but as a model of the problem in its own right. With the introduction of computers and their application in the solution of numerical models, solutions of complex groundwater problems have become relatively easy.

Analytical Models

Such models enable investigators to conduct a rapid preliminary analysis of groundwater contamination and to perform sensitivity analysis. A number of simplifying assumptions regarding groundwater system are necessary to obtain an analytical solution. For application and analyzing an analytical model in context to the "real-life" problem, it requires sound professional judgment and experience. Analytical models should be viewed as a useful complement to numerical models.

Numerical Models

Depending on the numerical technique(s) employed in solving the mathematical model, there exist several types of numerical models:

- Finite-difference models
- Finite-element models
- Boundary-element models
- Particle tracking models
  - Method of characteristics models
  - Random walk models, and
- Integrated finite difference models.

The main features of the various numerical models are:

- The solution is sought for the numerical values of state variables only at specified points in the space and time domains.
- The partial differential equations replaced by a set of algebraic equations written in terms of discrete values of the state variables at the discrete points in space and time.
- The solution is obtained for a specified set of numerical values of the various model coefficients.
- Because of the large number of equations, which are to be solved simultaneously, a computer program is prepared.

In the present global computational environment, software codes of almost for all classes of problems encountered in the management of groundwater are available. Some codes are very comprehensive, popular and widely used, such as; MODFLOW & MT3D (Modular Three-Dimensional Finite-Difference Groundwater Flow Model) developed by U.S. Geological Survey (McDonald and Harbaugh, 1988) and associated modules; MODPATH, RT3D; GMS (Groundwater Modeling Environment for MODFLOW, MODPATH, MT3D, RT3D, FEMWATER, SEAM3D, SEEP2D, PEST, UTCHEM, and UCODE); FEFLOW (Finite Element Sub-surface Flow System); Groundwater Vistas (Model Design and Analysis for MODFLOW, MODPATH, MT3D, RT3D, PEST, and UCODE); HST3D (3-Dimensional Heat and Solute Transport Model); SEWAT(Density Driven flow and transport model); SUTRA (2-Dimensional Saturated/ Unsaturated Transport Model) etc. The strength and computational competency of these models are well recognized amongst the groundwater modelers.

Groundwater Resource Management Model

Management of groundwater resources primarily involves the allocation of groundwater supplies in terms of quantity and quality to competing demands. Groundwater models are utilized to explore groundwater management alternatives. A groundwater management model is the combination of groundwater simulation models and the optimization methods, which are coupled together to produce a single program to optimize management objectives while meeting physical and technical constraints on groundwater behavior. The optimization scheme is the mathematical transformation of management objectives (e.g., maximize benefits or effectiveness, or, minimize cost) or design criteria and the physical constraints. In a groundwater system, management decisions may be related to rates and location of pumping and artificial recharge, changes in water quality, location and pumping in pump-and treat operations, etc. The resulting optimization problem is then solved to determine the optimal strategy for dealing with the management objectives and design criteria. However, the value of management's objective function usually depends on both the variables and on the response of the aquifer system. Constrains are expressed in terms of future values of state variables of the considered groundwater system. An essential part of a good decision-making process is that the response of a system to the implementation of contemplated decisions must be known before they are implemented.

Optimization modeling involves the development of a systematic method of determining optimum water supply strategies that would satisfy various environmental and hydrologic requirements. The purpose of this type of water supply strategy is to balance the projected needs against available sources. Although the simulation models provide the resource planner with important tools for managing the groundwater system, the prediction tools don't identify the optimal groundwater development, design and operation policies for an aquifer system. In contrast, groundwater optimization models identify the optimal planning or design alternatives in the context of the system objectives and constraints. It is the groundwater planners or the decision makers, who has to decide the best among the possible alternatives. Fig.4 represents a generalized structure of a simple Simulation-Optimization framework. Structurally, the coupled Simulation-Optimization (S/O) models have an optimizer linked to an external simulator. The S/O approach is appealing because it can readily use existing simulation models and can account for the nonlinear and complex behavior of a groundwater flow system.

Both linear and non-linear optimization techniques are used to develop groundwater management models. Simplex method for linear problems, sequential linear programming for nonlinear problems, and branch and bound algorithm for mixed integer problems are some conventional techniques of optimization. Besides those, the other advanced techniques developed in recent time for optimization of groundwater quantity and quality management strategies, and also for remediation are: (i) nonlinear chance-constrained groundwater management model (Tung, 1986; Wagner and Gorelik, 1987; Gailey and Gorelik, 1993; Tiedman and Gorelik, 1993), (ii) simulated annealing method (Dougherty and Marryott, 1991), (iii) Sharp interface model for seawater intrusion (Finney et al., 1992), (iv) simulation-optimization model for well field, capture zone design, groundwater levels predictions for pumping policy, supply-demand scheduling, etc (Varlein and Shafer, 1993; Chau, 1992; Danskil and Freckleton, 1992; Lall and Lin, 1993; Gharbi and Peralta, 1994). The method of optimization is another subject, which requires a separate discussion and is not included in the scope of the paper.

Need of Groundwater Management Models

Management problems of groundwater resources primarily deal with three aspects: (i) supply-side components (availability and distribution), (ii) demand-side components (allocations for different requirements), and (iii) impinging components

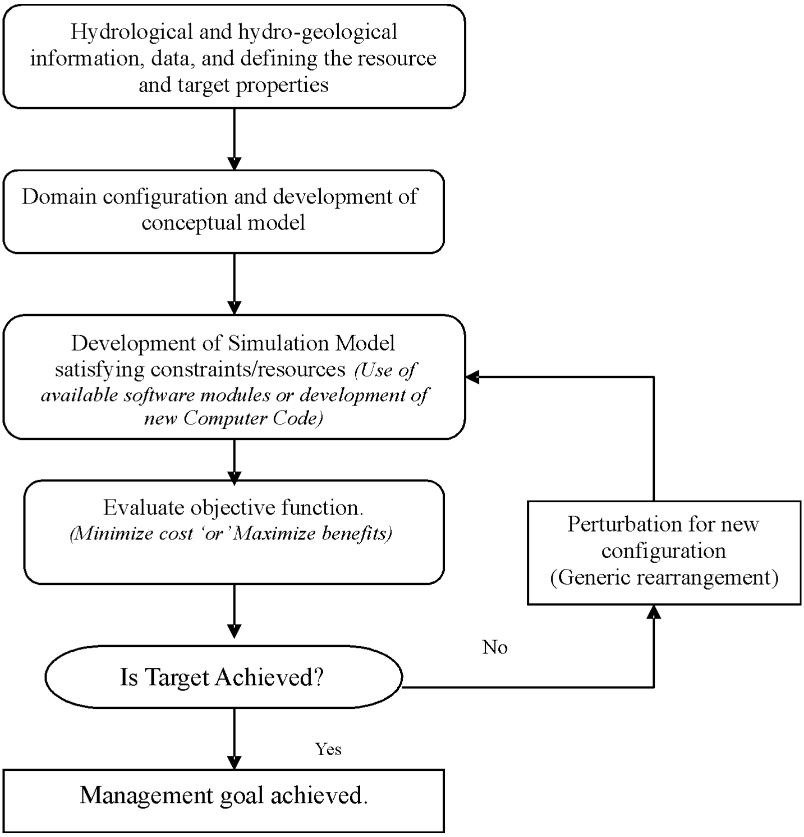

Figure 4. A generalized structure of a simple simulation-optimization framework

(threat to the availability). The supply-side and demand-side components mostly deal with quantitative aspect, while the impinging issues could be of both quantitative and qualitative form of the groundwater system. Impinging or encroaching issues mainly indulge into the prospect of availability and demand as well. To exemplify the components of exploitations and their consequences with the components of availability, let us look into the schematized Fig.5; in which some of the key issues of supply, demand and impinge components are depicted, which are self explanatory. The supply-side components are those, which create positive potential to the storage (i.e., increases the storage volume), the demand-side components are those, which withdraw water from storage (or, reduce the storage potential), while the impinging components have the characteristics of defunct and reduce of the potential of storage. Causes and factors responsible to these issues are also illustrated in the figure. To the supply-side, recharge from rainfall and irrigation application, and seepage from surface interactions are the main components of supply of water to the groundwater system, while all other factors (such as, permeability, hydrogeology, aquifer properties, etc) give shape to the availability and distribution of flow in space and time. The rainfall recharge and the seepage from surface waters depend largely on the rainfall, whose distributions also vary on space and time, but by and large, the fluctuation of

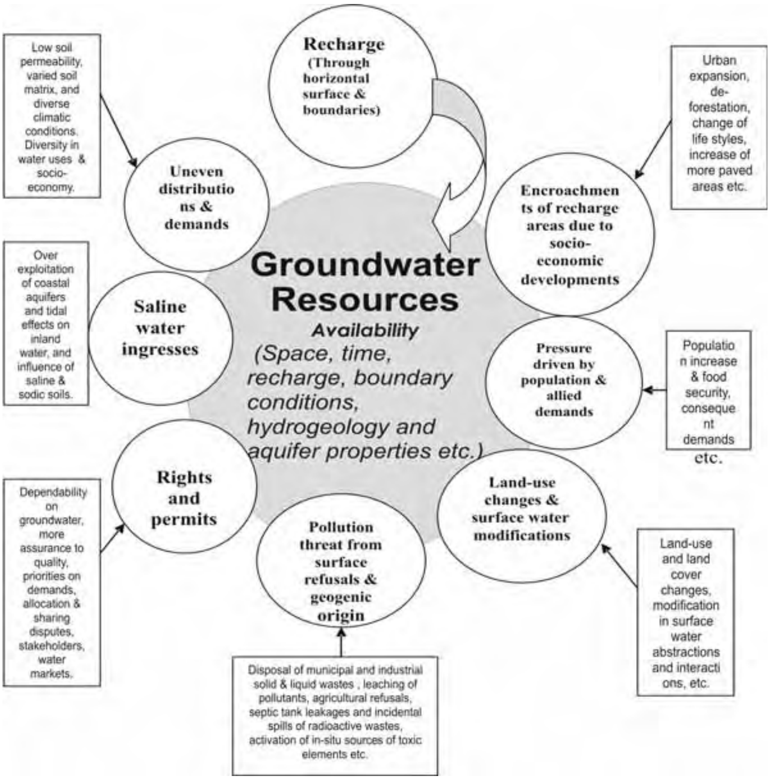

Figure 5. Supply-Demand-Encroachment components of an exploited groundwater resource system

average annual rainfall between years at a specific location is very less except severe years. Thus, recharge area remaining same; the supply of replenishable groundwater resources in an area does not change much over the years but turns into a limiting state.

The demand-side constitutes all those components, which are driven mainly by the population expansion and associated demands, food security, socio-economic development and regulatory provisions, etc. Unlike the characteristics of supply-side components, the characteristics of demand-side components vary in magnitude between years besides spatial variation. It is the multidimensional demands including their increase over time, which brings susceptibility to the supply-side. Multiple demands supported by limited supply eventually suggest for requirement of management decisions for operation of the system.

Impinge on the availability resulting from the exploitations of the demand-side appends threat in terms of quality and quantity both on time and space to the existing storage and to the future storage. These unfavorable factors originate from pollution due to solid and liquid waste disposal, refusal of agricultural waste, septic tank leakages, change of oxidation-reduction potential in hydro-geological environment due to overexploitation of groundwater, seawater intrusion, influence of saline and sodic soils to the groundwater, etc., while others, such as, encroach to the recharge zones, land-use changes, etc, are due to the socio-economic and socio-cultural development of the society. Economic development side by side increasing health awareness are giving rise to problems of right to use of groundwater, and permit to stakeholders for use of groundwater. Conflict in sharing of groundwater of a common pool is another emerging problem. Management of coastal aquifers against threat of saline water ingress requires special skill and attention. Groundwater contamination and its mobilization and spreading in the soil pores and in the groundwater are emerging as gigantic issues other than the groundwater flow management. Vulnerability of contamination to the freshwater zones of a contaminated aquifer would increase if the contaminated aquifers remain untreated. Aquifer restoration and remediation are, therefore, needed to ensure the risk free replenished groundwater. The management decisions cannot be prejudiced to quantity without assuring the quality of water being supplied. These multi-faceted complexities insist upon to develop appropriate decision support system for management of groundwater system.

The purpose of the groundwater resource management model being determining the optimal allocation strategy against demands under the constrains of availability and supply or with some limiting conditions either to the supply-side or to the demand-side, it is essentially required to recognize and understand the characteristics and behavior of associated components. The characteristics and behavior of components of a system can be described when their physical realism are understood to the possible extent. More is the understanding of the hydrological and hydro-geological processes better is the prospect of conceptualize framework of the models. Figure 6 depicts some of the key issues and factors, which are to be addressed for achieving the goal of groundwater resource management.

Finally, a management approach is said to be perfect, if the demand-side elements balance with its supply-side inputs. In case of groundwater management, the elements are: (i) hydrogeologic and socio-economic conditions of the system, (ii) regulatory interventions, (iii) regulatory provisions, and (iv)costs and benefits of management activities and interventions. Figs.7 and 8 depicts how a supply

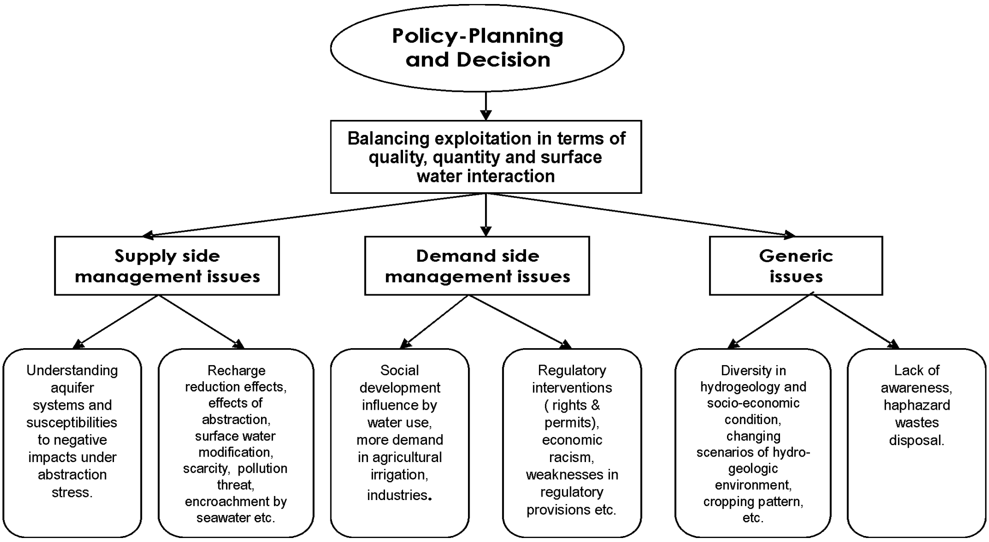

Figure 6. Key issues of policy planning and decisions of groundwater resource management

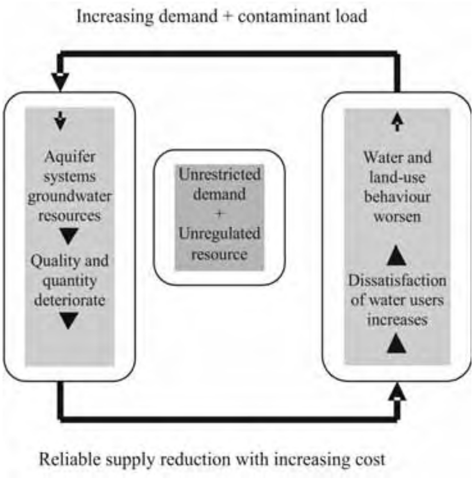

Figure 7. Supply-driven groundwater development – leading to a vicious circle *(Source: GW-MATE, 2004)*

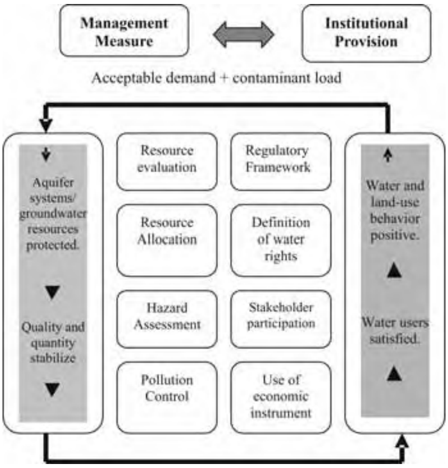

Figure 8. Integrated groundwater resource management – leading to a virtuous circle *(Source : GW-MATE, 2004)*

driven 'vicious circle' of groundwater development can be transformed into a 'virtuous circle' of integrated groundwater resource management through integration of supply-side management with the demand-side management.

Concluding Remarks

Models are conceptual framework of physical systems represented by well-posed mathematical equations derived from the physical laws that the system must obey. Models are used to bring quantitative data and qualitative information together in a predictive framework, and hence can be regarded as tools in insight the behavior of a system in response to imposed stresses/strains without intervening physically into the system.

Groundwater models are simplified versions of a conceptualized groundwater system that approximately simulates the relevant excitation-response relations of the system. Being a simplified version of real-world system, no model is unique to a given system. Groundwater models are one of the management tools used for the assessment of the resource potential and prediction of future impact under different circumstances. Predictive capacity of a model makes it the most useful tool for planning, design, implementation and management of the groundwater resources.

Groundwater management model is a coupled framework of the groundwater simulation models and the optimization methods that produces a single program to optimize management objectives while meeting physical and technical constraints on groundwater behavior. It is simulation models, which actually impart science of hydrological and hydro-geological processes into the management approaches. Optimization method has its own mathematical authenticity. These facts bring strength to the genuineness of a groundwater management model.

Increasing pace of multidimensional demands pulled by the limiting state of supply and pollution threats direct only towards development and use of best management approach.

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