GROUND WATER MODELLING

C.P. KUMAR*

INTRODUCTION

Ground water modelling is a tool that can help analyse many ground water problems. Models are useful for reconnaissance studies preceding field investigations, for interpretive studies following the field programme, and for predictive studies to estimate future field behaviour. In addition to these applications, models are useful for studying various types of flow behaviour by examining hypothetical aquifer problems. Before attempting such studies, however, one must be familiar with ground water modelling concepts, model usage, and modelling limitations.

Ground water modelling begins with a conceptual understanding of the physical problem. The next step in modelling is translating the physical system into mathematical terms. In general, the final results are the familiar ground water flow equation and transport equations. These equations, however, are often simplified, using site-specific assumptions, to form a variety of equation subsets. An understanding of these equations and their associated boundary and initial conditions is necessary before a modelling problem can be formulated.

Partial differential equations may be used to describe a large number of problems in ground water hydrology. Without a solution, however, these equations are of little value. Only a simplified subset of the general equations can be solved by analytical means, and these often describe idealized situations that are limited in application. Numerical solution of these equations using high speed digital computers offers a logical alternative.

The numerical models used in ground water studies are general computer programs that can be applied to a variety of hydrogeological conditions. These programs are based on approximations to the governing partial differential equations for ground water flow and transport. To use these models requires an understanding of the physical problem and field data. Although program input data and output results are quantitative, the appropriate application of numerical models remains a partly subjective procedure. To use models, the hydrologist must assess the merits of alternative numerical methods, evaluate available data, estimate data where missing or absent, and interpret computed results. The review of previous model applications can provide valuable insight on how these tasks may be approached.

Mathematical ground water models essentially comprise (i) appropriate differential equations governing the ground water behaviour in a domain of interest and (ii) an

**Scientist 'C', National Institute of Hydrology, Roorkee-247 667 (UP)*

algorithm to solve the equations - analytically or numerically. The analytical solutions are generally based upon many restrictive assumptions e.g. homogeneity; isotropy; time and (or) space independent withdrawals, recharge, boundary conditions; regular geometry of the domain. On the other hand the numerical solutions can follow the real world conditions quite closely and in fact, subject to the data availability, the only assumptions which need to be made, are the validity of Darcy's law and the continuity equation. However, the data inadequacy mostly does necessitate many assumptions even in numerical solutions. Nevertheless such solutions can generally provide far more realistic solutions than what can be provided by the analytical solutions.

The domain of interest can be unsaturated zone or the saturated zone. For a ground water hydrologist, the main objective of modelling the flow through the unsaturated zone is to estimate recharge (distributed in space and time or lumped) occurring at the water table in response to a known input at the ground from rainfall and applied irrigation.

The main objective of a saturated ground water modelling exercise is to forecast the response of the aquifer to a proposed man-made excitation (e.g. pumpage, artificial recharge) acting in conjunction with other forms of natural excitation. A critical evaluation of the computed response can determine whether the proposal is acceptable or unacceptable in respect of prestipulated constraints. The response computed directly through the solution of the governing equations comprises water table or piezometric elevations distributed in space and time. The distributions can provide other forms of the response (e.g. stream-aquifer interaction, maximum and minimum depths to water table and (or) saturated thicknesses) that a planner may be interested in. The various stages of development and subsequent usage of these models in planning process, are described in the following paragraphs.

MODELLING OF FLOW IN UNSATURATED ZONE

The necessity of modelling the flow through unsaturated zone arises from the fact that vertical recharge, an important input requirement of the saturated flow models is not directly measurable on a regional scale. For example, a saturated flow model can provide an estimate of the rise of water table in response to introduction of an irrigation system, provided the distribution of the recharge (from the applied irrigation) is known. However, the information which is directly available, will be the distribution of applied irrigation at the ground. The unsaturated flow models can transform the known input at the ground to the recharge at the water table - necessary for saturated flow modelling.

The flow through unsaturated zone is governed by a non-linear second order partial differential equation, generally known as Richards' equation. The non-linearity originates from the dependence of hydraulic conductivity and specific moisture capacity on the soil moisture. Nonlinear equations (algebraic or differential) are difficult to solve. Nevertheless researchers have proposed various numerical algorithms to solve Richards' equation for time - distributed soil moisture profiles for given boundary and initial conditions. Boundary condition at the ground can be in the form of known infiltration (Neumann type) or known ponding (Dirichlet type). The computed soil moisture profiles can provide time-distributed estimates of recharge at the water table. The primary data required for modelling of unsaturated flow are h(θ) and K(θ), characteristics of the soil and an equation describing actual evapotranspiration in terms of potential evapotranspiration, field capacity, wilting point and soil moisture for the various crops.

In India, there have been some efforts lately towards development of unsaturated flow models aimed at, amongst others, estimation of recharge, soil moisture profiles, irrigation schedules, crop response functions and mass transport through the unsaturated zone. The main problem in the estimation of recharge by modelling unsaturated zone is the poor availability of the data related to soil characteristics. There have been some efforts lately to determine these characteristics. The studies so far carried out in India as related to modelling of flow in unsaturated zone are briefly given below:

Verma and Brutsaert (1970) presented a numerical scheme to analyse a two-dimensional unconfined aquifer of rectangular cross-section to determine the fall of the water table, the water content and the rate of outflow into an adjoining water body which fully penetrates the aquifer. The capillary or unsaturated flow above the water table was considered through the use of Richards' equation. It was found that the problem can be solved by an alternating explicit-implicit finite difference scheme. It has the advantage of being efficient and of being suitable even when the fully saturated flow zone is very small. The unknown position of the seepage surface and the unknown boundary between the saturated and the unsaturated zone constitute a very critical aspect of the calculations.

Verma and Brutsaert (1971) analysed seepage in a two-dimensional unconfined aquifer of rectangular cross-section to determine the rate of outflow into an adjoining water body which fully penetrates the aquifer. The analysis was made by using capillary flow theory as well as saturated Darcy flow theory with and without the Dupuit assumptions. In addition to the usual criteria of similarity of geometry, initial and boundary conditions, also the relative capillary conductivity and the dimensionless water content-suction relationship must be similar. From the latter criterion, a convenient parameter was formulated which expresses the effect of capillarity in relation to the depth of the aquifer. It was found that this parameter is useful to determine whether or not the capillary flow above the water table is important. An analysis was made which shows the errors that may arise in the prediction of the outflow rate by neglecting capillarity and using the Dupuit assumptions.

Panikar and Nanjappa (1976) compared the results of the Parlange solution with the Smith and Mein-Larson model for time of ponding. Rehovot Sand was used as the medium. Ponding time was computed over a wide range of non-dimensional rainfalls varying from 1.002 to 1,000. The agreement was good at high relative rainfall intensities. For low values, it was found to be unsatisfactory.

Basak (1978) presented an analytical solution to the problem of evaporation from horizontal soil columns in which diffusivity increases linearly with moisture content. The exact solution of the non-linear governing differential equation was compared with the solution of the linearised governing differential equation. The solution of the problem with variable diffusivity in relation to the constant diffusivity case was discussed. The analysis showed that the existing solution for constant diffusivity was a special case of the solution for variable diffusivity.

Sarma et al. (1980) developed a computer program which computes the daily evapotranspiration as a residue from the water balance equation. Moisture profiles from field observations of soil moisture tensions were used as an input into the model. Further, the program evaluates the effects of rainfall or irrigation during the periods of observation and also calculates the water loss from deep drainage . It takes care of the limitation in the availability of data due to occasional skipping of records for two or more days at a stretch. The additional features of the program include the procedures for the computation of infiltration and the moisture flow. The model was applied to actual field data.

Banerjee and Watson (1984) discussed the significance of an intermittent system of water application to the surface of a vertical homogeneous profile of unsaturated porous material in relation to the establishment within the profile of a zone of material where uniform water content conditions prevail and flow is essentially gravitational in nature. A numerical analysis of water movement for such a system involving the simulation of upto 20 on-off cycles of water application was outlined, and the approach used in modelling the hysteresis behaviour for such an exacting pattern of reversals was detailed. The results support the hypothesis that the section of the profile where water movement is continuously affected by hysteresis during the intermittent water application is limited to the near-surface horizon with a lengthening zone of uniform water content material existing at greater depths.

Rao (1987) proposed a simple conceptual model of soil water balance and tested with field data obtained from an irrigation project area. The model estimates the actual evapotranspiration and the soil moisture content at the end of each week using available information on soil water availability and plant water uptake. It can be usefully incorporated into larger computer-based irrigation management models.

Rama Prasad (1988) proposed a model of root water extraction, in which a linear variation of extraction rate with depth is assumed. Five crops were chosen for simulation studies of the model, and soil moisture depletion under optimal conditions from different layers for each crop was calculated. Similar calculations were also made using the constant extraction rate model. Rooting depth was assumed to vary linearly with potential evapotranspiration for each crop during the vegetative phase. The calculated depletion patterns were compared with measured mean depletion patterns for each crop. It was shown that the constant extraction rate model results in large errors in the prediction of soil moisture depletion, while the proposed linear extraction rate model gives satisfactory results. Hypothetical depletion patterns predicted by the model in combination with a moisture tension dependent sink term developed elsewhere were indicated.

Rama Prasad (1989) examined the possibility of advance indication of moisture stress in a crop by small prepared plots with compacted or partially sand-substituted soils by an analytical simulation. A series of soils and three crops were considered for the simulation. The moisture characteristics of the soils were calculated with an available model. Using average potential evapotranspiration values and a simple actual evapotranspiration model, the onset of moisture stress in the natural and indicator plots was calculated for different degrees of sand substitution and compaction. Cases where sand substitution fails were determined.The effect of intervening rainfall and limited root depth on the beginning of moisture stress was investigated.

Mohan Rao et al. (1990) assessed relative performance of a soil moisture accounting model in estimating return flow. They presented (i) a method for quantifying field capacity as a flow parameter, and (ii) assessment of a proposed soil moisture accounting (SMA) model for estimation of return flow, in comparison with an earlier distributed model based on a finite difference solution of the Richards' equation, for studying the possibility of replacement of the more elaborate distributed model by the easy to adopt SMA model.The method for quantifying field capacity as a flow parameter is more suitable for coarse soils. The assumptions implicit in the SMA model result in estimated daily rates of return flow which are not acceptable although seasonal totals are reasonably acceptable.

MODELLING OF FLOW IN SATURATED ZONE

The flow in the saturated zone is governed by a second order linear or non-linear differential equation, depending upon whether the flow is under confined or unconfined condition respectively. The non-linear equation governing unconfined flow can be linearised either by replacing space-time variant saturated thickness by an average space variant saturated thickness (first method of linearisation) or by change of variable from saturated thickness to the square of saturated thickness (second method of linearisation). The differential equations may account for only the horizontal flow (one or two dimensional) or may account for vertical flows also. The numerical solutions may be based upon either the finite difference or finite elements.

The ultimate objective of saturated flow modelling is to be able to forecast the aquifer response to a variety of excitation patterns. Such a modelling is termed as Direct Problem. However, for solving a direct problem it is necessary to know spatially distributed estimates of the aquifer parameters. It is generally not feasible to carry out test pumping at large enough number of space points to get an adequate spatial distribution of the parameters. The way out is to arrive at such a distribution of the parameters which yields the best possible reproduction of historical water table/ piezometric elevations under historical excitation. The inverse problem can be solved by either repeated solutions of the Direct Problem with varying aquifer parameters (Indirect method of solving inverse problem) or by solving the governing differential equation directly for the parameters (Direct method of solving inverse problem). The indirect methods can be based upon either simulation or rigorous optimization theory.

Most of the saturated flow modelling studies carried out in India have been related to unconfined alluvial aquifers bounded by rivers. The flow has generally been assumed to be two dimensional horizontal and the non-linear differential equation governing such a flow linearised by the first method. The resulting equation has been mostly solved by finite differences although there have been a few studies employing finite elements. The inverse problem has been generally solved by the simulation based indirect method (i.e. repeated solution of the direct problem). Keeping in view the large areal extent of hard rock aquifers in India, the number of model studies on such aquifers has been rather marginal. Similarly, the number of studies on confined aquifers has been very marginal.

Ground Water Development/Recharge

The modelling studies in India have so far been confined to academic and research organisations. The practising professionals mostly still prefer to employ lumped models for planning of ground water development/recharge. Such models completely ignore the distributed character of the ground water regime. Thus, they are based upon rather conservative concepts like safe yields and are incapable of accounting for the stream-aquifer interaction and the dependence of lateral recharge on the water table pattern. Consequently permissible mining (i.e. withdrawals in excess of vertical recharge) and perennial yield can not be arrived at.

The objectives of modelling studies have been mainly (i) ground water recharge, (ii) dynamic behaviour of the water table, (iii) stream-aquifer interaction, and (iv) sea-water intrusion etc. The studies so far carried out are briefly given below.

Verma (1970) analytically discussed a theoretical model of ground water replenishment in a cracked porous medium, with simultaneous occurrence of the phenomena of fingering and imbibition under certain conditions. It was assumed that the injection of water bodies is initiated by imbibition, and the 'injected' and 'native' water from two immiscible liquid phases of different salinities with small viscosity difference. If only the average behaviour of fingering is considered, the non-linear differential equation is solved by a perturbation technique. An expression for the average cross-sectional area occupied by fingers was obtained.

Chandra and Pande (1975) presented studies on recharge using a mathematical model for the Varuna Basin in Uttar Pradesh. The available pump test data was analysed to evaluate the formation constants of the aquifer and an overall hydrologic balance was made to determine the average annual recharge and water balance available for the year 1972-73 for which water-level elevation data was available. The area was divided into polygonal sub-areas and a ground water model prepared according to the Tyson-Weber Scheme. The recharge for each polygon was worked out using the available water table elevation records and found to give reasonably good agreement with the average value.

Sukhija and Shah (1976) utilised environmental tritium profiles studied over an interval of two years in a semi-arid region of western India (Gujarat) to evaluate ground water recharge to unconfined and confined aquifers. The recharge rate (11% of local rainfall) determined for confined aquifers for a part of the selected area using a diffusion-type unsteady ground water flow model was in fair agreement with that determined using the tritium method. The tritium method wherever applicable has the advantages of being direct, fast, economical and does not require much hydrological data.

Vappicha and Nagaraja (1976) presented an approximate solution for the transient interface in a coastal aquifer. The transient interface phenomenon in sea-water intrusion into coastal aquifers leads to the solution of non-linear partial differential equations involving large computer memory and computer time. Adopting the principle of quasi-steady state analysis, the basic equation was formulated as an ordinary differential equation of first order. The equation was solved analytically and numerically for three different boundary conditions. The solution was compared with experimental results from a viscous-flow analog model. The method leads to an approximate but simple solution for a rough estimate of the rate of movement of the interface and length of intrusion.

Singh and Jacob (1977) studied transient analysis of phreatic aquifers lying between two open channels. The non-linear term involving the highest derivative in the Boussinesq equation was approximated by a linear term, and the resulting approximate equation was linearised to a Fokker-Planck equation by the method of functional transformation. Solutions to the problem of ground water flow through phreatic aquifers lying between (i) constant water level boundaries and (ii) variable water level boundaries were obtained from the general solution of the Fokker-Planck equation for constant and variable rates of recharge and withdrawal. Variable rates of recharge and withdrawal were approximated by periodic step functions which represented two different rates, one each for both rainy and dry seasons. Variable water levels in the open channels were approximated by step functions, and the initial condition was represented by straight line segments. An analytical solution of the approximate Boussinesq equation was compared with the finite difference solution of the original Boussinesq equation. The difference between the two solutions was almost negligible, and therefore the applicability of the analytical solutions to ground water resource management was established. The effect of variable water level boundaries on ground water dynamics was studied by performing a sample calculation.

Singh and Sagar (1977) developed analytical solutions to determine aquifer diffusivity explicitly by specifying an extra boundary condition in terms of hydraulic gradient at the stream-aquifer interface and using the Green's function of the linearised Boussinesq equation. Four different types of Dirichlet boundary condition describing stream gauge hydrographs were employed. They are (i) linearly rising water level in the stream; (ii) exponentially rising water level in the stream ; (iii) water levels represented by a sinusoid; and (iv) hydrographs approximated by cubic splines. The last one is quite general and is capable of analysing different shapes of smooth stream hydrographs expected to occur in nature. Hydraulic gradient at the interface was computed using splines. The solutions were validated by analysing the stream-aquifer data observed in a sand tank model. They yielded consistent values of the aquifer diffusivity at different times and therefore are useful in determining the parameter of the aquifers contiguous to streams.

Basak (1979) analytically investigated the problem of the transient water table between two parallel ditches which are subject to a uniform recharge. A closed-form solution of the governing non-linear partial differential equation (the Boussinesq equation with a recharge term) was obtained for the first time and reported in the paper.

Gupta et al. (1979) carried out aquifer modelling studies keeping in view the over exploitation of ground water in Krishni-Hindon interstream region in Uttar Pradesh. The area lies in Gangetic alluvial plain. The interconnections in the phreatic aquifer and the lower semiconfined aquifer led to the assumption of a single-story aquifer for which an R-C analog model was constructed. The input-output quantities in the model were simulated using current/voltage generators and current sinks which were appropriately programmed in time-domain with the help of wave-form synthesizers for a realistic representation of the field system. The model study showed that the aquifer can sustain the output rate of 200 mcm/year without much damage to the ground water regime. In another scheme, an annual increase of 5% in exploitation rate showed deleterious effects on the aquifer. Decreased rainfall/droughts would worsen the situation.

Sagar and Singh (1979) used the linearised Boussinesq equation to describe the flow in a semi-infinite aquifer with a fully -penetrating stream at its boundary. The recorded stream hydrograph and the computed hydraulic gradient at the boundary were assumed to be corrupted with Gaussian noise. The aquifer diffusivity was then found to be given by the ratio of squares of two Normal random variables. The mean and standard deviation of the diffusivity were computed for various levels of errors in the boundary data. The mean value of the diffusivity is a function of the errors in data and increases with increasing errors. The increase in the mean diffusivity,however, is not of as much significance as the increase in the standard deviation, which increases at a much faster rate with increasing errors. Any significant increase in the standard deviation would reduce the confidence in the computed diffusivity value. Based on the acceptable value of standard deviation in the diffusivity, one can therefore stipulate bounds on permissible errors in data.

Elango and Swaminathan (1980) carried out the numerical simulation of the situation of concurrent confined and unconfined zones in a ground water aquifer system by using the finite element method with four-sided mixed-curved isoparametric elements. The model is limited to the steady state and is based on Dupuit's assumptions. The results of the model for a test situation indicate that the model can be used for prediction of the occurrence of unconfined regions around over-pumped wells in an originally confined aquifer of which the interfaces between the confined and unconfined regions may be estimated.

Rao and Sarma (1980) suggested a method of identifying the extent of the ground water mound using solutions of the equation of flow for finite aquifers. These solutions were obtained using two different procedures of linearisation, those of Baumann and Hantush, and Laplace transforms. The resulting expressions were of a general nature and the equations of Hantush for infinite aquifers were shown to follow as a special case. The range of validity of the two procedures of linearisation was tested using experimental results from sand tank models of finite aquifers, available in literature. The Hantush procedure was shown to have wider applicability. However, both procedures were found to yield results which have satisfactory agreement with experimental results over larger ranges than earlier reported for infinite aquifers. The effect of variation of the horizontal extent of the recharge mound on the water table profile was studied by treating the limit of the horizontal mound itself as a parameter. The water table rise was computed using the Hantush linearisation procedure for different values of the ratio B/L (B/L = 15, 20, 25, 30, 35, 40 and infinity) where 2B is the horizontal extent of the mound and 2L the width of the recharge strip. The finite extent of the ground water mound in an infinite aquifer was given by that value of B/L for which the predicted profile was identical to that produced when B/L = infinity.

Singh and Rai (1980) obtained an approximate closed form solution of the Boussinesq non-linear parabolic equation for a time varying recharge. It was shown that for unit value of a non-dimensional recharge parameter the water table profile is a function of time whereas in the uniform recharge case it was time independent.

Briz-Kishore and Avadhanulu (1981) designed and developed a generalized aquifer simulation program to handle problems connected with different kinds of complex ground water systems on microprocessors. The characteristic aspect of the program, involving the 'Strongly Implicit Procedure' is that it requires only 10 K bytes of memory for the generated code. Using the program, the effect of pumping on an aquifer can be studied for multiple pumping periods and predictions or observations can be scrutinized at various time steps within each pumping period. The program can also handle conversion problems between confined and water table aquifers under leaky or nonleaky states along with the effects of evapotranspiration, constant recharge or discharge boundaries.

Rai and Singh (1981) presented a mathematical model of the water table fluctuation in an unconfined aquifer subject to a typical localized transient recharge. The aquifer was taken to be homogeneous, isotropic, underlain by a horizontal impermeable base, and linked with a surface reservoir on one side. Sensitivity characteristics of the water table due to variations in the rate of recharge, hydraulic conductivity, and specific yield were illustrated with the help of a numerical example.

Rao and Sarma (1981a) derived a generalized analytical solution for the growth of ground water mound in finite aquifers bounded by open water bodies, in response to recharge from rectangular areas. Finite Fourier transforms were used to solve the linearised differential equation of ground water flow. The solution was evaluated by comparison with existing numerical and analytical results. In stream-aquifer systems similar to those mentioned above, application of the proposed solution is more realistic than using solutions available for infinite aquifers.

Rao and Sarma (1981b) studied ground water recharge from rectangular areas. The formation of ground water mounds in response to recharge from ponds had been described earlier by equations that had been developed for infinite aquifers. In this study, an equation for the formation of ground water mounds on recharge from a rectangular area to a finite aquifer was derived.The validity of the equation was tested by comparison with field data of recharge from square ponds. The equation derived appeared to describe the actual field response of water table to recharge better than the equation derived for infinite aquifers.

Basak (1982) presented closed-form analytical solutions for ground water buildup and depletion under constant recharge and evaporation in unconfined aquifers on islands. The solutions were obtained through the use of Grinisky's potential and Dupuit's assumptions and the results were provided in non-dimensional form. They can be used for long and short term predictions for estimating, assessing and managing ground water potential in freshwater islands.

Basak and Rajagopalan (1982) presented an analytical solution for the sea water intrusion length in coastal aquifers (under steady state) under non-Darcy flow. The flow dynamic law was taken as $v = Ki^n$, where v is the macroscopic seepage velocity under the hydraulic gradient i, K is the permeability of the aquifer, and n is dependent on Reynolds' number but constant throughout the flowfield. The results show that the seawater intrusion length increases when the flow deviates (i.e. as n decreases) more and more from Darcian linearity and is seen to be a function of the ratios ND/q and KD/q_o over and above the non-Darcy index n and the ratio of density of seawater to that of freshwater, where N is the constant recharge rate in the aquifer, D the depth of water and q_o the freshwater discharge to the sea.

Kashyap and Chandra (1982) developed a numerical scheme to estimate quantitatively parameters related to geohydrological and hydrological characteristics of ground water aquifers, employing historic data of hydraulic head, rainfall, pumpages etc. The scheme is based upon the constrained minimisation of the sum of the squares of the residues in the Boussinesq equation. Derivatives of hydraulic head were estimated by the least squares polynomial approximation.

Briz-Kishore and Avadhanulu (1983) developed an optimization for simulation of complex aquifer systems which is efficient in terms of memory required. The program code developed for the technique was tested using a strongly implicit procedure in a two dimensional aquifer system . The results showed a saving of 98% as compared to iterative solutions of the relevant equations.

Rao and Sarma (1983) solved analytically the problem of ground water recharge from strip basins to finite aquifers by the method of finite Fourier transforms. Both impermeable and recharge boundaries were considered.The analytical solutions were evaluated by comparison with experimental results in sand tank models reported in the literature.

Rao and Sarma (1984) solved the problem of localized ground water recharge from a strip basin to an aquifer bounded by stream and impermeable boundaries by the use of extended finite Fourier transforms. The solution was evaluated by comparison with the method of images, and with numerical and experimental results. The existing expression for the inverse of the extended finite Fourier cosine transform was corrected.

Singh et al. (1984) used a ground water simulation model to predict the dynamic behaviour of the water table in response to ground water pumpage and net recharge in a part of the Lower Ghaggar basin, Haryana. The pumped water was proposed to be used together with canal water for irrigation of crops and for drinking water demands considering the quality constraints.

Dasgupta and Biswas (1985) directly transferred the theoretical formulation of the steady state fluid potential of a basin to an algorithm with the help of Fourier transform and a sequence of recurring filter functions for the computation of a three-dimensional mathematical model of unconfined multi-aquifer ground water basins having relatively simple geometry. The algorithm is readily programmable and works very fast producing a large volume of nodal values in considerably small CPU time. The memory requirement of the program being sufficiently low, the computations. can also be carried out in mini- or micro-computer system. The method may be a useful substitute to finite element technique in a number of cases with respect to economy, time and technicalities.

Gupta et al. (1985) evoluted the regional hydrogeologic setup of a hard rock aquifer through R-C analog model. Conceptualization of regional hydrogeologic setup in a hard rock granitic terrain by employing sparse data obtained through conventional methods is usually not possible. In such situations, aquifer simulation could be employed as a useful tool. An attempt was made to evolve the regional pattern of hydrogeologic parameters in a granitic basin. During the process of model calibration, the field estimates of hydrogeological parameters as well as those of recharge and ground water extraction were appropriately modified. A first order estimate of the effluent outflow from the aquifer to ephemeral streams was made only from the flow model. The calibrated model satisfactorily reproduced the historical response of the aquifer and could be used for prognosis.

Gupta et al. (1985) made a quantitative study of conjunctive utilization of surface water and ground water to arrest the water level decline in an alluvial aquifer in the Daha region, northern India, using an interactive finite difference aquifer model. The system was assumed to be a monostratum aquifer. The finite difference form of the ground water flow equation was solved by using the backward difference approximation and successive over-relaxation technique. The model was validated for steady and dynamic conditions by progressive modification of the model parameters. The aquifer response to a probabilistic input-output scheme was estimated to have a substantial influence of the proposed canal network.

Shakya and Singh (1986) analysed steady ground water flow from constant head recharge wells in semi-confined aquifers. Gravity recharge of filtered runoff water into aquifers through existing irrigation wells has potential to solve numerous water management problems. Three cases of a fully penetrating irrigation wells installed in a two-aquifer system were analysed . Equations for the steady piezometric head distribution and recharge rate to each aquifer for the three cases were developed. Computations were performed and application of the solutions was discussed.

Kashyap et al. (1988) developed an optimization model for computer-assisted estimation of aquifer parameters. It is based upon the principle of minimization of the sum of squares of the differences between observed and computed drawdowns. The objective strategy eliminates the subjectivity associated with the conventional curve-matching procedures. Apart from the parameter estimation, the model can assist in identifying certain hydrogeological features like leakage, discontinuities, vertical anisotropy, etc. It also can provide a check on consistency among different data sets monitored during a test pumping (e.g., drawdown and recovery data). The application of the proposed model was illustrated by analysis of field data. The model-computed parameters honoured the observed data more closely than the graphical estimates. The model could also identify leakage as the cause of departure of the time-drawdown curve from the Theis type curve. In another study, the model results lead to an inference that the recovery data of the pumped well are inconsistent with the rest of the data.

Singh and Rai (1989) presented an analytical solution of the non-linear Boussinesq equation using the integral balance method. The solution obtained was the same as that obtained by Basak (1979) following a different approach.

Sondhi et al. (1989) presented a methodology for determining the available additional ground water potential and its distribution in the Mahi Right Bank Canal Project in Gujarat. The procedure was based on the use of specific empirical constants for estimating ground water recharge from the water conveyance and distribution system and the annual water balance of the project. The spatial distribution of ground water potential was determined by 'recharge distribution coefficients' derived from a digital simulation model of the ground water basin of the project area.

Sridharan et al. (1990) considered the problem of pumping an aquifer in an aquifer-water table aquitard system, accounting for the elastic properties of both the aquifer and the aquitard, the gravity drainage in the aquitard and treating the water table as an unknown boundary. The coupled partial differential equations were nondimensionalised, yielding three principal parameters governing the problem. The numerical solution of these equations was obtained for a wide range of parameter values. Type curves were generated and their use was illustrated through a field application.

Singh et al. (1991) presented an analytical solution of the linearised Boussinesq equation with a complex transient recharge function to describe the water table fluctuation in a sloping aquifer of finite width. The solution was obtained by using an eigenvalue-eigenfunction expansion method. Some previously known solutions for different recharge functions were shown to be special cases of the present general solution. Applications of the solutions in prediction of the spatio-temporal distribution of the water table in a ditch drainage system were illustrated with the help of synthetic examples.

Analysis of Flow Towards Wells

Wells are used to solve several water management problems. The theory of ground water flow towards partially and fully penetrating wells in unconfined, confined, and leaky aquifers has been developed by numerous authors. Results reported for wells in confined aquifers are derived as solutions to Jacob's differential equation for flow of slightly compressible fluids through deformable porous media. Results in unconfined aquifers are solutions to either the Laplace or Boussinesq equations describing hydraulic head distribution in porous media. The studies carried out in India are briefly given below.

Abdul Khader and Veerankutty (1975) derived equations for transient flow to a well penetrating two aquifers - a water table aquifer overlying a confined aquifer. Two cases were considered for analysis. In the first case flow towards a well of zero discharge with different initial heads was analysed. In the second case the solution was obtained for a well penetrating two aquifers with a constant discharge and identical initial heads. Schapery's method of inversion for Laplace transform was used in the analysis. Solutions of these two cases were combined to obtain general solutions for different field conditions. From the equations derived, it is also possible to calculate the contributions from individual aquifers to the total discharge.

Abdul Khader and Ramadurgaiah (1978) developed a more realistic theoretical solution to the problem of artesian well flow taking into consideration the partial penetration of the well and finiteness of its radius. The aquifer was assumed to be homogeneous, anisotropic, confined between horizontal, impervious boundaries, and bounded laterally by a recharge boundary of uniform radius. Important results of the analysis were discussed both in the transient and the steady states of flow with reference to the solutions of the previous investigators.

Chowdhury and Anjaneyulu (1978) studied drainage by partially penetrating recharge wells in a leaky aquifer. Recharge wells can be considered as a possible solution for the drainage of waterlogged areas which have no gravity outlets. A knowledge of the capacity of the recharge wells is useful in estimating the number of wells needed to provide drainage relief to a particular area. Laboratory experiments were conducted on a sand model simulating a leaky artesian aquifer underlying an unconfined aquifer. The unconfined aquifer in the model was overlain by topsoil which was kept ponded to simulate a waterlogged condition. The recharge characteristics of a well partially penetrating the leaky artesian aquifer were studied under different conditions. Based on experimental data, empirical equations were proposed for predicting the recharge rate.

Jaiswal and Chauhan (1978a) formulated a differential equation for axisymmetric radial transient flow to a nonpenetrating well in an infinite leaky aquifer in spherical coordinate system. A general solution for nonsteady state flow was obtained for nonpenetrating wells in leaky artesian aquifers with a general time variable discharge function, as well as for the specific case of exponential decay discharge function. The solution was expressed in terms of standard mathematical functions.

Lakshminarayana and Rajagopalan (1978) sought a digital model solution for the unsteady state radial flow to a partially penetrating well pumping at a constant rate from an unconfined anisotropic aquifer. The solution technique used was the iterative alternating-direction implicit method. Attention was focused on the utility of the digital model to analyse aquifer test-data in unconfined aquifers, so as to evaluate the lateral permeability, vertical permeability, specific storage and specific yield of the aquifer. That an approximate steady-state solution of flow to partially penetrating wells in unconfined aquifers can be sought was also illustrated. The digital model was applied to analyse field aquifer test data of the time distribution of average drawdown at well screen depths, and of water table drawdown at two radial distances from the test well.

Rama Rao and Das (1978) made a study, by the finite element method, of a few specific cases of the problem of steady non-Darcy seepage to a fully penetrating well in an unconfined aquifer based on Forchheimer's non-linear seepage flow. Two types of problems were considered: in one type the entire seepage domain around the well was assumed to experience non-Darcy flow, and in the other type the seepage domain close to the well was assumed to have non-Darcy flow, with the rest of the domain having Darcy flow. A qualitative appraisal was made of the difference between Darcy and non-Darcy flow conditions in relation to the discharge into the well, the form of the free surface , the potential and the potential gradients in the flow domain.

Patel and Mishra (1983) analysed unsteady flow to a large diameter well by a discrete kernel approach, taking well storage into consideration. The variation of drawdown with time was obtained at the well and inside the aquifer. The validity of the new method was verified by comparing the drawdown at the well with the drawdown given by Papadopulos and Cooper (1967). The aquifer contribution to discharge at various times was estimated.

Mishra et al. (1985) described a methodology using a discrete kernel approach, to analyse unsteady flow to a multi- aquifer well. The well taps two aquifers which are separated by an aquiclude. The contribution of an individual aquifer to well discharge was estimated when the well is pumped at a constant rate. It was found that the contribution of an aquifer is governed by its hydraulic diffusivity value. In case both the aquifers have equal diffusivity, the aquifers' contributions are independent of time but proportional to the respective transmissivity value.

Rajagopalan and Jose (1986) presented a digital simulation model for the solution of the unsteady state radial flow to a large diameter dug well perforating the full saturated thickness of an unconfined aquifer. The numerical solution is based on the finite difference approach. The computational algorithm is an iterative version of the alternating direction implicit method. The time variant discharge from the aquifer, and the reduction in saturated thickness due to water withdrawal during both the abstraction and recovery phases were suitably incorporated in the simulation model. A sensitivity analysis was carried out on the model parameters of the aquifer, namely lateral permeability, anisotropy, specific storage and specific yield. The results indicated that the model response of hydraulic heads in the aquifer is mainly sensitive to variations in lateral permeability and specific yield alone. The simulation model was also applied to analyse data from well pumping tests. The particular combination of parameters characterizing the aquifer at the test-site were identified by a parameter adjustment procedure.

Shakya et al. (1986) analysed hydraulics of fully penetrating injection wells in two semi-confined aquifers overlain by a thick soil slab. Equations for steady piezometric head distribution in the two semi-confined aquifers arising due to constant rate of injection into (i) the lower aquifer, (ii) the upper aquifer, and (iii) both aquifers, were derived. These solutions were developed under conditions of accretion from the land surface. In absence of accretion, when the well is fully penetrating both aquifers, it was analytically shown that the ratio of fluxes through the aquifers is equal to their transmissivity ratio . Sample computations of the three cases ascertained the validity of the solutions.

Gupta and Singh (1988) studied the flow regime associated with partially penetrating large diameter wells in hard rocks. In case of a large diameter well which penetrates an aquifer only partially, significant vertical flows may set in as a result of withdrawal from the well provided the vertical permeability below the well bottom is appreciable. A finite difference model of ground water flow regime associated with a partially penetrating well in a hard rock terrain was presented. Use of the model in the estimation of hydrogeological parameters in such a situation was illustrated by a field example. The analysis of pump test data showed that parameter estimation will be in error if the vertical flows are neglected. The same model was also used for prognosing the efficacy of a bore well in a large diameter partially penetrating well to increase the yield.

Singh and Shakya (1989) proposed a non-linear equation for the entry of water through the perforations in well screens and a new parameter, screen hydraulic conductivity was described. A problem of steady ground water flow through a confined aquifer was formulated using the usual differential equation and a non-linear (gradient and head) boundary condition incorporating the proposed flux law at the aquifer-screen interface. The semi-analytical solution yields the drawdown distribution in the aquifer. It is useful in computing yields from a screened well for different water levels in the well.

Sridharan et al. (1990) made a numerical analysis of flow to a dug well in an unconfined aquifer, taking into account well storage, elastic storage release, gravity drainage, anisotropy, partial penetration, vertical flow and seepage surface at the well face, and treating the water table in the aquifer and water level in the well as unknown boundaries. The pumped discharge was maintained constant. The solution was obtained by a two-level iterative scheme. The effects of governing parameters on the drawdown, development of seepage surface and contribution from aquifer flow to the total discharge were discussed. The degree of anisotropy and partial penetration were found to be the parameters which affect the flow characteristics most significantly. The effect of anisotropy on the development of seepage surface was very pronounced.

Chachadi et al. (1991) used a generalized discrete kernel approach to analyse the effect of both production well storage and observation well storage on drawdown at any point in the aquifer during pumping and recovery. Non-dimensional time-drawdown plots were presented for four different combinations of a production well and an observation well, which may or may not have storage. The non-dimensional time-drawdown plots include the response of the aquifer during the recovery phase. The contribution from the observation well storage to the aquifer during pumping, and the replenishment of the observation well storage during recovery were presented for specific cases.

Evaluation of Aquifer Parameters

Distributed aquifer parameters form an important input for forecasting problems. The distribution can be arrived at by solving inverse problem. However, to arrive at a realistic distribution of aquifer parameters by such a procedure, it is necessary to have reliable values of the parameters at few points. Such values can be arrived at by analysis of test pumping data. A number of models have been developed for computer-assisted or analytical analysis of test pumping data. However, these models are yet to be adopted by the practising professionals. The studies so far carried out are briefly given below.

Jaiswal and Chauhan (1978b) obtained the analysis of flow to a flowing nonpenetrating well in a leaky artesian aquifer. A method was suggested to determine the aquifer parameters using the pump test data on such wells with constant drawdown in the well. A technique was also suggested to determine the aquifer parameters using the well itself as the observation well.

Sondhi and Singh (1978) developed an analytical solution to determine unconfined aquifer parameters by conducting pump tests on partially penetrating wells. The aquifer was assumed to be homogeneous, isotropic and infinite in areal extent. A new concept of 'effective penetration' was introduced. A dimensionless curve was developed to find the effective penetration of the well. A circular sand tank model was used to check the applicability of the relationships developed.

Chander et al. (1981) used Marquardt algorithm for estimating aquifer parameters from pump test data in nonleaky and leaky aquifers. It emerged from the study that in spite of poor initial estimates, the convergence is quick, and the residual square error. for the difference between the observed drawdowns and those calculated from parameters estimated using Marquardt algorithm and the known methods, is minimum in the case of Marquardt estimates.

Rajagopalan (1983) presented a mathematical model for analysis of test data from dug wells, with the boundary condition along the well face being defined on the basis of alternative assumptions made on how the radial hydraulic gradient is distributed over the well face. Approximate equations for the recovery phase were obtained based on an additional assumption that the radial hydraulic gradient along the well face is linearly related to the drawdown in the dug well. The use of these equations leads to the determination of a parameter of the form P_rB (where P_r is the lateral permeability of the aquifer and B is a constant) and of the time required for the dug well to recoup fully. A simple field test procedure was adopted to obtain conditions of different discharges from the well and an empirical relationship between the parameter P_rB and the well discharge was established for the test well site. The approximate equations that were developed also find use in correcting some of the common anomalies in the abstraction phase data.

Rushton and Singh (1983) studied drawdowns in large diameter wells due to decreasing abstraction rates. Due to characteristics of centrifugal pumps, most pumping tests in large diameter wells exhibit a decreasing abstraction rate with increasing drawdown . Type curves were obtained for the case of abstraction rates which are functions of the well drawdown; values for the type curves were obtained from a numerical model. For the case of constant abstraction, these curves provide an alternative to the classical approach. By plotting the ratio of drawdowns at different times, it is possible to identify more easily when the aquifer begins to contribute to the well discharge. The practical application of the technique was illustrated by a field example.

Gupta and Singh (1985) analysed the pump test data on large diameter well tapping the weathered zone of granitic terrains. As these are low-permeability zones, the recovery after each pumping phase is slow and remains incomplete even till the onset of the next pumping phase. Their study showed that a reliable estimate of hydrogeologic parameters is possible through a pump test in such a well provided the recovery rate prior to the test is fed into a numerical model used for the interpretation of the data.

Mishra and Chachadi (1985) analysed unsteady flow to a large diameter well in a confined aquifer during recovery by discrete kernel approach. A family of type curves was presented for different durations of pumping. These type curves provide a fairly accurate means of determining aquifer parameters from data of pump tests conducted in a large diameter well. The replenishment of well storage at various times was estimated.

Sridharan et al. (1985) presented a method for identification of parameters in unconfined aquifers from pumping tests, based on the optimization of the objective function using the least squares approach. Four parameters were evaluated, namely: the hydraulic conductivity in the radial and the vertical directions, the storage coefficient and the specific yield. The sensitivity analysis technique was used for solving the optimization problem. Besides eliminating the subjectivity involved in the graphical procedure, the method takes into account the field data at all time intervals without classifying them into small and large time intervals and does not use the approximation that the ratio of the storage coefficient to the specific yield tends to zero. It was found that the parameter estimates from the computational and graphical procedures differ fairly significantly.

Singh and Gupta (1986) presented a versatile and easy method using numerical modelling for the estimation of aquifer parameters from pump tests on a large diameter well. The method is applicable even when the abstraction rate is not constant during the pump test. All observational data during the pumping and recovery phases were used in the estimation of the aquifer parameters. A field example of the pump test carried out on a large diameter well in granitic terrain was presented to illustrate the method. The computer program written in BASIC may be executed on a hand held calculator and aquifer characteristics can be determined in the field itself.

Rushton and Singh (1987) presented a method of analysing the pumping and recovery phases of large diameter wells based on a kernel function method. Consideration was given to the effect of the seepage face, which is the difference between the well water level and the aquifer level on the well face. A computer program for the kernel function method was written in BASIC. In the analysis of a representative field test, the importance of including the seepage face was demonstrated; if the seepage face ignored, both the transmissivity and storage coefficient were underestimated.

Sharma et al. (1987) presented a technique to evaluate aquifer constants by pumping test data of a cavity well. Most of the solutions proposed by various workers to solve a nonequilibrium equation for the flow towards a nonpenetrating cavity well are based on the curve-matching technique or an approximate straight-line method. They proposed another technique to solve an inverse problem. This approach is simpler and more realistic since the element of human judgement is practically eliminated.

Sridharan et al. (1987) presented a method for identification of parameters from pumping tests, in semiconfined aquifers with storage release from the aquitard. Four parameters were evaluated, namely: the transmissivity of the aquifer; the storage coefficient of the aquifer; the leakage coefficient of the aquitard; and the storage coefficient of the aquitard. The Neuman and Witherspoon solution for the drawdown, valid for all time intervals was used. The optimization problem was solved by the sensitivity analysis technique. The method has the merit of utilizing the field data for all times without classifying them into small and large time intervals. A computational procedure for evaluating the drawdown integral was presented.

Rushton and Srivastava (1988) interpreted injection well tests in an alluvial aquifer. Artificial recharge using injection wells can present practical difficulties and it is important to be able to identify and quantify the features which cause these difficulties. They described the analysis, using a mathematical model, of field information which was obtained from an injection test in an alluvial aquifer; the test continued for 250 days. Aquifer parameters were estimated both for the more permeable sand layers and the less permeable clay layers. During the test severe clogging occurred in the vicinity of the well and the mathematical model was also used to quantify the reduction in hydraulic conductivity due to the clogging.

Singh and Gupta (1988) presented a numerical method for the interpretation of pump test data for a large diameter well situated near such a boundary as a river, a lake or a dyke which commonly occur in hard rock terrains. The technique considers the time-drawdown data for the pumping as well as for the recovery phase. A field example was presented to illustrate the use of the technique. The computer code for numerical modelling was given in BASIC language which can easily be implemented on a portable microcomputer for the estimation of aquifer parameters in the field.

Sakthivadivel and Rushton (1989) outlined a methodology for estimating the aquifer parameters from pumping tests in large diameter wells taking into account the dynamic seepage face. A general expression for the seepage face, which is the difference between the well water level and the phreatic surface at the well face, was deduced from experimental observations. A numerical model was used to simulate both the pumping and recovery phases of the test. Both the drawdown in the pumped well and the flow from the aquifer to the well were used in matching the model and field results. Examples were used which show that if the seepage face is ignored in the analysis, the value of the hydraulic conductivity is underestimated.

SOLUTE TRANSPORT

The solute transport equation is used with the ground-water flow equation to address pollution problems. These problems are not as well understood, especially the characterization of source terms and dispersion. In solute transport applications, one of three general situations exists: (i) variations in concentration have negligible effect on fluid density and ground water flow is steady;(ii) variations in concentration have negligible effect on fluid density and ground water flow is transient; and (iii) variations in concentration have significant effect on fluid density and ground water flow is transient. When steady flow is assumed, it is necessary to solve the ground water flow equation only once to obtain the velocity distribution for the convection term in the transport equation. If the velocity distribution changes with time, the ground water flow equation and the transport equation must be solved simultaneously. The few studies carried out related to solute transport are briefly given below.

Basak and Murty (1977) presented an analytical solution to the problem of concentration dependent diffusion with increasing concentration at the source. The solution is of travelling wave type and was applied to predict the contamination in an aquifer from a source wherein the contamination concentration was increasing with time.

Basak and Murty (1978a) presented an analytical solution to the problem of concentration - dependent diffusion with decreasing concentration at the source. The solution is nondimensionalised and it can be used to predict the contamination in an aquifer from a source in which the contamination concentration decreases with time.

Basak and Murty (1978b) presented an analytical solution for the prediction of the spread of contaminant caused by non-linear diffusion in an aquifer adjoining a polluted source. The solution is based on the assumption of the existence of a sharp diffusion front and is similar to the solution of a two-dimensional unsaturated flow problem.

The effect of concentration dependency of the diffusion coefficient on the contamination spread was discussed.

Gupta and Singh (1980) presented analytical solutions to the dispersion-convection equation for leaching of saline soils under exponentially decreasing, and arbitrary initial salt profile. The soil profile was considered semi-infinite and homogeneous. Another solution incorporating an exponentially decreasing time-varying boundary condition at the surface was developed.The effect of the initial condition and solute transport parameters on the predictive behaviour of the model was studied by arbitrarily choosing the values of the parameters. The results indicate that the prediction accuracy of the model increases if the initial salt distribution profile is represented by a function which approximates this profile closely. The effect of the time-varying boundary condition was negligible for most practical purposes at or below 15 cm depth of the soil profile. The changes in the transport parameter may not only enhance or retard the pace of reclamation but also affect the final salt distribution in the soil profile.

Basak and Murty (1981) presented an analytical solution to the transient problem of ground water quality improvement through non-linear diffusion. The diffusion coefficient was assumed to be linearly proportional to the concentration. The exact solution was compared with the solution of the linearised governing differential equation. The solution of the problem with a concentration - dependent diffusion coefficient in relation to the solution for constant diffusion coefficient was discussed.

Batta and Murty (1982) conducted experiments on undisturbed and disturbed samples to find the effect of medium disturbance on the hydrodynamic dispersion coefficient under laboratory and field conditions. A comparison of the hydrodynamic dispersion coefficient under laboratory and field conditions was made. Using the field data, a method to determine the dispersion coefficient was suggested. The method uses finite differences and the values obtained with this method were found to compare favourably with other existing methods. Disturbance of a sandy loam caused a reduction of the dispersion coefficient to 0.6 -0.8 of its in situ value.

Pandey et al. (1982) formulated the one-dimensional dispersion equation with non-linear adsorption isotherm with the assumption that equilibrium exists between the adsorbed and the solution phase. The equation was solved numerically, using the extrapolated Crank-Nicolson finite difference scheme. The numerical results were compared with the analytical solution, numerical results and some experimental data. The agreement was good.

Prakash (1982) described analytical methods to predict the concentrations of effluents released in a two- or three-dimensional ground water flowfield from a point, line, plane or parallel piped source. The effects of the upper and lower confining boundaries in an artesian aquifer and those of the bedrock and water table in an unconfined aquifer were accounted for by the method of images. The same technique was used to model the contribution of a constant concentration boundary in the flowfield like the one provided by a fully penetrating perennial stream. Using the results of a sensitivity analysis, the number of images at which computations can be truncated without significantly affecting the accuracy of the results, was indicated. To validate the model, concentration isopleths were developed for the release of effluents from an ashpond in a two-dimensional stream-aquifer system and the results were compared with those obtained from a finite element study.

Naveen Kumar (1983) presented analytical solutions for dispersion (in a finite non-adsorbing and adsorbing porous medium) which is controlled by flow (with unsteady unidirectional velocity distribution) of a low concentration fluid towards a region of higher concentration. An exponential function concentration was enforced at the source of the dispersion, while zero concentration, or a condition in which the change in concentration is proportional to the flow, was applied at the other boundary. A new time variable was introduced to solve the unsteady flow problem.

Gupta et al. (1985) derived an expression for the leaching of a profile with superficial accumulation of soluble substances. Use was made of existing analytical solutions, adapted to a 'Dirac delta function' input of solute. From the concentration profile c(x,t) obtained, a formula followed for the fraction of solute leached beyond depth x at a given time t.

Misra and Mahapatra (1989) used the Laplace transformation to obtain an analytical solution for the one-dimensional differential equation governing the transport of soluble salts through soil. The initial condition used was an exponentially varying salinity with depth. The velocity dependence of the apparent diffusion coefficient, D, was recognized and the best known formulation for computing salt profiles consequent upon leaching at realistic flow rates was applied. The model also includes the case of irrigation water that may contain some salt and yet has to be used for leaching under special circumstances.

CONCLUSION

The effective application of ground water flow models involves several interrelated areas: model selection (need), computer program use, sensitivity analysis, system conceptualization, data collection design, history matching- calibration and prediction. The use of models can not be considered a step-by-step procedure. Actually, it is an iterative process to which one never achieves a fully satisfactory conclusion. The reason for this is that when dealing with real systems, a model is never exact and complete data are never available . Consequently, considerable scientific judgement of a subjective or intuitive nature is necessary for any degree of success. For transport problems, the need for subjective judgement is greater than with ground water flow.

Some areas of ground water modelling are well developed while others are not. For flow in fractured or cavernous media and for transport problems, in general, the predictive validity of the models is not high. Consequently , a significant amount of effort needs to be directed toward understanding and characterizing basic processes. For transport applications, these basic processes include those associated with attenuation. For fracture flow research, these processes include flow in individual fractures and mechanical-fluid interactions.

Ground water flow in saturated porous media is an area for which models are well developed. For this area, confidence in model validity is high. Further, it is generally recognized that the major limitation on application predictions is the adequacy of the data base for the specific site. One current area of research, parameter estimation, addresses the problem of data adequacy. Another area of research involves new solution techniques that are more efficient for applications with limited data.

In India, there has been a significant amount of work in the area of ground water modelling. However, a lot more needs to be done. An awareness and expertise among the practising professionals should be build up about the potential of ground water modelling techniques. This may be accomplished by imparting a systematic and formal training to them.

ACKNOWLEDGEMENT

The citation of various studies above is intended to present the efforts in India. However, it may not be possible to include all the published studies. Further, many studies remain unpublished primarily because of the classified nature of the data involved. The author apologises to all those ground water modellers of India, whose works could not be included. The author acknowledges the support provided by Dr. Deepak Kashyap, Reader, Department of Hydrology, University of Roorkee, Roorkee in preparation of this document.

REFERENCES

Abdul Khader M.H. and M.K. Veerankutty (1975), 'Transient well-flow in an unconfined-confined aquifer system', Journal of Hydrology, Vol.26, 1975, pp.123-140

Abdul Khader M.H. and D. Ramadurgaiah (1978), 'Flow toward a partially penetrating well in a bounded artesian aquifer', Journal of Hydrology, Vol.36, 1978, pp.95-107.

Banerjee M. and K.K. Watson (1984), 'Numerical analysis of soil water movement under conditions of rapid intermittency of water application', Water Resources Research, Vol.20, No.1, January 1984, pp. 119-125.

Basak P. (1978), 'Evaporation from horizontal soil columns with variable diffusivity', Journal of Hydrology, Vol.37, 1978, pp.129-136.

Basak P. (1979), 'An analytical solution for the transient ditch drainage problem', Journal of Hydrology, Vol. 41, 1979, pp.377-382.

Basak P. (1982), 'Groundwater buildup and depletion in islands during monsoon and summer', Journal of Hydrology Vol. 56, 1982, pp.265-275.

Basak P. and V.V.N. Murty (1977), 'Nonlinear diffusion applied to groundwater contamination problems', Journal of Hydrology, Vol. 35, 1977, pp.357-363.

Basak P. and V.V.N. Murty (1978a), 'Concentration-dependent diffusion applied to groundwater contamination problems', Journal of Hydrology, Vol.37, 1978, pp.333-337.

Basak P. and V.V.N. Murty (1978b), 'Pollution of groundwater through nonlinear diffusion', Journal of Hydrology, Vol.38, 1978, pp.243-247.

Basak P. and V.V.N. Murty (1981), 'Groundwater quality improvement through nonlinear diffusion', Journal of Hydrology, Vol.53, 1981, pp.151-159.

Basak P. and S.P. Rajagopalan (1982), 'Effect of non-Darcy flow on computing seawater intrusion lengths', Journal of Hydrology, Vol.58, 1982, pp.83-87.

Batta R.K. and V.V.N. Murty (1982), 'In situ determination of the hydrodynamic dispersion coefficient and its correlation under laboratory and field conditions', Journal of Hydrology, Vol.59, 1982, pp.139-147.

Briz-Kishore B.H. and R.V.S.S. Avadhanulu (1981), 'An aquifer simulation program for micro-based processors', Ground Water, Vol.19, No.4, July-August 1981, pp.400-406.

Briz-Kishore B.H. and R.V.S.S. Avadhanulu (1983), 'An efficient procedure in the digital simulation of aquifer systems', Journal of Hydrology, Vol.64, 1983, pp.159-174.

Chachadi A.G., G.C.Mishra and B.B.S. Singhal (1991), 'Drawdown at a large-diameter observation well', Journal of Hydrology, Vol.127, 1991, pp.219-233.

Chander Subhash, P.N. Kapoor and S.K. Goyal (1981), 'Analysis of pumping test data using Marquardt algorithm', Ground Water, Vol.19, No.3, May-June 1981, pp.275-278.

Chandra Satish and P.K. Pande (1975), 'Recharge studies for a basin using mathematical model', IWRA - Proc. 2nd World Congress, New Delhi, pp.205-211.

Chowdhury P.K. and B. Anjaneyulu (1978), 'Drainage by partially penetrating recharge wells in a leaky aquifer', Journal of Hydrology, Vol.39, 1978, pp.51-57.

Dasgupta S.P. and A.B. Biswas (1985), 'Mathematical modelling for multiaquifer groundwater basins', Journal of Hydrology, Vol. 82, 1985, pp.381-392.

Elango K. and K. Swaminathan (1980), 'A finite-element model for concurrent confined-unconfined zones in an aquifer', Journal of Hydrology, Vol.46, 1980, pp.289-299.

Faust Charles R. and James W. Mercer (1980), 'Ground-water modeling: numerical models', Ground Water, Vol.18, No.4, July-August 1980, pp.395-409.

Gupta C.P. and V.S. Singh (1985), 'Effect of incomplete recovery prior to a pump test in a large-diameter well', Journal of Hydrology, Vol.79, 1985, pp.141-144.

Gupta C.P. and V.S. Singh (1988), 'Flow regime associated with partially penetrating large-diameter wells in hard rocks', Journal of Hydrology, Vol.103, 1988, pp.209-217.

Gupta C.P., M. Thangarajan and V.V.S. Gurunadha Rao (1979), 'Electric analog model study of aquifer in Krishni-Hindon interstream region, U.P., India', Ground Water, Vol.17, No.3, May-June 1979, pp.284-290.

Gupta C.P., M. Thangarajan and V.V.S. Gurunadha Rao (1985), 'Evolution of regional hydrogeologic setup of a hard rock aquifer through R-C analog model', Ground Water, Vol.23, No.3, May-June 1985, pp.331-335.

Gupta C.P., Shakeel Ahmed and V.V.S. Gurunadha Rao (1985), 'Conjunctive utilization of surface water and ground water to arrest the water level decline in an alluvial aquifer', Journal of Hydrology, Vol.76, 1985, pp.351-361.

Gupta Suresh K. and Sita Ram Singh (1980), 'Analytical solutions for predicting solute movement and their interpretation in reclamation', Journal of Hydrology, Vol.45, 1980, pp.133-148.

Gupta S.K., D. Ramadurgaiah and W.H. Van Der Molen (1985), 'The leaching fraction beyond depth x, caused by percolation of a soil profile with an initial salt accumulation at its surface', Journal of Hydrology, Vol.79, 1985, pp.123-126.

Jaiswal C.S. and H.S. Chauhan (1978a), 'Transient spherical flow to a nonpenetrating well with constant drawdown', Ground Water, Vol.16, No.6, November-December 1978, pp.432-436.

Jaiswal C.S. and H.S. Chauhan (1978b), 'Flow to a nonpenetrating well in a leaky artesian aquifer with variable discharge', Ground Water, Vol.16, No.2, March-April 1978, pp.119-125.

Lakshminarayana V. and S.P. Rajagopalan (1978), 'Digital model studies of unsteady-state radial flow to partially penetrating wells in unconfined anisotropic aquifers', Journal of Hydrology, Vol.38, 1978, pp.249-262.

Kashyap Deepak (1989), 'Mathematical modelling for ground water management-status in India', Indo-French Seminar on Management of Water Resources, 22-24 September 1989, Festival of France-1989, Jaipur, pp.IV-59 to IV-75.

Kashyap Deepak and Satish Chandra (1982), 'A nonlinear optimisation method for aquifer parameter estimation', Journal of Hydrology, Vol.57, 1982, pp.163-173.

Kashyap Deepak, Prasong Dachadesh and L.S. Jageshwar Sinha (1988), 'An optimization model for analysis of test pumping data', Ground Water, Vol.26, No.3, May-June 1988, pp.289-297.

Mercer James W. and Charles R. Faust (1980), 'Ground-water modeling: An overview', Ground Water, Vol.18, No.2, March-April 1980, pp.108-115.

Mercer James W. and Charles R. Faust (1980), 'Ground-water modeling: Mathematical models', Ground Water, Vol.18, No.3, May-June 1980, pp.212-227.

Mercer James W. and Charles R. Faust (1980), 'Ground-water modeling: Applications', Ground Water, Vol.18, No.5, September-October 1980, pp.486-497.

Mishra G.C. and A.G. Chachadi (1985), 'Analysis of flow to a large-diameter well during the recovery period', Ground Water, Vol.23, No.5, September-October 1985, pp.646-651.

Mishra G.C., M.D. Nautiyal and S. Chandra (1985), 'Unsteady flow to a well tapping two aquifers separated by an aquiclude', Journal of Hydrology, Vol.82, 1985, pp.357-369.

Misra C. and S.N. Mahapatra (1989), 'Prediction of salt transport during leaching of saline soils for reclamation', Journal of Hydrology, Vol.106, 1989, pp.185-189.

Mohan Rao K.M., Deepak Kashyap and Satish Chandra (1990), 'Relative performance of a soil moisture accounting model in estimating return flow', Journal of Hydrology, Vol.115, 1990, pp.231-241.

Naveen Kumar (1983), 'Unsteady flow against dispersion in finite porous media', Journal of Hydrology, Vol.63, 1983, pp.345-358.

Pandey R.S., S.R. Singh and B.K. Sinha (1982), 'An extrapolated Crank-Nicolson method for solving the convection-dispersion equation with nonlinear adsorption', Journal of Hydrology, Vol.56, 1982, pp.277-285.

Panikar J.T. and G. Nanjappa (1976), 'Time of ponding-comparison of results of the Parlange solution with the Smith and Mein-Larson models', Journal of Hydrology, Vol.31, 1976, pp.175-179.

Papadopulos I.S. and H.H. Cooper (1967), 'Drawdown in a well of large diameter', Water Resources Research, Vol.3, No.1, pp.241-244.

Patel S.C. and G.C. Mishra (1983), 'Analysis of flow to a large-diameter well by a discrete kernel approach', Ground Water, Vol.21, No.5, September-October 1983, pp.573-576.

Prakash Anand (1982), 'Ground-water contamination due to vanishing and finite-size continuous sources', Journal of the Hydraulics Division, ASCE, Vol.108, No.HY4, April 1982, pp.572-590.

Rai Shivendra Nath and Rishi Narain Singh (1981), 'A mathematical model of water table fluctuation in a semi-infinite aquifer induced by localized transient recharge', Water Resources Research, Vol.17, No.4, August 1981, pp.1028-1032.

Rajagopalan S.P. (1983), 'Analysis of dug-well test data', Journal of Hydrology, Vol.64, 1983, pp.175-188.

Rajagopalan S.P. and U. V. Jose (1986), 'A digital simulation model for the unsteady-state radial flow to a dug well', Journal of Hydrology, Vol.87, 1986, pp.233-244.

Rama Prasad (1988), 'A linear root water uptake model', Journal of Hydrology, Vol.99, 1988, pp.297-306.

Rama Prasad (1989), 'Detection of moisture stress by indicator plots - A simulation', Journal of Hydrology, Vol.109, 1989, pp.11-24.

Rama Rao B.S. and R.N. Das (1978), 'A study of unconfined non-Darcy seepage to a well', Journal of Hydrology, Vol.38, 1978, pp.161-178.

Rao N.H. (1987), 'Field test of a simple soil-water balance model for irrigated areas', Journal of Hydrology, Vol.91, 1987, pp.179-186.

Rao N.H. and P.B.S. Sarma (1980), 'Growth of ground-water mound in response to recharge', Ground Water, Vol.18, No.6, November-December 1980, pp.587-595.

Rao N.H. and P.B.S. Sarma (1981a), 'Recharge from rectangular areas to finite aquifers', Journal of Hydrology, Vol.53, 1981, pp.269-275.

Rao N.H. and P.B.S. Sarma (1981b), 'Ground-water recharge from rectangular areas', Ground Water, Vol.19, No.3, May-June 1981, pp.271-274.

Rao N.H. and P.B.S. Sarma (1983), 'Recharge to finite aquifers from strip basins', Journal of Hydrology, Vol.66, 1983, pp.245-252.

Rao N.H. and P.B.S. Sarma (1984), 'Recharge to aquifers with mixed boundaries', Journal of Hydrology, Vol.74, 1984, pp.43-51.

Rushton K.R. and V.S. Singh (1983), 'Drawdowns in large-diameter wells due to decreasing abstraction rates', Ground Water, Vol.21, No.6, November-December 1983, pp.670-677.

Rushton K.R. and V.S. Singh (1987), 'Pumping test analysis in large diameter wells with a seepage face by kernel function technique', Ground Water, Vol.25, No.1, January-February 1987, pp.81-90.

Rushton K.R. and N.K. Srivastava (1988), 'Interpreting injection well tests in an alluvial aquifer', Journal of Hydrology, Vol.99, 1988, pp.49-60.

Sagar Budhi and Sita Ram Singh (1979), 'Aquifer diffusivity from noisy boundary data', Journal of the Hydraulics Division, ASCE, Vol.105, No. HY8, August 1979, pp.943-954.

Sakthivadivel R. and K.R. Rushton (1989), 'Numerical analysis of large diameter wells with a seepage face', Journal of Hydrology, Vol.107, 1989, pp.43-55.

Sarma P.B.S., N.H. Rao and K.V.P. Rao (1980), 'Calculation of water balance in the crop root zone by computer', Journal of Hydrology, Vol.45, 1980, pp.123-131.

Shakya Shri Krishna and Sita Ram Singh (1986), 'Steady groundwater flow from constant head recharge wells in semi-confined aquifers', Journal of Hydrology, Vol.84, 1986, pp.323-332.

Shakya Shri Krishna, Sita Ram Singh and Bandaru Anjaneyulu (1986), 'Steady flow from an injection well in leaky aquifers', Journal of Hydrology, Vol.86, 1986, pp.329-341.

Sharma H.C., H.S. Chauhan and K.K. Singh (1987), 'A technique to evaluate aquifer constants by pumping test data of a cavity well', Ground Water, Vol.25, No.2, March-April 1987, pp.207-211.

Singh R.N. and S.N. Rai (1980), 'On subsurface drainage of transient recharge', Journal of Hydrology, Vol.48, 1980, pp.303-311.

Singh R.N. and S.N. Rai (1989), 'A solution of the nonlinear Boussinesq equation for phreatic flow using an integral balance approach', Journal of Hydrology, Vol.109, 1989, pp.319-323.

Singh R.N., S.N. Rai and D.V. Ramana (1991), 'Water table fluctuation in a sloping aquifer with transient recharge', Journal of Hydrology, Vol.126, 1991, pp.315-326.

Singh Sita Ram and C.M. Jacob (1977), 'Transient analysis of phreatic aquifers lying between two open channels'. Water Resources Research. Vol.13. No.2. April 1977. pp.411-419.

Singh Sita Ram and Budhi Sagar (1977), 'Estimation of aquifer diffusivity in stream-aquifer systems'. Journal of the Hydraulics Division. ASCE. Vol.103. No.HY11, November 1977. pp.1293-1302.

Singh Sita Ram and Shri Krishna Shakya (1989), 'A nonlinear equation for groundwater entry into well screens'. Journal of Hydrology. Vol.109. 1989. pp.95-114.

Singh V.S. and C.P. Gupta (1986), 'Hydrogeological parameter estimation from pump tests on a large diameter well'. Journal of Hydrology. Vol.87. 1986. pp.223-232.

Singh V.S. and C.P. Gupta (1988), 'Analysis of pump test data for a large-diameter well near a hydrogeological boundary'. Journal of Hydrology. Vol.103. 1988. pp.219-227

Singh Rajinder, S.K. Sondhi, Joginder Singh and Ranvir Kumar (1984), 'A groundwater model for simulating the rise of water table under irrigated conditions'. Journal of Hydrology. Vol.71. 1984. pp.165-179.

Sondhi Satish K. and Sita Ram Singh (1978), 'Determination of unconfined aquifer parameters using partially penetrating wells'. Journal of Hydrology. Vol.36, 1978. pp.225-231.

Sondhi S.K., N.H. Rao and P.B.S. Sarma (1989), 'Assessment of groundwater potential for conjunctive water use in a large irrigation project in India'. Journal of Hydrology. Vol.107. 1989. pp.283-295.

Sridharan K., R. Ramaswamy and N.S. Lakshmana Rao (1985), 'Identification of parameters in unconfined aquifers'. Journal of Hydrology, Vol.79, 1985. pp.73-81.

Sridharan K., R. Ramaswamy and N.S. Lakshmana Rao (1987), 'Identification of parameters in semiconfined aquifers'. Journal of Hydrology, Vol.93, 1987, pp.163-173.

Sridharan K., M.Sekhar and M.S. Mohan Kumar (1990), 'Analysis of an aquifer-water table aquitard system', Journal of Hydrology. Vol.114. 1990, pp.175-189.

Sridharan K., D.Sathyanarayana and A. Siva Reddy (1990), 'Analysis of flow near a dug well in an unconfined aquifer', Journal of Hydrology, Vol.119, 1990, pp.89-103.

Sukhija B.S. and C.R. Shah (1976), 'Conformity of groundwater recharge rate by tritium method and mathematical modelling', Journal of Hydrology. Vol.30, 1976. pp.167-178.

Vappicha V.N. and S.H. Nagaraja (1976), 'An approximate solution for the transient interface in a coastal aquifer'. Journal of Hydrology. Vol.31. 1976. pp.161-173.

Verma A.P. (1970), 'Fingero imbibition in artificial replenishment of ground water through cracked porous medium', Water Resources Research. Vol.6, No.3, 1970, pp.906-911.

Verma Rameshwar D. and Wilfried Brutsaert (1970), 'Unconfined aquifer seepage by capillary flow theory', Journal of the Hydraulics Division, ASCE, Vol.96, No.HY6, Proc. Paper 7363, June 1970, pp.1331-1344.

Verma Rameshwar D. and Wilfried Brutsaert (1971), 'Similitude criteria for flow from unconfined aquifers', Journal of the Hydraulics Division, ASCE, Vol.97, No. HY9, September 1971, pp. 1493-1509.