SR-1/2000-01

# STATUS REPORT ON SALTWATER INTRUSION AND GROUNDWATER MANAGEMENT STUDIES IN COASTAL AND DELTAIC REGIONS

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2000-2001

# PREFACE

A fundamental question that confronts any engineer in coastal and deltaic areas is to efficiently manage water resources without any adverse affects from adjoining sea. The coastal aquifers are highly productive and have a sensitive balance with adjacent seawater. If the seawater intrudes into the freshwater aquifer due to increased pumpages then the water portability as well as its usefulness diminishes. Therefore a quantitative understanding of the patterns of movement and mixing between freshwater and saline water, and the factors that influence these processes become necessary to manage and protect these resources on a sustainable basis.

In south India, there are several deltaic formations along the east coast. Coastal and deltaic environments are typically characterized by highly productive and alluvial aquifers involving use of surface water and ground water. Although the government policies have been for sustainable use of water resources, there is little control with groundwater, a common resource presently under private control. The government and institution funding agencies are primarily concerned with groundwater assessment, monitoring and evolving policy guidelines for drilling boreholes. There is a need to develop management models and evolve policy guidelines for optimal utilization of surface water and groundwater. With increasing population groundwater legalization involving policy instruments such as power pricing, subsidy, tax etc are inevitable.

In the present report a literature review and status of seawater intrusion and groundwater management studies relevant to coastal and deltaic environment is presented for further studies. The report was prepared by Sh S V N Rao, Sc E1.

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## 1.0 INTRODUCTION

A fundamental question that confronts any engineer in coastal and deltaic areas is to efficiently manage water resources without any adverse affects from adjoining sea. The coastal aquifers are highly productive and have a sensitive balance with adjacent seawater. If the seawater intrudes into the freshwater aquifer due to increased pumpages then the water potability as well as its usefulness diminishes. Therefore a quantitative understanding of the patterns of movement and mixing between freshwater and saline water, and the factors that influence these processes become necessary to manage and protect these resources on a sustainable basis.

A major factor that determines the movement of freshwater/ saltwater is the density. The principle governing floatation of steady state, fresh groundwater lens on top of a steady saltwater was first recognised by Bodon Ghyben (1889) in the Netherlands and also independently by Herzberg (1901) in his studies of the islands in the north sea of German Coast. Both Ghyben and Herzberg related the freshwater head above sea level ($h_f$) to the depth to the interface below sea level ($h_s$).

Figure 1, shows the idealized Ghyben-Herzberg model of an interface in coastal phreatic aquifer. Essentially Ghyben and Herzberg assume static equilibrium and a hydrostatic pressure distribution in the freshwater/ seawater. Under this condition we have the following relationship

$$h_s = [\gamma_f / (\gamma_s - \gamma_f)]\, h_f$$

Where, $\gamma_s$ = 1.025 g/m$^3$ for seawater and $\gamma_f$ = 1.000 g/m$^3$ for freshwater and therefore $h_s$ = 40 $h_f$. However Figure.2 shows the actual conditions of flow near the coast under dynamic conditions

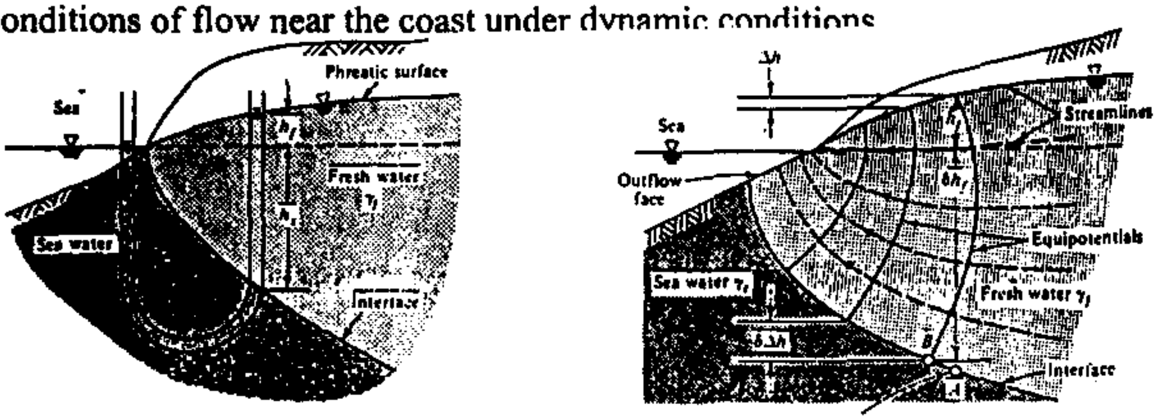

Fig1 & 2. Ghyben Herzberg interface model and the actual flow pattern near the coast

The subsurface flow in the coastal region involves both flow and solute transport..In relatively homogeneous porous media in a coastal area, the denser saltwater tends to remain separated from the overlying freshwater. However, a zone of mixing, known as zone of diffusion or dispersion forms between two fluids. In this zone of mixing some of the salt water mixes with freshwater and moves seaward causing the salt water to flow toward the area of mixing. This forms a perpetual circulation of saltwater. The zone of mixing has been found to be of variable thickness. In coastal areas where the porous medium is heterogeneous in nature, a system of layered mixing zones can form. The 3D nature of flow system and the gradual increase in salt concentration across the zone of mixing are important factors that effect the physical system as found in nature.

Aquifer simulation models predict the behavior of subsurface flow and transport processes. These involve solution of partial differential equations (PDE) governing flow and transport to obtain solute concentration in space and time. The coupled PDE's may be solved in a conceptual framework using two approaches. The first one is called the miscible (or advection-dispersion) approach wherein the saltwater is assumed to mix with freshwater at the interface. Although closer to realism, computational requirements and other considerations limit practical applicability of this approach. The second approach, known as sharp interface approach, considers freshwater and saltwater as two immicible fluids of different densities separated by sharp interface. This assumption may be reasonable for analysis on a regional basis.

The partial differential equations (PDE's) describing groundwater flow and solute transport can be solved mathematically using either analytical solutions or numerical solutions. Analytical solutions need oversimplifications. In the numerical solutions, the continuous variables are replaced with discrete variables that are defined at grid blocks or nodes. Thus the continuous differential equation, which defines hydraulic head or solute concentration everywhere in the system, is replaced by a finite number of algebraic equations that define the hydraulic head or concentration at specific points. This system of algebraic equation is solved using matrix techniques.

The nonlinear solute transport equation is generally more difficult to solve numerically than the groundwater flow equation, largely because the mathematical properties of the transport equation vary depending upon which terms in the equation are dominant in a particular situation. Changes in chemical concentration occur within a dynamic groundwater system near the coast primarily due to; (i) advective transport and (ii) hydrodynamic dispersion. When solute transport is dominated by advective transport as is common in many field problems then the transport equation is approximates a hyperbolic type of equation. On the other hand if dispersive terms are dominating i.e. low velocities occur, then the transport equation is more parabolic in nature (similar to transient groundwater flow equation). The numerical methods, which work best for parabolic PDE's are not best for solving hyperbolic equations and vice versa. Thus no one numerical model or simulation model is best for the entire spectrum of groundwater transport problems likely to be encountered in field. Further compounding this difficulty is the fact that in the field, seepage velocity in groundwater may be highly variable, due to the effect of complex boundary conditions. Thus in low permeability zones, or near stagnation points, the velocity may be close to zero and the transport may be dominated by dispersion processes, while in high permeability zones, or near stress points (such as pumping wells), the velocity may be several meters per day, and the transport may be advection dominated. Therefore, regardless of which numerical method is chosen as the basis for simulation model, it will not be ideal or optimal over the entire range or domain of the problem, and significant numerical errors may be introduced somewhere in the solution. The transport modeling effort must recognise this inherent difficulty and strive to minimize and control the numerical errors. Using finer discretization in space and time can generally reduce numerical errors.

Models, which solve governing flow and solute transport equations, in conjunction with optimisation techniques have become powerful aquifer management tools in the recent times. Ground water management models are broadly classified into two categories. These are hydraulic management models and policy evaluation models. In the former, only mechanics of flow or physical variables are chosen as decision variables for optimisation, while in the latter economic and policy aspects are also included. Groundwater simulation models have been developed in the past and successfully applied to field problems. However, very few studies have been reported indicating the application of groundwater management models to field situations. The application of groundwater management models is bound to grow with time under competing demands for water use.

Management models or policy evaluation models that optimise surface water with ground water in space and time are referred as conjunctive use models. The conjunctive use groundwater and surface water management models are distinct in considering a variety of recharge/ discharge strategies along space and time from surface/ subsurface and import sources. Most of the existing models deal with quantity management at regional level using lumped or distributed approach. Very few models reportedly deal with quality aspect. A variety of conjunctive use formulations can be developed to meet objectives under a given set of conditions and physical setting.

In south India, there are several deltaic formations along the east coast. Coastal and deltaic environments are typically characterized by highly productive and alluvial aquifers involving use of surface and ground water. However, the conjunctive use is not often optimally used with due regard to SWI. Although the government policies have been for suitable and sustainable use of water resources, there is little control with groundwater, a common resource presently under private control. The government and institution funding agencies are primarily concerned with groundwater assessment, monitoring and evolving policy guidelines for drilling boreholes. There is a need to develop management models and evolve policy guidelines for optimal utilization of surface water and groundwater. With increasing population groundwater legalization involving policy instruments such as power pricing, subsidy, tax etc are inevitable.

## 2.0 LITRATURE REVIEW

### 2.1 Mechanics of Saltwater Intrusion:

Two European scientists Bodon Ghyben and Herzberg first established the relationship between freshwater/ saltwater along seacoast in late 1800's. Although the relationship was developed for static equilibrium conditions it soon became clear that apart from hydraulic gradient, density variations between seawater and fresh water were important. Subsequently Hubbert (1940) improved this relation to evolve the concept of sharp interface between sea and fresh water.

Reilly and Goodman (1985) have made a comprehensive review of various studies relating to saltwater intrusion. A brief summary of this study is presented below.

During early 1940's the problem of saltwater intrusion was observed and several field studies were undertaken in United States, Israel, Netherlands etc. Many of the field studies showed the importance of the geologic framework and variations in permeability characteristics. Lusczynski and Swarzenski (1960, 62) documented a staggered interface due to the multiaquifer groundwater system on Long island, New York. They also documented multiple saltwater wedges in the same aquifer that apparently are caused by variations in the permeability characteristics of the system.

Glover (1959) developed a formula to describe the Saltwater-Freshwater '*sharp*' interface in a coastal aquifer using potential theory. Cooper (1959) developed the hypotheses of hydrodynamic dispersion to explain the mixing and associated perpetual circulation of seawater observed in various field investigations. Bear and others (1964, 1974) also contributed to the quantification and understanding of saltwater/ freshwater dynamics using Hele-Shaw model. Henry (1959) developed some solutions for delivering the sharp interface under various conditions and also made the first attempt to quantitatively determine the effects of dispersion and density dependent flow on salt water encroach-ment in coastal aquifers (Henry, 1964) by investigating 2D hypothetical cross section. The main significance of Henry's work at that time was that it corroborated Cooper's hypothesis that opened a new approach - namely, using *advection-diffusion* equation compared to sharp interface models in vogue.

Later advances in understanding saltwater-freshwater relationship have occurred with the development of numerical models. Numerical simulations using sharp interface approach assume freshwater and saltwater as two immiscible fluids. The interface is obtained by solving the coupled partial differential equations governing the two fluid flows. The miscible fluids or solute transport approach is more general and closer to reality, in which saline and fresh water mix producing a continuous variation in concentration. In general, this approach requires simultaneous solution of groundwater flow equation and the advection-diffusion equation because density is a function of concentration. Although the codes built using miscible approach are useful and powerful, there are many difficulties associated with their practical application. These difficulties include numerical oscillations and numerical dispersion in the solution, which frequently limits the applicability of the technique. Several simplifications have been introduced to solve the transport equations such as neglecting density effects, Dupuits horizontal flow approximation, etc.

### 2.1.1 Sharp Interface Models

When the width of transition zone between freshwater and saline water is small relative to the thickness of the aquifer it can be assumed for the purpose of analysis that the saltwater and the freshwater are immiscible fluids separated by a sharp interface, reducing the problem to that of coupled flow of two fluids; freshwater and saltwater. This approach reproduces the general position , shape and behavior of the interface and simulates the distribution of heads in the freshwater and saltwater zones.

Some sharp interface models incorporate an additional simplification i.e. Ghyben-Herzberg approximation and are referred as one fluid sharp interface models (Andersen, 1976; Volker and Rushton, 1982; Voss, 1984). The other sharp interface models solve the coupled freshwater and saltwater flow equation and are referred as two fluid sharp interface models. In this approach, the partial differential equations for freshwater and saltwater flow are coupled by the boundary condition at the interface such that pressure must be equal on either side (Shamir and Dagan, 1971; Polo and Ramis, 1983; Essaid, 1986). It is assumed that flow within the aquifers is predominantly horizontal and therefore the equations can be integrated over the vertical. The coupled nonlinear parabolic PDE's are solved using Newton Raphson procedure. Sometimes the equations are liberalized within the iterative solution by evaluating the coefficients at the previous levels (Picard's iteration) using SIP. For multilayered coastal systems, the two flow equations are solved in each layer using corresponding aquifer properties, and are coupled to the equations in the adjacent layers by the vertical leakage terms

Wilson and Sa Da Costa (1982) used an approach that simulates freshwater system and salt water system as two different flow systems coupled by interface boundary, which satisfies the Hubbert (1940) equilibrium formulation. This simulation requires simultaneous solution of the coupled equations describing the flow of fresh water and saltwater. The governing equation of flow in the freshwater and saltwater are:

$$S_f \partial h_f/\partial t + \nabla . q_f - Q_f = 0 \qquad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$S_f \partial h_s/\partial t + \nabla . q_s - Q_s = 0 \qquad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where h is hydraulic head; q is the Darcy velocity (a vector quantity); S is specific storage; Q is a source / sink term; $\nabla = \partial/\partial x i + \partial/\partial y j$ (where i, and j are unit vectors in the x and y directions respectively); $q_f = -K_f . \nabla h_f$; $q_s = -K_s . \nabla h_s$; K is hydraulic conductivity (a tensor quantity) and subscripts f and s refer to freshwater and saltwater respectively.

Essaid (1986,1990) developed a quasi 3D; finite difference model which simulates coupled, freshwater and salt water flow, separated by a sharp interface to investigate the effects of storage characteristics, transmissivity, boundary conditions and anisotropy on the transient responses of flow system. He applied the model to a field situation of Waialae aquifer of southeastern Oahu, Hawaii. He concluded that the model simulated reasonably well.

Andersen et al (1989) developed and applied 3 numerical models using field data to assess saltwater intrusion at Hallendale, Florida, US. These included cross sectional model and a 3D well field model to conceptualise the system. He used the finite element SWISCHA (Huyokorn et al, 1987) to simulate salt-water intrusion under various predictive scenarios of pumpages.

Ledoux et al (1990) developed a 2D finite difference single phase/ two-phase (sharp interface) model called NEWVAR to simulate transient movement of interface using nested squares and compared with an analytical model. He further applied the model to a case study of coastal aquifer in Mexico to obtain satisfactory results.

Essaid (1990) developed a quasi 3D; finite difference model that simulates freshwater and saltwater flow separated by a sharp interface to study layered coastal aquifer systems. The model allows for regional simulation of coastal groundwater conditions, including the effects of saltwater dynamics on the freshwater systems. The locations of the interface, tip and toe within grid blocks are tracked by linearly extrapolating the position of the interface. The model has been verified by using available analytical solutions and experimental results.

Mahesha (1996) studied the effect of series of injection wells near the coast under steady state conditions using a 2D, finite element sharp-interface model. He used the model to perform parametric studies on the effects of location of injection wells, spacing of wells and the freshwater injection rate on the seawater intrusion into coastal aquifers. The performances of the injection wells in single and double series along the coast were studied and compared. The key variables were grouped into nondimensional parameters, and the relationship between them was presented as a set of characteristic curves. Results indicate that the reduction of seawater (up to 60 – 90%) can be achieved through proper selection of injection rate and spacing between the wells.

Huyakorn et al (1997) developed a sharp interface numerical model to simulate saltwater intrusion. Unlike earlier two phase models which were formulated using hydraulic heads of freshwater and saltwater as dependent variables, this model employs a mixed formulation of one fluid potential and a pseudosaturation as dual dependent variables. The numerical solution incorporates upstream weighting and nonlinear algorithams with several enhanced features including rigorous treatment of aquitard leakage and well conditions, and a robust Newton-Raphson procedure with automatic time stepping. The model has been verified for test problems.

### 2.1.2 Miscible Flow Models

Pinder and Cooper (1970) were first to present a miscible (advection - dispersion) flow model. The method of characteristics was used to solve the solute transport equations. The governing equations for density dependent flow are given below. The simultaneous solution of coupled partial differential equations gives the solute concentration along space and time.

$$q = k/\mu \,\{\nabla p + \rho g \nabla z\} \qquad \ldots\ldots\ldots\ldots(3)$$

$$\nabla . \{k/\mu \;\nabla P\} - g\, \partial/\partial z[\,\rho . k/\mu] = 0 \qquad \ldots\ldots\ldots\ldots(4)$$

$$D\nabla^2 c - q/n \,.\, \nabla c = \partial c/\partial t \qquad \ldots\ldots\ldots\ldots(5)$$

Where: c is concentration of salt, in mass per unit volume of solution; D is dispersion coefficient; g is gravitational acceleration; k is intrinsic permeability; n is porosity; P is pressure; q is specific discharge; ρ is fluid density; and μ is dynamic viscosity. The density ρ is related to concentration c through an empirical relationship.

Huyakorn et al (1987) developed a 3D finite element model for the simulation of salt-water intrusion in single and multiple aquifer systems for confined and unconfined conditions. The model formulation is based on two governing equations, one for fluid flow and the other for salt transport. Density coupling of these equations is accounted for and handled using a Picard sequential solution algorithm. A few examples are solved under various boundary conditions for model verification and utility. A fairly large number of unknowns (of the order of five to ten thousand) can be handled conveniently on a medium size personal computer.

Moore et al (1992) published a paper based on field studies and measured within fractures and boreholes, hydraulic heads, and depth profiles of conductivity along a 70 km section of the northeastern coast of Yucatan Peninsula, Mexico. Hydraulic heads ranged from 40 to 60 cm above m.s.l between 2 and 4 km from the coast. Fluid velocities estimated from point dilution tests, in the dual porosity rock in a borehole several kms from coast were 0.021 cm/sec in the fresh-water lens and 0.082 cm/sec near a fracture in the underlying seawater zone. Velocities in large fractures increased from 1 cm/sec to 12 cm/sec near discharge points along the coast. This increase is attributed to the decrease in thickness in fresh water lens. Further he noted that the thickness of fresh water lens at some measured points was approximately 40% less than that of Ghyben-Herzberg relation for static conditions.

Xue et. al. 1995, developed a 3D miscible transport model for seawater intrusion using characteristic finite element method. The model considers many important factors, such as the effect of variable density on fluid flow, the effect of precipitation infiltration and phreatic surface fluctuation on the process of saltwater intrusion. The model was validated by a field application in China.

Bobba et. al (2000), applied SUTRA (Voss, 1984) model to Laccadive islands in India to assess the extent of saltwater intrusion along space and time on a regional basis due to climate change.

## 2.2 Ground Water Management Models

The management of groundwater resources primarily involves the allocation of groundwater supplies and water quality to competing demand and uses. Simulation models are often utilized to explore groundwater management alternatives. In such cases a model is executed repeatedly under various design scenarios which attempt to achieve a particular objective such as preventing saltwater intrusion, etc. Use of such an approach often sidesteps rigorous formulation of groundwater management goals and fails to consider important physical and operational restrictions. Although simulation models provide the resource planner with important tools for managing the groundwater system, the prediction tools do not identify the optimal groundwater development, design or operational policies for an aquifer system. In contrast groundwater optimisation models can identify the optimal planning or design alternatives in the context of the system objectives and constraints. Thus models which solve governing flow and transport equations in conjunction with optimisation techniques have become powerful aquifer management tools. Gorelick (1983) has given an excellent review of distributed parameter groundwater management modeling methods. He broadly classified classified groundwater management models into two categories (fig 3.0)

In the first category the modeling is primarily concerned with groundwater hydraulics for managing stresses and hydraulic heads directly as management decision variables. In the second category, involves models that can be used to inspect complex economic interactions such as the influence of institutions upon the behavior of an agricultural economy or complex groundwater-surface water conjunctive use problems. Although these models do not explicitly determine regional groundwater policy they can be used in policy evaluations. These models are generally characterized by multiple optimisations, one for each sub area in a region and have a strong economic component. In both categories the models employ the optimisation techniques such as linear or non linear programming. Such techniques attempt to optimize, an objective function, such as minimisation or maximisation of well production and are subject to a set of linear/ non linear algebraic constraints which limit or specify the value of decision variables such as local drawdown, hydraulic gradients or pumping rates.

Groundwater hydraulic management models incorporate a simulation model of a particular groundwater system as constraints in the management model. Two techniques have been widely used to accomplish this. In the embedding approach the discretised flow equations are included in the LP as constraints and a complete simulation model solved simultaneously as a part of management model. Decision variables include hydraulic heads at each node as well as local stresses such as pumping rates, boundary conditions, etc. This technique was first introduced by Aquado & Remson (1974) for groundwater hydraulic management. The method is straightforward but the constraint matrix becomes large, especially for transient conditions and difficult to handle with commercial LP packages using sparse matrix methods. Although several methods (such as stepwise solutions) have been suggested to over come this difficulty the embedding method is yet to find useful applications for transient simulations.

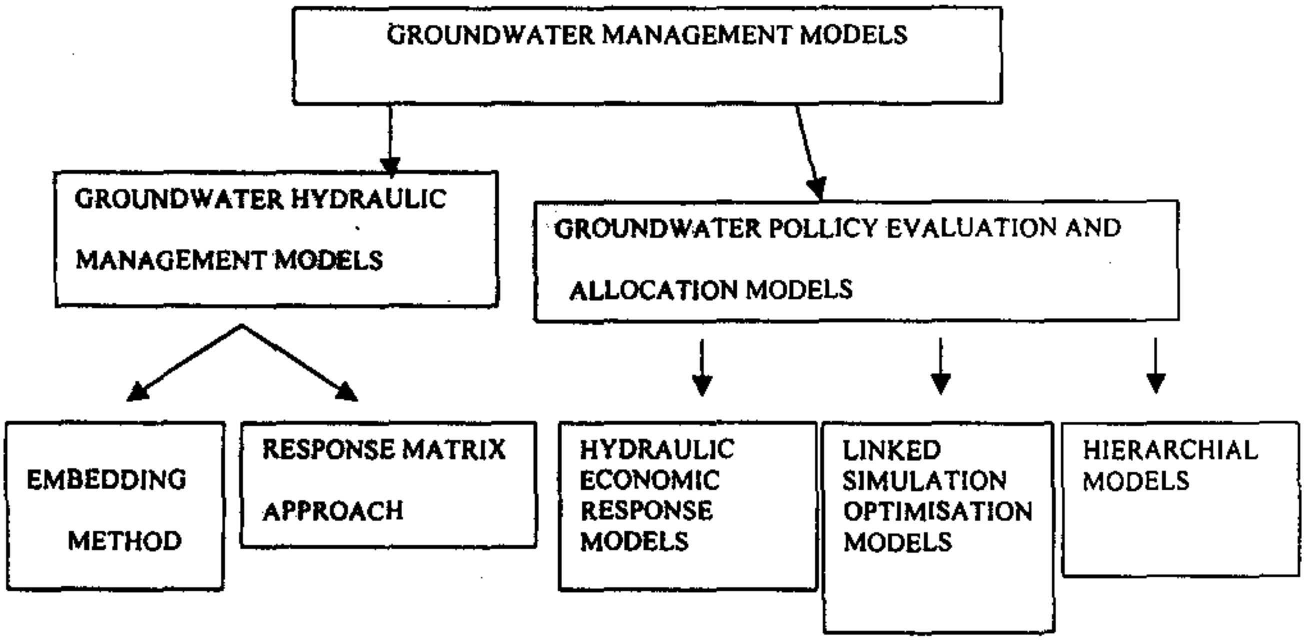

**Fig 3. Classification of groundwater management models (after Gorelick, 1983)**

In the 'response matrix approach' an external groundwater simulation model is used to develop unit responses. Each unit response describes the influence of a pulse stimulus (such as pumping) upon hydraulic heads in parts of interest throughout the system. An assemblage of unit responses i.e. a response matrix is included in the management model. The response matrix approach is sometimes referred to, as influence matrix or discrete kernel or superimposition methods. Schwarz (1971) and later Maddock (1972) introduced this approach in groundwater modeling originally from petroleum engineering literature.

In the embedding method finite difference or finite element approximations of the governing groundwater flow equations are treated as part of the constraint set of a linear programming model. The hydraulic heads and stresses (recharge/ discharge) are decision variables along space and time. Thus a great deal of information is available in a single run. However the management model may not require all the information unnecessarily contained in the output. For computational economy and avoidance of numerical difficulties application of embedding technique is currently restricted to small scale steady state problems. Research is required to improve revised simplex algorithms and decomposition methods to enable embedding technique to be used for transient case studies. In the response matrix approach, the solution to the flow equation is used in the LP constraint matrix. This approach yields incomplete information regarding system functioning but is generally more economical method. The response matrix requires running the simulation model several times (one run for each node) and hence large initial expenditure of computational effort. Since constraints are there only at specified location and time, unnecessary constraints and decision variables are not incorporated in the LP. Therefore response matrix approach is relatively suitable for large transient systems in an efficient manner.

Groundwater policy evaluation models are intended for large scale (regional) transient problems which study the behavior of an agricultural economy in response to institutional policies, such as optimization of conjunctive use of surface and groundwater. Three types of models have been developed for groundwater policy evaluation and allocation problems. Hydraulic – economic response models are a direct extension of the response matrix approach problems in which agricultural and/ or surface water allocation economics play a key role. 'Linked simulation – optimisation models' use the results of an aquifer simulation model as input to a series of sub area economic optimisation models. 'Hierarchical models' use sub area decomposition and a response matrix approach. They are generally used for large-scale optimization where detailed hydraulic management is required in the context of a complex water allocation problem.

Linked simulation - optimisation model approach is concerned with economics and evaluation of institutional policy instruments rather than hydraulics. In comparison with the response matrix approach the linked model enables greater economic complexity to be considered. Social and legal factors can be integrated into the management model. Further, the hydraulic nonlinearities (like unconfined aquifers) do not enter into the management model because the hydraulic simulation model is a separate component. Nonlinear programming need not be used.

Most groundwater quantity management models involve linear objective functions and linear constraints (with unconfined aquifers linearised). Hence linear programming is used. In LP the model searches only at the corners of a hypercube formed by linear constraints set in a multidimensional space of variables, as it is known that optimum point exists at a corner. On the other hand problems involving groundwater quality management (like salt water intrusion) are essentially nonlinear and have to be solved using nonlinear programming. Here the objective function and constraints are both nonlinear. Nonlinear programming is broadly of two categories. The first one being unconstrained optimisation, which include the steepest decent, conjugate direction and quasi Newton methods. The second approach is called the constrained optimisation, which use primal, dual, penalty and quasilinearisation search methods. Some of the commonly used algorithms include reduced gradient, projected lagrangian, cutting plane and quadratic programming.

Groundwater quality management involving simulation of solute transport involves nonlinearities. Nonlinearities arise from management decision variables (such as pumping) that create unknown velocity components that occur in advective and dispersive transport terms. This also occurs in saltwater intrusion. The density difference between fresh and saltwater serves as a significant driving force for the migration of solutes. In such cases, the groundwater velocity field is a function of solute concentrations. Hence nonlinearities appear in advection and dispersion terms. In essence this is a nonconvex programming problem containing a quadratic objective function subject to nonlinear constraints.

Multi objective programming models optimise a vector valued objective functions, given the economic, hydraulic or water quality constraints of the planning problem. The optimal solutions of the model are referred to as the noninferior solution set. The central problem in multi-objective programming is to identify these noninferior solutions. Although the non-inferior set is infinite, the solutions can be determined by the optimal solutions of a series of scalar objective problems that are equivalent to the multi-objective problem. The optimisation process does require, however, information regarding the weighting or preferences associated with each of the system objectives. The two commonly used multi objective programming techniques are - the weighting and constraint methods.

More recent trends in nonlinear and discrete optimisation include direct search methods using simulated annealing (SA), genetic algorithm (GA) and other heuristic (non exact) methods. Discrete and combinatorial optimization involves the maximization or minimization of a function of one or more decision variables where each variable is restricted to a set of possible discrete values. Simulated annealing (SA) is a simple technique to find a global minimum for continuos-discrete-integer nonlinear programming problems (Kirkpatrick, et. Al., 1983; Johnson et. Al., 1989). The basic idea of the method is to generate a random point and evaluate the objective function. If the trail point is infeasible, it is rejected and a new point is generated. If the trial point is feasible and the cost function value is smaller than current best record, then the point is accepted, and the record for the best value is updated. If the point is feasible but the cost function is higher than the best value, then the point is sometimes accepted and sometimes rejected. The acceptance is based on the value of the probability density function of Boltzman distribution. In computing the probability a parameter called the temperature is used. For the optimisation problem, this temperature can be a target value for the cost function corresponding to a global minimum. Initially a larger target value is selected. As the trials progress, value is reduced (this is called cooling schedule) and the process is terminated after a fairly large number of trials. The acceptance probability steadily decreases to zero as temperature is reduced. Thus in the initial stages, the method is likely to accept worse designs while in the final stages, the worse designs are almost always rejected. This strategy avoids getting trapped at a local minimum. The main deficiencies of the method are the unknown rate at which the target level is to be reduced and the uncertainty in the total number of trials and in the number of trials after which the target level needs to be reduced. Dougherty and Marryott (1991) and Cunha (1999) have demonstrated the application of SA to hypothetical groundwater management problems. Lee and Ellis (1996) made a comparative study of eight heuristic algorithms to solve a nonlinear integer optimization problem involving groundwater monitoring network design.

Genetic algorithms (GA) also belong to the class of stochastic search methods. In GA, several design alternatives, called a population in a generation, are allowed to reproduce and cross among themselves, with bias allocated to the most fit members of the population. Combination of most desirable characteristics of mating members of the population results in new designs that are more fit than their parents. An advantage of the approach is that gradients are not needed. In a GA each design must be represented by a finite length string. Usually binary strings are used for this purpose. Three operators are needed to implement the algorithm: (1) reproduction (2) crossover and (3) mutation. The three steps are repeated for successive generation of population until certain stopping criteria are satisfied. The member in the final generation with best fitness level is the optimum design. The fundamental advantages of SA and GA are that nonconvexity can be handled easily for determining a global solution and there is no subproblem to be solved. GA takes more CPU time than SA for test problems (Huang and Arora, 1997). For large scale problems parallel processing capabilities can reduce the CPU times dramatically. Mckinney and Lin (1994) demonstrated the application of GA to a simple hypothetical groundwater remediation problem.

Heijde et al (1985) from International groundwater modeling centre (IGWMC) undertook a comprehensive survey of all the groundwater simulation and management models reported in literature until 1985. A systematic review of more than 399 models were made to classify the models and identify the gaps for further research. Some of the important gaps in research included the effect of scale and heterogeneity on transport phenomena, characterization of spatial and temporal variability in system parameters, quantification of management objectives and adequate description of kinetics of chemical and biological processes.

Bredehoeft et al (1995) also made an extensive review of papers until 1995 and emphasised the changing context of groundwater management in a free market economy in democratic societies. He discussed the institutional issues for regional groundwater management in terms of quality and quantity.

The above mentioned three review papers by Gorelick (1983), Heijde et. al (1985) and Bredehoeft et al (1995) cover extensively on the subject of groundwater quantity/ quality management. However few more papers relating groundwater management to saltwater intrusion in particular are discussed below.

Shamir et. al (1984) presented a multi objective linear programming model for optimal management of a coastal aquifer. Two of the objectives incorporate quality concerns: minimizing the difference between actual and desired location of the seawater/ freshwater interface and minimising the total sum of chloride concentrations in all locations.

Willis and Finney (1988) developed an optimisation model for controlling seawater intrusion in Taiwan. The linked nonlinear optimisation with a sharp interface model. They used a composite objective function that included the location of toe of the interface, target quantities of both pumping and costs and artificial recharge. Their results suggested that the resulting objective function is had a plateau (i.e. several solutions provide nearly equal benefits.

Hallaji and Yazicigil (1996) developed seven optimisation models based on different objectives using MINOS for management of a coastal aquifer in southern Turkey. The management objectives included maximising agricultural water withdrawals and minimising draw downs and pumping costs, subject to constraints related to systems response equations; demand requirements; draw down limitation in saltwater intrusion control locations and pumping well; and discharge bounds. The results are shown in the form of a tradeoff curves relating optimal pumpage rates and pumping costs, basin wide drawdowns and salt containment. Saltwater intrusion is controlled indirectly by constraining the heads in the nodes near the coast at a given level. The response matrix is generated using 2D, SUTRA model.

Emch et al (1998) developed a nonlinear multiobjective management model for conjunctive use of coastal surface water and groundwater. Two conflicting objectives are considered: cost effective allocation of surface water and ground water supplies, and minimisation of saltwater intrusion.

System constraint includes economic, operational and institutional requirements. Uses a sharp interface, quasi 3D, finite difference model. The model is formulated assuming all facilities to exist for conjunctive use such as (a) supply of surface water to user points (b) cost coefficients are known for operation and maintenance and (c) capital costs are ignored. The nonlinear optimisation problem is solved with MINOS (commercial linear/ nonlinear packages) and applied to a hypothetical case study. The final product is a trade-off curve that allows the manager to assess the relative importance of objective i.e. allocation of surface water/ groundwater while minimising saltwater intrusion.

Das and Dutta (1999a, 1999b) developed a number of nonlinear multi-objective management models for managing coastal aquifers under steady and transient conditions. The management objective sought to maximising the water withdrawal for beneficial uses while minimising seawater intrusion through an extraction barrier of a series of pumping wells along the coast. The nonlinear finite difference form of density dependent miscible flow and salt transport model for seawater intrusion in coastal aquifers is embedded within the constraints of the model. The management model is solved for a hypothetical unconfined coastal aquifer system using constrained method of NLP (non linear programming). The results indicate the potential applicability of planned pumping strategy as a tool for controlling and managing coastal aquifers prone to seawater intrusion.

Dougherty and Maryott (1991) used simulated annealing to solve a design problem with a constant well installation cost and a linear pumping cost and a linear pumping cost that implicitly includes the cost of treating the extracted water. Marryott et al (1993, 1996) used simulated annealing methodology and compared the results with gradient search approach. He discussed that simulated annealing provides an optimal framework that is flexible enough to incorporate a number of different remedial technologies into the design process.

Mckinney & Lin (1994) applied genetic algorithm (GA) on typical groundwater resource management. He concluded that GA could be effectively and efficiently used to obtain near global optimal solutions. Here the formulation of the problem is straightforward and provides solutions better than those by linear and nonlinear programming. He indicated that the computational burden could be reduced through parallel computing.

## 3.0 REFERENCES

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## SOME POPULAR MODELS USED FOR SIMULATING SALT WATER INTRUSION

| S.No. | Year | Model | Authors /Source /Publication | Brief Description of Model |
|---|---|---|---|---|
| 01. | 1978 | MOC -- USGS | Konikowl L F and J D Bredehoeft – USGS, Va, USA | It is a computer model for solute transport and dispersion in Groundwater. It is a non reactive – 2 D explicit model using Method of Characteristics. |
| 02. | 1982 | RD3D | T A Prickett and Associates, II, USA | It is a 2 – D finite difference model using Method of Characteristics and is consistent with MODFLOW. |
| 03. | 1983 | SHARP Interface | Polo Ferrer Jose and Franciso, J Romos Ramis, W R R, Vol. 90, No.1, pp.61-68 | It is a Sharp interface model using finite difference which is unconditionally stable. The model simulates salt water to a motion. |
| 04. | 1986 | SHARP Interface | H I Essaid, 345, Middle field road, Mentro Park, USGS, Ca., USA 94025 | Simulates 3-D, anisotropic, coupled fresh water, salt water sharp interface model. |
| 05. | 1987 | SWISHA | Huyakorn Peter S, Peter F Andersen, James W Mercer, and Harold O White Jr., W R R, Vol.23, No.2, pp.293 – 312. | Models Saltwater intrusion in 3-D, finite element – using sharp interface. |
| 06. | 1987 | HST3D | Kipp K L, USGS Co., USA | For modeling heat and solute transport in 3D system. |
| 07. | 1988 | BIO1D | Srinivasan P and J W Mercer Geo Trans Inc. Va., USA | It is a 1-D finite difference flow and solute transport model with aerobic and anaerobic degradation. |
| 08. | 1989 | SUTRA | Voss CT, USGS, Va. USA | It is a 3-D finite element variably saturated, density dependent, non conservative flow model. |
| 09. | 1990 | NEWVAR | Ledoux Emmanuel, Serge Sauvagnac, and Alfonso River. Groundwater Vol.28, no.1, 79-87. | It is a 2-D finite difference single phase /two phase sharp interface model to simulate salt water intrusion. |
| 10. | 1990 | MT3D | Zheng C, Papadopulas and Associates Inc., Md, USA | Simulation of 3-D solute transport non conservative flow model. Solves Partial difference equations using various options including finite difference and modified method of characteristics and is consistent with MODFLOW. |
| 11. | 1991 | SWIFT | Ward DS, GW-Trans, Inc., Va, USA also Standard Software Group, Washington DC, USA | It is a finite difference – 3 D density dependent flow model. |
| 12. | 1994 | SALTFLOW | J W Moison and E O Frind, Water Loo Centre for groundwater research, Ontario, Canada | It is a 3-D finite element, distributed, density dependent flow and mass transport model. |
| 13. | 1996 | SHARP Interface | Huyakorn Peter S., Y S W U, and N S Park, W R R, Vol.32, No.1 pp.93-102. | Simulates Sharp interface in 3 D and employes the mixed formulation one fluid potential as a psuedo saturation as dwell dependent variables. The numerical solution incorporates upstream weighting and nonlinear algorithms with a robust Newton – Raphson procedure for solving the model. |

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