Groundwater Modeling and Management: An Overview

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INTRODUCTION

Surface water and groundwater originate from the same hydrological cycle, however, groundwater differs from surface water because of the contrasting physical and chemical environment in which it occurs (Tuinhof *et al.*, 2004). Groundwater is increasingly getting importance and popular because of the relatively easy access and dependability. 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 is also emerging as a poverty reduction tool (IWMI, 2001). However, developing and managing this resource in a sustainable way poses many challenges including threats. On the other hand, over-depletion of groundwater is becoming a major problem in western and peninsular India and in most of the urban areas. Groundwater overdraft is common in many aquifers in India. The most far-reaching impact of groundwater depletion and water quality deterioration is on the health of large sections of rural populations. Some of the concerns are: in western and peninsular India, overuse of the groundwater resource is depleting water tables; groundwater mining is causing the drilling of ever-deeper wells and an ever-increasing cost of tapping of those aquifers; in Gujarat and Rajasthan States, groundwater overuse is causing fluoride contamination of drinking water supplies, creating a major public health crisis, in many eastern states including West Bengal, overexploitation causes arsenic contamination of groundwater; in coastal India, overexploitation of groundwater results in high levels of salinity in the water, making it unfit for human consumption or farming. The challenge in those areas is to promote sustainable and equitable development of the resource.

Groundwater resources management has to deal with balancing the exploitation of this important complex resource (in terms of quantity, quality and its interaction with surface water bodies) with increasing demands of water and land uses. It is essential to recognize that managing groundwater is as much about managing people (water and land users) as it is about managing water (aquifer resources). The socio-economic dimension (demand-side management) should get equal importance as given for the hydrogeological dimension (supply-side management) and integration of both is always required.

To address the key issues of the groundwater supply-management, one needs to understand: (i) aquifer systems and their specific 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, the key issues need to be understood 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.

The main driving issues in groundwater as envisaged by many experts are protection, restoration, development of groundwater supplies as well as remediation of contaminated aquifers. But, the ultimate drivers are population expansion and increasing demands for water.

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 hydrological processes of the aquifer system govern the technical rules in case of groundwater. Without knowing the behavior of an aquifer for a given input, one can not achieve the goal as envisaged in a management programme. To predict, forecast, compute, and evaluate responses of an aquifer towards some imposed forcing functions, which could be dynamic in nature, groundwater modeling is necessary.

Groundwater modelling is one of the main tools of management used in the hydrogeological sciences for the assessment of the resource potential and prediction of future impact under different circumstances. Its predictive capacity makes it the most useful tool for planning, design, implementation and management of the groundwater resources. Thus, to meet the goal of increasing demand for water, groundwater modelling and management should go side by side.

GROUNDWATER MODELLING

Modelling is a management tool. In a groundwater system, management decisions may be related to rates and location of pumping and artificial recharge changes in water quality, location and rates of pumping in pump-and-treat operations, etc. Analyses of groundwater systems are necessary to supplement these decision variables. Groundwater modelling provides the framework to decide and to predict the fate of decision variables considering hydrogeological processes into account. Estimation of pumping rates for wells, analysis of hydraulic barriers, estimation of contaminant source terms from land fills or accidental spills, etc. are other elements analyzed by modelling. Groundwater models are tools used to simulate current groundwater behavior and predict future groundwater behavior.

The very first step in the modelling process is the construction of a conceptual model consisting of a set of assumptions, which describe the system's composition, the transport processes that take place in it, the mechanisms that govern them, and the relevant medium properties. Selecting the appropriate conceptual model for a given problem is one of the most important steps in the modelling process. Oversimplification may lead to a model that may lack the required information, while under simplification may result in a costly model. It is therefore important that all features relevant to a considered problem be included in the conceptual model and the irrelevant ones be excluded. The selection of an appropriate conceptual model and its degree of simplification depends on:

- *the objective of the management problem,*
- *the available resources,*
- *the available field data,*
- *the users and beneficiaries, attitude to the use of water,*
- *the legal and regulatory framework applicable to the situation.*

The next step in the modelling processes is to express the conceptual model in the form of a mathematical model. The solution of the mathematical model yields the required predictions of the system's behavior in response to various sources and/or sinks. Mass balance approach is usually considered in mathematical derivations, which usually takes the form of a partial differential equation. Finally, the partial differential equations are solved with the initial and boundary conditions of the area, which is to be modeled and then responses are evaluated for the various stress conditions. The content of a mathematical model generally consists of the following items (Bear et al., 1992; Sun, 1993):

- *a definition of the geometry of the modelling domain and its boundaries,*
- *an equation (or equations) that expresses the balance of the considered quantity (or quantities),*
- *flux equations that relate the flux(es) of the considered quantity (or quantities) to the relevant state variables of the problem,*
- *constitutive equations that define the behavior of the fluids and solids involved,*
- *an equation (or equations) that expresses initial conditions, which describe the state of the system at some initial time, and*
- *an equation (or equations) that defines boundary conditions, which describe the interaction of the considered domain with its environment.*

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. 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. A model is a simplified version of real-world system and hence no model is unique to a given groundwater 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. Models are constructed by mathematical equations, which describe the physical laws that groundwater must obey. To accommodate complex aquifer geometry and heterogeneity in aquifer properties, numerical methods are used to solve the resulting mathematical equations.

The major processes associated with groundwater problems are fluid flow, solute transport, heat transport and deformation. Accordingly different models associated 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 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. A groundwater flow modeling is prerequisite for developing a transport model of an area of interest, but vice *versa* is not true. Groundwater modeling is not just about entering data into existing modeling packages and reporting the results. It requires thorough understanding of the groundwater system to refine the conceptualized elements to maximize knowledge about current state of groundwater body and the possible future impacts of proposed development. Models are used to bring quantitative data and qualitative information together in a predictive framework.

The development of groundwater flow and solute transport models may provide the following potential applications:

- *design and/or evaluation of pump-and-treat systems,*
- *design and/or evaluation of hydraulic containment systems,*
- *evaluation of physical contaminant systems,*
- *analysis of "no action" alternatives,*
- *evaluation of migration patterns of contaminants,*
- *assessment of attenuation/transformation processes,*
- *evaluation of the impact of non-aqueous phase liquids (NAPL) on remediation activities.*

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. Thus, appropriate methods are necessary to estimate the system's parameters and model coefficients. Fig 1 illustrates a simple diagram of a model application process (Bear *et al.*, 1992).

Modelling Equations

The modeling equations basically originate from water balance or mass balance, i.e., based on principle of conservation of mass, of flow and contaminant transport in porous medium domains. A number of simplifying assumptions is usually made before any of these equations are written. In some cases, momentum balance is also considered. The well-known Darcy's law has been derived from simplified assumptions of momentum balance equation.

Mass balance for 3-D saturated flow in porous medium

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

$$S_0 \frac{\partial \phi}{\partial t} = \nabla \bullet \{K \bullet \nabla \phi\} \qquad \text{..........} \quad (1)$$

where S_0 = specific storativity of porous medium,
ϕ = piezometric head,
K = hydraulic conductivity tensor,
∇ = the vector operation in the xyz plane.

The specific storativity, S_0, is defined as the volume of water added to storage in a unit volume of porous medium, per unit rise of piezometer head. Hence, the left hand side of Eq.(1) expresses the volume of water added to storage in the porous medium domain per unit volume of porous medium per unit time. Thus, Eq.(1) 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 being stored.

Mass balance for 2-D saturated flow in a confined aquifer

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

$$S\frac{\partial \phi}{\partial t} = \nabla \bullet \{T \bullet \nabla \phi\} - P(x,y,t) + R(x,y,t) \quad \text{..........} \quad (2)$$

where S = aquifer storativity = $b\,S_0$,
b = aquifer thickness,
ϕ = piezometric head,
T = aquifer transmissivity tensor,
$P(x,y,t)$ = rate of pumping (per unit area of aquifer),
$R(x,y,t)$ = rate of recharge (per unit area of aquifer).

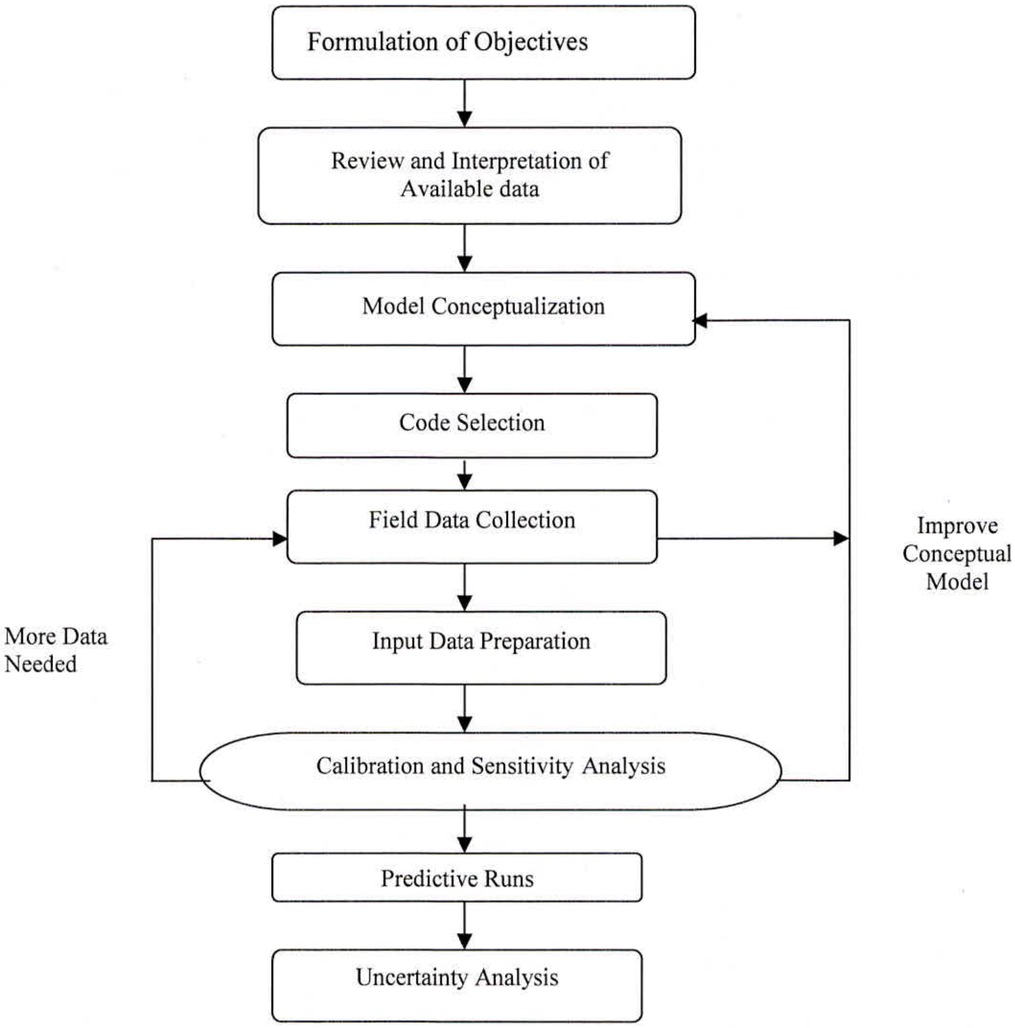


Figure 1. Model application process ***(Source: Bear et al., 1992)***

The storativity, S, is defined as the volume of water added to storage in a unit area of aquifer, per unit rise of piezometric head. Hence, the left hand side of Eq.(2) expresses the volume of water added to storage in the aquifer, per unit volume of porous medium per unit time. Thus, Eq.(2) 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 being stored .

Mass balance for a solute in 3-D saturated flow

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

$$\frac{\partial\{n\,C\}}{\partial t} = -\nabla\bullet\left\{Cq + nJ^{*} + nJ\right\} + \Gamma \qquad \text{..........}\ (3)$$

where C = concentration of considered solute,

n = porosity of porous medium,

q = specific discharge of water (= volume of water passing through a unit area of porous medium per unit time),

J^* = diffusive flux of solute (per unit area of fluid),

J = dispersive flux of solute (per unit area of fluid),

Γ = strength of solute source (added quantity per unit volume of porous medium per unit time).

The left hand side of Eq.(3) expresses the mass of the conservative solute added to storage per unit volume of porous medium per unit time, while the first term on the right hand side of Eq.(3) expresses the excess of the solute's inflow over outflow, per unit volume of porous medium, per unit time. The second term on the right side of Eq.(3) expresses the added mass by various sources. The total flux is made up of an advective flux with the fluid, a diffusive flux and a dispersive flux.

The diffusive and dispersive fluxes appearing in Eq.(3) are expressed in terms of the concentration, C, as:

$$J^{*} = -D_m\ \nabla C \quad ; \quad J = -D\ \nabla C \qquad \text{..........}\ (4)$$

where D_m = coefficient of molecular diffusion in a porous medium,

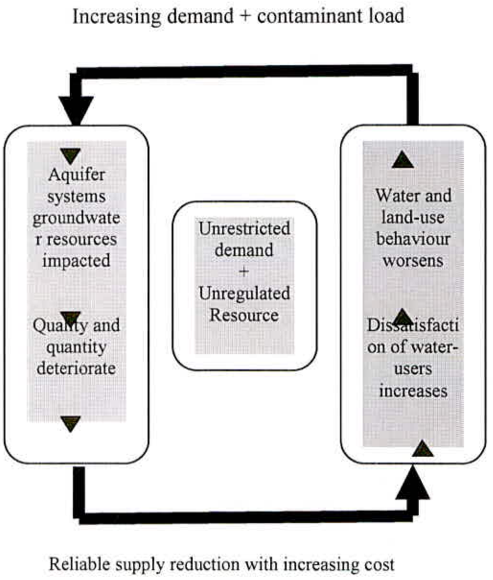
D = coefficient of dispersion.

GROUNDWATER RESOURCE MANAGEMENT

Groundwater management is the combination of groundwater simulation models and the optimization methods, which finally produce a single programme that optimizes management objectives while meeting physical and technical constraints on groundwater behavior. The programme, which provides a tool for design, and the management objectives together are thereafter translated into mathematical constraints and objectives imposed on the groundwater simulation models. The resulting optimization problem is then solved to determine the optimal strategy for addressing the management objectives and design criteria.

However, the value of management's objective function (e.g., minimize cost and maximize effectiveness of remediation) usually depends on both the values of the decision variables and on the response of the aquifer system. Constraints are expressed in terms of future values of state variables of the considered groundwater system, such as, water table elevations and concentrations of specific contaminants in the water.

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. In the management of a groundwater system, the decision must be made with respect to both the water quality and quantity. A regional or basin wide groundwater management modeling should be preferred to plan and develop the groundwater resource without affecting the environment and the potential of the resource.



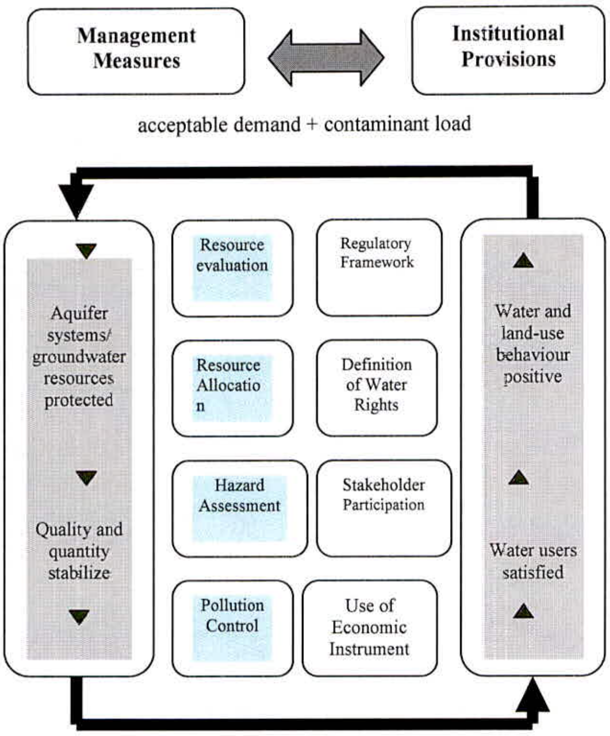


Figure 2 Supply-side groundwater development & management issues (Source: GW-MATE, 2004)

Figure 3. Demand-side groundwater management issues (Source: GW-MATE, 2004)

A management approach is said to be perfect, if the demand-side of the elements of interest 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. In Figs. 2 and 3 *(Tuinhof et al., 2004),* the key elements and issues of supply-side and demand-side of the groundwater resource management, which are to be addressed to attain a sustainable groundwater resource management, are illustrated.

Management Tools and Techniques

Optimization is a mathematical technique for finding the maximum or minimum value of a function subject to constrains. Both linear and non-linear optimization techniques are used to develop models for groundwater management strategies. Simplex method for linear problems, sequential linear programming for nonlinear problems, and branch and bound algorithm for mixed integer problems are some conventional techniques. 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 Gorelick, 1987; Gailey and Gorelick, 1993; Tiedman and Gorelick, 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. (Varlien and Shafer, 1993; Chau, 1992; Danskil and Freckleton, 1992; Lall and Lin, 1993; Gharbi and Peralta, 1994).

There are a number of groundwater management tools and instruments, whose implementation and importance depend upon the type of problems and their complexities. Some of the management tools and their stages of requirement are listed in Table 1. In practical terms, to develop an integrated groundwater management strategy, it is preferable and also necessary to set all possible management interventions and their stages of development.

Table 1. Groundwater management tools

Groundwater Management Tools and Instruments	Requirement/ Purpose
TECHNICAL TOOLS	
Resource Assessment	Basic knowledge of aquifer to develop models linked to decision-support for planning and management.
Quality Evaluation	Basic knowledge of water quality constituents and their effects to develop allocation plans.
Aquifer Monitoring	No regular monitoring program (monitoring programs are used for decision support).
MANAGEMENT ACTIONS	
Prevention of side effects	Reorganization of side effects, and their preventive measures techniques.
Resource Allocation	To define priorities of uses and their allocation.
Pollution Control	To develop appropriate strategies for pollution free water supply and prevention of the resource.

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