GROUNDWATER MODELLING

Edited by

K.D. Sharma

CENTRAL ARID ZONE RESEARCH INSTITUTE
JODHPUR 342 003, INDIA
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DATABASE FOR GROUNDWATER RESOURCES: STRENGTHS AND WEAKNESSES

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At the threshold of the third millennium it is the prime duty of a planner to make informed and intelligent decisions; as the water resources are finite and its need is continuously growing. To accomplish this a planner needs a sound database with a built-in mechanism for feedback to evaluate the user-needs of the sector. (1.)

An interactive computerized database is therefore, a prerequisite and quite a headway has been made in this direction by the eight peninsular states namely the Andhra Pradesh, Tamilnadu, Karnataka, Kerala, Maharashtra, Gujarat, Orissa and Madhya Pradesh under the Hydrology Project. The Central Ground Water Authority (CGWA) is very keen and active in exacting the ground water resources and devising alternative ways of replenishing the resources (e.g. rain water harvesting). The ongoing programmes of Central Ground Water Authority has brought very strange facts to light which were hitherto never thought of (like the assumed/computed groundwater draft based on the number of GW structures). Thus, the mass awareness campaign of CGWA is not only to make the masses aware of the finite nature of the resource but also to educate them to optimally utilize the resource and at the same time strengthen the ground water database by feedback received from the users. (2.)

STRENGTHS

The Internet is a classical example of a distributed-interactive-database, where, millions of users (presently 50 million) have access to a great pool of resources. Queries could be made, opinion could be gathered, many things of utility could be downloaded, and information could be submitted instantly. Similarly, a groundwater database should offer an easy-to-use and comprehensive means of organizing geological, geotechnical, and hydrogeologic data. (3.)

A groundwater database includes water-level data from several thousands of wells with millions of records and represents many years of collection effort from various agencies. The Groundwater, soil and geology databases must be integrated with Geographic Information

System (GIS) facility or site maps to prepare data visualization maps, time series charts and geologic sections. (3.)

Now, when we talk of a database of groundwater resources, we mean that the user must be able to get answer to his queries such as the following to name a few; (4.)

I. *Water quality in the area of interest,* the user must be able to know the quality of the groundwater in the area in terms of its suitability with regard to potability, agriculture, industrial or any other specific use with regard to all the aquifers present in the area

II. *Water quality standards* for specific purposes along with the maximum permissible limits for various constituents of water. In case of hazardous constituents special warning may also be available

III. *Aquifer disposition* in the area of interest: number and type of aquifers occurring at various depths along with their characteristics, including the grain-size, etc.

IV. *Long and short term water level trends* in terms of deepest and shallowest levels and annual decline or rise etc. in the area.

V. *Yield and other well characteristics* such as range of yield in the given aquifer along with the well characteristics

VI. *Nature and type of wells* such as type of wells, assembly material and screens suited along with types of pumps suitable for the area

VII. *Water balance indicators* in terms of possibility of number and type of GW structures which could be had or added to the existing system

VIII. *Thematic maps* of Integration with GIS would help in preparation of thematic maps for the area of interest, so that overlapping interests/inferences could be drawn, e.g. a particular type of geology supports a particular type of well and so and so is cropping pattern with such and such is the population density, etc.

A database must be capable of integrating itself with the state-of-the-art tools like mathematical modelling, GIS and optimization procedures, which would facilitate preparation of relevant thematic maps and overlays for the area of interest. (5.)

The quest for knowing the future has always been a fascinating field! Whether it is science or any other field. Now a days Planners rely more and more on the simulation studies for prognostication. The simulation studies require a very sound historical database for calibration and verification of the model based on which predictions are made. (6.)

The historical data may not be available for every nodal point, in the area of interest; here comes the use of the GIS tool to generate approximate values for the unknown points based on the known data points in space and time; which in turn depends on the availability of a database with spatial values at differing times and their accuracy is reflected in the interpreted/computed values. (7.)

A database constantly evolves with time as long as it makes adjustments with the changing needs and contemporary practices. As long as constant feedback from the users and user groups are available, the system would continuously evolve and serve the requirement. The Client-Server database systems are presently the best ones and could be adopted for the groundwater resource also. (8.)

The groundwater information system must be capable of assimilating the feedback to the system regarding; (9.)

I. the user requirements
II. bugs in the system
III. areas for upgradation and improvement

Therefore, a groundwater database should also serve as a information system and must encompass; (10.)

I. a query system
II. a GIS system
III. historical data and trends
IV. Automated data collection, validation and entry for crucial areas
V. User must be encouraged to download specific forms, questionnaires, and diagrams and maps relevant to his area of interest

VI. Online system feedback recording for identifying the user-needs, system bugs and routine checkups.

The strength of any electronic database lies in its integrity, reliability, portability, facilities for user interaction and downward compatibility; the same should also be adopted for the database for groundwater resources. (11.)

WEAKNESSES

The greatest weakness in the groundwater sector is non-standardization of parameters, units of representation and the formats. The first and foremost task for the managers should be to standardize the parameters, units of representation, formats for data collection, distribution and archiving along with the procedures of hydrometry, water sampling and water quality determination. (12.)

Any user of these data should be aware that the information contained in such database has an inherent range of accuracy caused by differing and evolving data maintenance and collection methods. Data inaccuracies can also occur from inaccurate well locations (latitude and longitude), water levels associated with the incorrect well, and data entry errors. Water levels from last few years are considered to be more correct than historical data, as more quality-control methods have been used in recent years. (13.)

To help users determine the accuracy of specific water-level data, a quality assurance (QA) code may also be added to each water-level value, e.g. a QA code of 1 would indicate that the water level has been checked for inaccuracies and QA code of 0 may indicate that only preliminary checking was done. QA codes for well site information, such as location, altitude, well depth, and construction parameters may also be added. (14.)

Correction of erroneous data should be done on a continuous basis to provide the best quality information. Inaccuracies should be corrected by examining paper copies of the original measurements and updating the database. This process is very time-consuming and all likely errors may not be discovered and corrected in a single go. Therefore, users feedback would help the system to single out anomalous data. Thus, it is in fitness of things to encourage users to bring anomalous data to the attention of system managers so that the errors could be corrected in the database. (15.)

EPILOGUE

In the next millennium we may talk of Transboundary Aquifers and Multinational Groundwater database in addition to the national groundwater database; as any system can not be developed in splendid isolation. The concept and existence of Transboundary Aquifers crossing the national boundaries will give rise to a more holistic approach of development in the groundwater sector resulting in Multinational Groundwater Data Base.

In that case the GW data has to be officially approved and archived by the CGWA and other International agencies (neighbouring countries of India) involved. By an international agreement the format of the reports has to be decided providing limited processing of groundwater data, but no discussion of the significance or ramifications of the data or figures. The reader must be at the liberty to derive independent conclusions from these data that do not reflect the official opinions, either expressed or implied, of the principal participants in such a study.

Transboundary Aquifers and Multinational Groundwater Data Base may form the thought for the day!

MODELLING GROUNDWATER RECHARGE PROCESSES

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ABSTRACT

Efficient planning and management of water resources needs precise estimation of groundwater potential of a region. This requires an estimation of groundwater recharge from different sources namely rainfall, canal systems and return flow from irrigated fields. In this paper various models available to represent different recharge processes are reviewed. Most of these models are applicable at a micro level. Thus, there is an urgent need to develop models for application at the regional level.

INTRODUCTION

Evaluation of groundwater potential is of vital importance in the assessment of a region's water resources. This requires an estimation of groundwater recharge from different sources, pumpage and resulting change in storage. On account of lack of proper assessment of recharge, there have been number of instances of over drafting or waterlogging in irrigated areas.

The processes by which the aquifer is recharged is not well understood and therefore, there is considerable difficulty in obtaining a good estimate of the groundwater potential. Herein the various methods used for modelling groundwater recharge process are reviewed.

Rainfall is the prime source of recharge to groundwater. The second important source is deep percolation from irrigated areas The irrigation may be by canals or by wells or tube wells. Seepage losses from canal distribution network are another source of recharge to groundwater. In addition, percolation from storage tanks, ponds and water harvesting structures also contribute to groundwater recharge. However, these have not been discussed in this paper.

RECHARGE FROM RAINFALL

The natural hydrological phenomenon of rainfall recharge is very complex to study, analyze, and evaluate due to variable nature of its input parameters in relation to the soil-vegetation-atmosphere system. According to the principles of the hydrological cycle, any rainfall occurring on earth's surface is presumed to disperse into interception or initial abstraction, infiltration into land surface, depression storage on the land surface, surface runoff or overland flow and evapotranspiration.

Rainfall infiltration primarily depends upon duration and intensity of rainfall, soil moisture characteristics, surface slopes, land use pattern, agronomic practices, weather conditions preceding, during and succeeding rainfall periods, and depth to water table.

Infiltration occurs mainly by diffusion, suction, and gravitation. Rainwater infiltrates into land surface both vertically as well as horizontally. The horizontal movement is due to suction of moisture by soil matrix. A portion of the infiltrated rainwater finally reaches the groundwater storage or aquifer which increases and improves the quantity and quality of the groundwater. This increase in the groundwater storage due to the naturally occurring rainfall infiltration in termed as 'rainfall recharge'. Ethirajan and Mishra (1985-86) have presented and excellent review on rainfall recharge to groundwater.

The recharge to groundwater from rainfall can be modelled by:

i) Water balance approach
ii) Water table fluctuation method
iii) Infiltration indices
iv) Empirical methods
v) Experimental studies
vi) Tracer techniques
vii) Vertical variation of soil moisture

Water Balance Approach

In this approach all the components of water balance equation, other than rainfall recharge, are estimated using relevant hydrological data by dividing the year into monsoon and non-monsoon periods. The rainfall recharge is estimated as residual of water balance equation.

Considering the various components, the terms of basic equation for groundwater balance can be written as (Chandra and Saksena, 1975):

$$R_r + R_c + R_I + I + S_I = S_e + O + CAP + T_p \pm \delta S_g \qquad (1)$$

where R_r is recharge from rainfall, R_c is recharge from canal seepage, R_I is recharge from irrigation water, I is inflow to the basin from other basins, S_I is influent seepage from streams, S_e is effluent seepage from streams, O is outflow from basin to other basins, CAP is evaporation from shallow water table areas due to the capillary rise, T_p is groundwater draft and δS_g is charge in groundwater storage.

A prerequisite for application of this technique is extensive and reliable data. The value of the water balance is thus dependent on the accuracy of the data. It is difficult to obtain estimate of some of the parameters and the errors can be reduced by selecting a time period over which the change in storage is small or components are not present. It is also desirable that the evaluation of parameters be carried out using as many independent parameters as possible.

Water Level Fluctuation Method

Groundwater levels rise during monsoon period is by and large due to rainfall recharge to the groundwater. The magnitude of rise depends on the specific yield of the formation materials comprising the zone of saturation. If the record of groundwater levels for pre-and post-monsoon period are available from adequately spaced observation wells with corresponding rainfall data, the rainfall recharge can be estimated by rewriting equation (1):

$$R_r = h * Sy * A + T_P + CAP + O + S_E - (R_c + R_I + I + S_I) \qquad (2)$$

where h is rise in water level in the monsoon season, Sy is specific yield, and A is area under evaluation.

Infiltration Indices

A reasonable approximation for rainfall recharge to groundwater can be made by use of infiltration indices. One of these is the $\in$ index, which is defined as the average rainfall intensity above which the volume of rainfall equals the volume of runoff. The volume of rainfall below the $\in$ index level, which does not appear as runoff represent infiltration, surface detention and evaporation. Since infiltration is the major component, it can be used as a means of assessing probable rainfall recharge to groundwater.

The $\in$ index is a function of storm duration and it tends to decrease as the storm duration increases. The $\in$ index curves can be established and calibrated from rainfall intensity data, and by comparing computed and observed runoff coefficient, estimated storm recharge, and piezometer response in a particular basin.

Empirical Formulae

Empirical relationship have also been developed for estimation of rainfall recharge. These formulae are generally derived from locally observed data and, thus, are not valid for universal application. One such formula proposed by Chaturvedi (1947) for Uttar Pradesh is:

$$R_r = 1.26\,(RF - 38)^{0.5} \tag{3}$$

where, R_r is rainfall recharge to groundwater (cm) and RF is annual rainfall (cm).

A similar formula proposed by Sehgal (1973) for the Punjab State is:

$$R_r = 1.58\,(RF - 41)^{0.5} \tag{4}$$

The Chaturvedi and Sehgal formulae imply that there will be no recharge for rainfall less than 38 and 41 cm, respectively.

The GWREC (1997) has suggested the following linear relationship between recharge and rainfall:

$$R_r = a\,RF \tag{5}$$

where, RF is annual (or seasonal) rainfall and a is rainfall infiltration factor (same for monsoon and non-monsoon rainfalls).

Table (1) gives the recommended value and range of infiltration factor for various type of formations. In case the normal rainfall during non-monsoon season is less than 10 per cent of the normal rainfall, the recharge during non-monsoon season may be taken as zero.

Experimental Studies

Field experiments may be conducted for estimating rainfall recharge. Double ring cylinder infiltrometer are commonly used to predict infiltration for ponded conditions. The main source of error with this technique is lateral divergence of the flow below the cylinder, which may be due to unsaturated flow or to restricting layers in the soil. Since this divergence will not occur when infiltration take place over a large area like a watershed, it will lead to overestimation of recharge. Moreover, surface infiltration is generally more variable than hydraulic conductivity lower down the profile, due to cumulative effect of raindrop and human compaction of the natural soil surface structure, and by vegetation cover.

Table 1. Recharge from rainfall.

S. No.	Formation	Recommended value (%)	Minimum value (%)	Maximum value (%)
(a)	**Alluvial areas**			
1.	Indo-Gangetic and inland areas	22	20	25
2.	East coast	16	14	18
3.	West coast	10	8	12
(b)	**Hard rock areas**			
1.	Weathered granite gneiss and schist with low clay content	11	10	12
2.	Weathered granite, gneiss and schist with significant clay content	8	5	9
3.	Granite facies like charnockite, etc.	5	4	6
4.	Vesicular and jointed basalt	13	12	14
5.	Weathered basalt	7	6	8
6.	Laterite	7	6	8
7.	Semi-consolidated sandstone	12	10	14
8.	Consolidated sandstone, quartzite, limestone (except cavernous limestone)	6	5	7
9.	Phyllites and shales	4	3	5
10.	Massive poorly fractured rock	1	1	3

Note: Usually, the recommended values should be used for assessment unless sufficient information is available to justify the use of minimum, maximum or other intermediate values.

Rainfall recharge can also be measured in the field with the help of lysimeters. These are round or square tanks that are filled with local soil and placed into the ground so that their surface is on the same level as that of surrounding land. A layer of fine sand or glass beads is placed on the bottom of the lysimeter tank to drain and measure the deep percolation water.

Another technique for measuring recharge rate is use of tensiometers. In this method, tensiometers are placed closely together at different depths in the representative soil profile. A soil area of several square meters at tensiometer site is flooded to saturate the profile to at least the deepest tensiometer. When all the water has infiltrated, the area is covered with a plastic sheet to prevent evapotranspiration, so that redistribution of water in the wetted zone is entirely due to downward movement. Downward fluxes can then be calculated from changes in the water content at various depths. Combining these fluxes with hydraulic gradients, as determined from tensiometer readings, enables the calculation of unsaturated hydraulic conductivity and evaluation of relation between K and θ. Once this is done, the plastic sheet is removed for normal conditions. Subsequently tensiometers are then used to evaluate deep percolation rate by multiplying vertical hydraulic gradient between lowest tensiometers by the average $K(\theta)$ value corresponding to the pressure head indicated by these tensiometers. The technique is restricted to relatively wet profile where, soil water pressure heads do not drop below about –0.8 m.

Tracer Techniques

Tracer techniques have been extensively used for the determination of rainfall recharge. The basis for recharge estimate using this technique is the piston flow mechanism. Environmental radio isotopes of H-3, C-14, Si-32, Kr-85, and stable isotopes of H-2, O-18 and C-13 have been found to have extensive application in groundwater recharge studies. Tritium tagging method (Zimmermann *et al.*, 1967) and the environmental tritium method (Munnich *et al.*, 1967) have been quite extensively used in India since mid 1970's for groundwater recharge estimates (Sukhija and Rama, 1973; Datta *et al.*, 1973; Sukhija and Shah, 1976; Athavale *et al.*, 1980; Gupta and Sharma, 1984). Athavale (1991) described the results of recharge measurements carried out in several basins spread all over India using injected tritium tracer technique. The broad pattern emerging from these measurements indicate an annual rainfall recharge of about 16 % in Indo-Gangetic alluvial tract and about 8 % in Peninsular hard rock areas.

Vertical Variation of Soil Moisture

In this method the recharge is estimated by studying the one dimensional vertical flow of water in the gravitational water zone, with its upper boundary at the ground surface and its lower boundary just below the water table.

RECHARGE DUE TO SEEPAGE FROM CANAL

In irrigated areas seepage occurs as water flows along the canals, distributories and field channels and recharges the aquifers (Fig. 2). Analytical solutions for steady state seepage from open channels have been developed by a number of investigators. Bouwer (1969) studied seepage from canals using numerical and analytical techniques. He covered a wide range of soil conditions, depths and shapes of the channel, and water table positions. For canals with thin layer of low permeability along their wetted perimeter (e.g. sedimentation of clay and silt particles or linings for seepage control) Bouwer gave the following equation for the seepage through the bottom and sides of a trapezoidal canal (Fig. 1):

$$I_s = \left(W_s R_a\right)^{-1}\left[\left(H_w - P_{cr}\right)W_b + \left(H_w - 2P_{cr}\right)\left(H_w / \sin\alpha\right)\right] \tag{6}$$

where, I_s is seepage rate per unit length of canal and per unit width of the water surface in the canal; W_s is top width of canal, R_a is hydraulic impedance, H_w is depth of water; P_{cr} is critical soil water pressure head, W_b is bottom width of the canal and α is side slope. For triangular canals, this equation is used with $W_b = 0$ and for rectangular canals, $\sin \alpha = 1$.

For a canal having hydraulic connection with underlying aquifer recharge due to seepage from unit length of the canal to aquifer can be assumed to have the following non-linear relationship (Rushton and Redshaw, 1979).

$$Q(t) = C_1 \left(1 - \exp(- C_2 (hr-h(o, t)))\right) \tag{7}$$

where, C_1 and C_2 are constants, hr is hydraulic head at the canal perimeter, h (o, t) is hydraulic head in the aquifer under the canal axis at time t. hr and h (o, t) are measured upwards from the impervious bed of the aquifer. The values of constant C_1 and C_2 are (Mishra *et al.*):

$$C_1 = K (B + AH) \tag{8}$$

$$C_2 = K_r / K (B + AH) \tag{9}$$

where K is hydraulic conductivity, B is width of the stream, H is maximum depth of water in stream and K_r is constant of proportionality known as reach transmissivity. For a stream with curved perimeter the parameter A is equal to 2. The K_r is estimated from:

$$K_r = \left[\frac{K}{\ln\left(0.5\left(\left(E + H\right)/R\right)\right)} \right] \tag{10}$$

where E is saturated thickness of the aquifer below the bed of the stream, R is radius of the equivalent semi-circular section of the stream and is equal to W_P/n; W_p is wetted perimeter of the stream.

Empirical Methods

Recharge from seepage from the canal distribution network is also calculated using empirical formulae based on investigations carried out to study the seepage losses. These formulae give the seepage losses in cubic meter per second per million square metre of the wetted area.

In Punjab, the losses in unlined channels are estimated as a function of discharge and are given by :

$$\text{Losses in cumecs / million Sq. metre of wetted area} = 4\ Q^{0.06} \tag{11}$$

where Q is the discharge in cumec.

The Ministry of Water Resources (GWREC, 1997) has recommended the following norms for estimating the recharge due to seepage from canal networks:

- For unlined canal in normal type of soil with some clay content along with sand: 15 to 20 ha–m/day/million square metre of wetted area of canal or 1.8 to 2.5 cumec/million square metre of wetted area.
- For unlined canals in sandy soils: 25 to 30 ha-m/day/million square metre of wetted area or 3 to 3.5 cumec/million square metre of wetted area.

- For lined canals and canals in hard rock area, the seepage losses may be taken as 20 % of the above values. The above values are valid if the water table is relatively deep. In shallow water table and waterlogged areas, the recharge from canal seepage may be suitably reduced.

Rushton (1986) has shown that if the lining is not perfect (assuming cracks and holes equivalent to 0.4 % of the perimeter), the seepage losses are about 75 % of the losses when there is no lining. Thus, the lining of canal is only successful when lining remains in perfect conditions.

RECHARGE DUE TO DEEP PERCOLATION FROM IRRIGATED FIELDS

Recharge to water table occurs in irrigated areas due to deep percolation. The amount that deep percolates depends on the flow rates, time of application, size of the fields, soil moisture characteristics, method of irrigation and depth to water table. Estimation of deep percolation is a complex problem and its solution requires a detailed study of the water balance in the study area. The recharge due to deep percolation can be determined as a residue of the water balance equation if all other components are known. Recharge can also be estimated using vertical variation of soil moisture approach described earlier, but losses from flooded rice fields require a more detailed analysis.

Rice is grown under wet land conditions in puddled fields. Puddling the bed of the field reduces the percolation and lysimeter studies suggest that the vertical percolation through puddled layers are usually less than 3 mm/day (Walker, 1984; Tuong *et al.*, 1994). However, measured percolation from the rice fields are far greater than the anticipated losses (Walker and Rushton, 1986).

Numerical models have indicated that the main source of the losses is flow through the bunds between the fields. Although the beds of the fields are puddled to reduce the downward percolation, puddling does not extend under the bunds. Fields studies have shown that the under bund percolation could be as high as 0.16 m^3 per day per metre of bund under ponding water depth of 10 cm (Tuong *et al.*, 1994). If the depth of water is reduced to 5 cm, the losses become 0.07 m^3 per day per per metre of the bund since the bund is no longer saturated across its full width.

Assuming saturated flow conditions and neglecting spatial variability inside the rice field, the vertical deep percolation can be computed as (Paulo *et al.*, 1995) :

$$Q_v = - K_v A\ (H/Z) \qquad (12)$$

where Q_v is vertical percolation, A is area of the rice basin, K_v is saturated vertical hydraulic conductivity and H is difference in hydraulic head between the water surface and the compacted layer or the water table. Further:

$$H = d + Z \qquad \text{when } Z < dw \qquad (13)$$

$$\text{or } H = d + dw \qquad \text{when } Z \geq dw \qquad (14)$$

where d is water depth in rice basin and dw is depth to water table. And:

$$Z = Z_l - Z_c \qquad (15)$$

where Z_l is average ploughing depth and Z_c is average hard pan depth.

Saleh (1989) developed a water balance model using one dimensional formulation of soil moisture from crop root zone to simulate the recharge from rainfall/irrigation that would replenish the aquifer. Khepar *et al.* (1999) have suggested the following non linear relationship for average rate of deep percolation (DP) per day (cm) and average depth of ponding (DPO) per day during crop growing season in case of sandy loam soil conditions:

$$DP = 0.4518\ (DPO)^{1.73} \qquad (16)$$

The above mentioned methods can be used to determine deep percolation at micro level. At regional level these methods are difficult to apply due to spatial variability of soil moisture characteristics, meteorological parameters, crop types, etc.

GWREC (1997) based on source of irrigation (groundwater or surface water), the type of crop (paddy or non paddy) and the depth of water table below ground level has suggested the use of following norms for estimation of recharge due to percolation from irrigated fields.

Table 2. Recharge as percentage of water application.

Source of irrigation	Type of crop	Water table below ground level (m)		
		< 10	10-15	> 25
Ground water	Paddy	45	35	20
	Non-paddy	25	15	5
Surface water	Paddy	50	40	25
	Non-paddy	30	20	10

Note : For surface water, recharge is to be estimated based on water released at the outlet. For groundwater the recharge is to be estimated based on gross draft.

CONCLUSIONS

Modelling groundwater recharge process from rainfall, canal distribution network and irrigated fields involve complex flow mechanism which are function of soils, vegetation, climatic and hydrogeologic characteristics of the basins. This paper has reviewed a number of models for recharge estimation to groundwater. Some of these models give an estimate of potential recharge. In many situations, this potential recharge has to move through the unsaturated zone until it reaches the water table. The actual recharge reaching the water table may be much less than the potential recharge due to the influence of unsaturated zone. Flow conditions within the unsaturated zone are far more complex than the flow mechanism in saturated zone. Since the computation of groundwater recharge is the most important aspect in groundwater resource estimation, considerable efforts must be made in modifying and refining the methods of its estimation on regional level.

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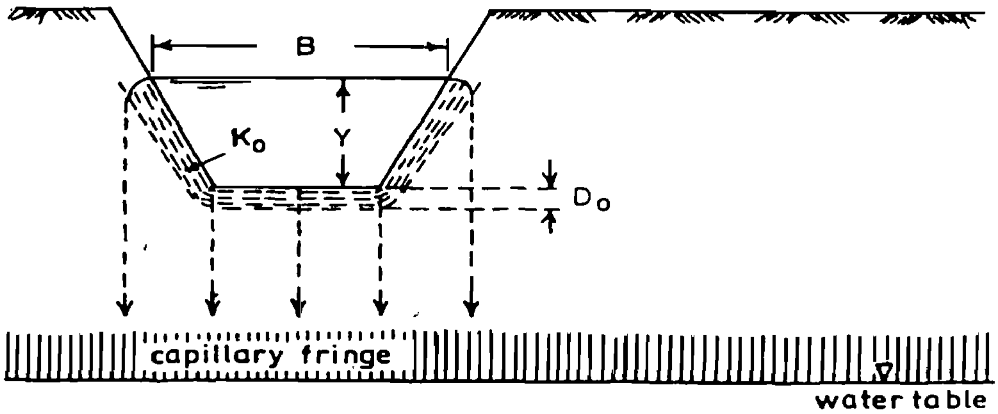

Fig.1 Geometry and symbols for seepage in canal with resistance layer at perimeter (after Bouwer, 1969)

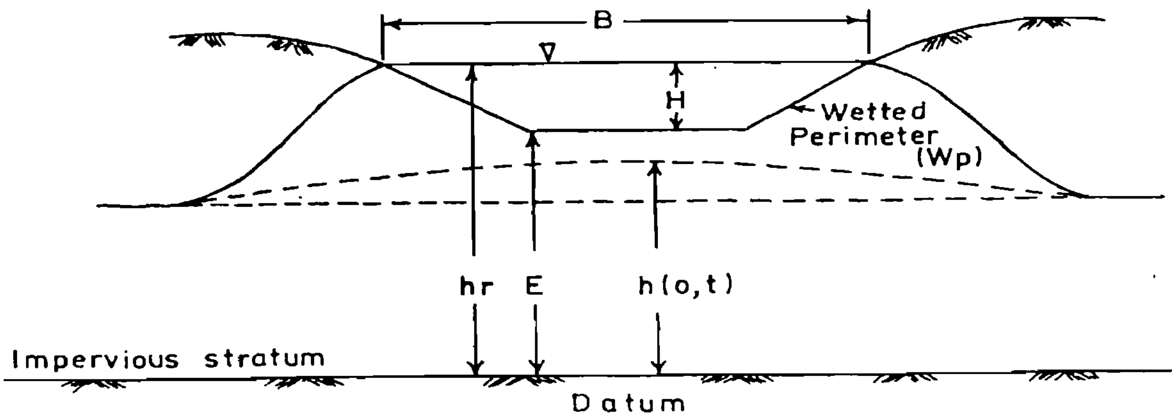

Fig. 2 A Canal hydraulically connected with aquifer

GROUNDWATER MODELLING IN HARD ROCK TERRAIN

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ABSTRACT

Hard rocks are complex and heterogeneous media where random fractures provide most of the porosities and permeabilities. Discrete models are more realistic for representing these heterogenities and spatial interconnectivities rather than homogeneous continuum porous media model. Although more advanced models from principles of statistical physics such as percolation theory, fractals and non equilibrium diffusion are available, a simple three dimensional channel network model for fractured hard rocks seems adequate for optimizing groundwater resource management, safe handling of nuclear wastes and for remediation of contaminant transport. These models are useful near field as well as far field regions of our interest. In the very far field regions, the more simplistic homogeneous continuum models based on Representative Elementary Volume (REV) could be adequate. Some details of channel 3D network model for fractured hard rocks are included here for optimal utility of groundwater resources. The channel 3D-network model is simple, flexible, and practical and can be tested with field and laboratory data for model validation and future use.

Keywords: fractured rocks, groundwater flow, 3D-channel network, modelling heterogeneous hard rocks, simulation models.

INTRODUCTION

Large tracts of Peninsular India comprises hard crystalline rock terrain having low porosity (less than 5%) and very low permeability (10^{-1} to 10^{-5} Darcy). These areas are drought prone and generally classified as semiarid to arid. Rainfall is characteristically low and wildly fluctuating hence requiring optimal management of groundwater resources for its municipal, agricultural and industrial sustenance and growth.

Geologically hard rocks are crystalline and compact rocks without layered (bedding, volcanic flows) structures which are not easily dissolved by weathering processes. Typically these hard rocks include fractured igneous rocks, fractured chert, fractured metamorphic such as quartzite, amphibolite, gneiss, etc. They are too complex and heterogeneous to model using concepts of simple and ordered structures such as continuum models. Discrete models are more realistic for representing the inherent heterogeneties and spatial dependence of hard rock porous media. These rocks are profitably modelled as fractured media with pore network models with pore nodes and pore throats. Modern concepts of statistical physics for disordered media can be applied to explain flow, dispersion and displacement processes through fractured hard rocks. The main concepts used include (i) percolation describing topology and interconnectivity (disordered node and throat characterization) (ii) fractals describing scale dependence and (iii) diffusion aggregation describing non-equilibrium growth.

Groundwater modelling techniques include: (i) Flow models and (ii) Solute transport models or (iii) Physical models and (iv) Mathematical models. We illustrate only mathematical models applied to flow and/or solute transport problems. The modelling involves the following steps:

1. Examination of physical problems and underlying physical behavior of the system in relation to cause and effects and systems operation.
2. Translation of physical problem into mathematical forms, making appropriate simplifying assumptions and developing the governing equations.

Solutions to mathematical modelling can be obtained by analytical methods for simple homogeneous porous media - problems, otherwise by using numerical methods for complex problems. Access to digital computers is a must for solutions of any mathematical and/or simulation technique. Models are essential for performing complex analysis and in making informed predictions. In general, fewer the simplifying assumptions made, the more complex is the resulting model. Hence, a model can always be improved as per our objectives and precision required.

The main objectives of groundwater modelling especially in hard rock regions are for predicting the consequences of a proposed action:

(i) mechanisms of operation of groundwater reservoir
(ii) response under various possible future conditions by simulations and thus avoiding hazard and costly real experimentation

(iii) checking and verifying new theory and safety requirements

(iv) for purposes of instruction and demonstration.

Flow and contaminant transport in fractured hard rocks are and will be of great interest especially for emergency municipal water storage and supply and for disposal of radioactive and hazardous chemical wastes.

GEOLOGICAL ASPECTS OF FRACTURES IN HARD ROCKS

Fractures in hard rocks develop by processes of rock formation and/or by later tectonic stresses and create secondary porosity. Interconnected fractures give a network of pore nodes and pore throats for groundwater flow. The fracture surfaces are rough with some zones connected (no porosity), others remaining open for flow and still others are dead end (no flow). The scale of study is important for modelling with reference to a source; as in near field single to a few fractures are relevant. Whereas in far field network model of several intersecting fractures with nodes and throats are relevant. In very far field the entire flow can be modeled as a continuum (equivalent homogenous porous medium). In most practical hard rocks modelling problems we are interested in the near field as well as far field rather than very far field where continuum approximation may be appropriate. A study of fracture sets and systems in hard rock areas would be of great value for ascertaining the area and vertical distribution of porous and permeable zones. For a given fracture spacing the probability of interaction in a bore hole decreases with increase in dip amount of fractures and is maximum for sheet fractures. Water table conditions can be expected in sets of vertical fractures or in shear zones with several sets of intersecting fractures. If the fractures are inclined and widely spaced, and then there may be little connectivity, which yields confined conditions. Allen and Davidson (1982) have reviewed the groundwater resources in fractured rocks in western Australia, which has similar geology as Peninsular India. Carla and Sharp (1992) have described the relationship between permeability and fracture patterns in volcanic of welded Santana Tuff. Snow (1965) introduced the parallel plate fissure models with networks to simulate flow in fractured rocks. Shapiro (1987) has developed transport equations for fractured aquifers and these could be useful for nuclear waste disposal as well as for contaminant remediation (Fetter, 1993)

During 1974-75, the Canadian assisted UNDP project in India investigated hard rock terrain to understand the control of fractured zones over aquifer potential (Brizkishore et al., 1982).

Karanth (1987) include much information on occurrence, developments and management of groundwater in hard rock areas of India. However, little research has so far been made on groundwater flow and transport modelling through fractured hard rocks of India (Ratha and Sahu, 1995)

MATHEMATICAL MODELLING ASPECTS

Primary permeability of hard rocks range from 10^{-2} to 10^{-16} cm^2 and corresponding hydraulic conductivities are 10^{-8} to 10^{-11} cm/sec (Freeze and Cherry, 1979). Secondary permeability due to interconnected fractures increase the effective hydraulic conductivity upto 5 orders of magnitude (Gale, 1982) depending on rock types, number of fractures and fracture intersections etc. However, if solution occurs within the fractures, permeability can increase to a much larger magnitude. Fracture flow models (excluding conduit flow) assume that fracture apertures and flow velocities are small, so that Darcy's law applies. Conceptually fractured rock can be modelled as (i) Discrete Fractures (DF), (ii) Dual Porosity (D.P) and (iii) Equivalent porous medium (EPM).

EPM is a continuum and a Representative Equivalent Volume (REV) is characterized by equivalent hydraulic parameters. EPM is a good model for very large scale and regional flow systems but poor for realistically simulating flow and transport in fractured hard rock acquifers. Hence, this model will not be considered further. Sahimi (1995) and Sahu (1999) have reviewed advanced techniques of mathematical modelling of porous and fractured rocks where percolation models were found to be useful.

(i) Discrete Fracture (D.F) Model

Water move through fracture network only and hence it is useful for crystalline hard rocks having no primary porosity. The total quantity of flow (Q_f) is given by:

$$Q_f = 2b\omega K_f (dh/dl) \qquad (1)$$

Where 2b is fracture aperture; ω is fracture width; K_f is hydraulic conductivity of fracture; dh/dl is slope of hydraulic head (h); l is length of flow.

Since

$$K_f = \rho g(2b)^2/12\mu \qquad (2)$$

where ρ is density of water and μ is fluid viscosity. We obtain Q_f as directly proportional to b^3. This model is computationally rather intensive and is useful when aperture 2b is less than 10 micrometer. Therefore, this model has so far been used only for a few research problems.

(ii) Dual Porosity (DP) Model

Aquifer may have primary porosity, on which fracture porosity is superimposed. Therefore, there is exchange of water to and fro from the fracture to primary pores of rock matrix. DP models have been confirmed through aquifer test results. Finite element dual porosity model has been applied to simulate solute transport in oil shale. The Dual Porosity model is applicable to fractured oil shale. The DP model is applicable to fractured soft rocks, fractured volcanic, fractured sedimentary rocks etc., but not to fractured hard rocks with no primary porosity in matrix.

(iii) Channel Network Model

Fracture openings are potential but not necessarily actual paths of flow as there may be real connectivity between the fractures or as water particle may choose the easiest flow path under prevailing pressure gradient (among several potential paths). We assume fluid flow and solute transport take place in a network of channels formed by intersecting fractures. Water flow in fractured media flows through channels in the plane of the fractures and only a small part of the fracture conducts most of the water flow. Thus, both fracture intersection as well as channels in the fracture planes play important roles in allowing water flow. Every channel member can connect to any number of other channels but up to six channel member are usually the upper limit as other fracture conductivity could be so low that these could be neglected. The permeability tensor k_{ij} in 3D has nine components and three components form the source face while the remaining six components could possibly form the distribution flow channels. Each node is connected up to six other nodes and channel conductance are log normally distributed with mean and standard deviation. Different values for mean conductance are to be used depending on whether the channel member is located in a fracture zone (high conductivity) or in good rock (low conductivity). In these senses, channel network model is included under percolation type models (Sahu, 1999).

For fluid flow at steady state under laminar conditions:

$$Q_{ij} = c_{ij} (P_i - P_j) \tag{3}$$

Where c_{ij} is conductance between i and j; P is Pressure at i & j; Q_{ij} is quantity of flow. The pressure field is computed by using the mass balance at each intersection point:

$$Q_{ij} = 0 \qquad \text{(4), for all i}$$

This method of channel network modelling is due to Gylling, Moreno and Neretnieks (1998). In a flow channel, diffusion is perpendicular to the channel surface and a simple analytical solution for cumulative residence time (F) is given by:

$$F = \mathrm{erfc}\left(\frac{(K_d D_c \rho_s)^{1/2}}{(t - t_w)^{1/2}} \frac{LW}{Q} \right) \tag{5}$$

where t_w is water plug flow residence time; K_d is sorption coefficient of solute species; D_c is effective diffusion coefficient and LW is flow wetted surface.

The travel time for each particle in a channel is determined by choosing a random number between 0 to 1 and substituting in for F in the equation (5) and then solving for t. This is the method of particle tracking (Yamastuta and Kimura, 1990).

The main difficulties with channel network model are the following:

(a) Input hydrogeological data must be obtained by expensive field tests such as bore hole radar, spinner hydraulic and tracer tests etc.
(b) No techniques are so far available to characterize channel length and channel width distributions.

The chief advantages of channel network model for fractured hard rock are:

(a) simple and flexible model and code CHAN3D is available for computer simulation and management of groundwater resources

(b) It simulates field experiments of solute transport and flow equations to determine safe repository of hazardous wastes.

It is suggested that more theoretical studies and practical experiments be undertaken with the 3D-channel network model especially to develop techniques for characterizing channel length and width distributions in fractured hard rocks.

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GROUNDWATER FLOW MODELLING IN HARD ROCK TERRAIN

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INTRODUCTION

Hard rock is a very general and vague term for all kinds of igneous and metamorphic rocks, typical for all shield areas (oldest part of continents) of the earth. Hard rocks are sometimes defined in UN-family of publications as "compact non-carbonate, non-volcanic rocks". The reason for exclusion of the carbonate and volcanic rocks is that they may have a primary porosity, which generally is not present in igneous and metamorphic rocks. The most common hard rocks are gneiss and granite. Narasimhan (1972) included igneous, and metamorphic rocks as well as highly compacted and indurated sedimentary formations under the term hard rock. Hard rocks are characterized by fracture porosity resulting from the presence of joints, fissures, solution channels and other such secondary openings.

In India about 73% of the area is occupied by hard rocks (Fig. 1). Based on lithology and structure, hard rocks are divided into four main categories:

- The crystalline rocks including granite, gneiss, schist, amphibolite and associated intrusive rocks.
- The effusive lava flows, e.g. basalt (Deccan Traps).
- Compact sedimentary formations, particularly of the Cuddapah and Vindhyan systems and to a lesser extent, the Gondwana system and compact sediments in the Himalayas.
- The carbonate rocks which are characterized by the development of solution channels.

Crystalline Rocks

The crystalline rocks, comprising varieties of granite, gneiss and schistose formations, occupy a major part of the Indian Peninsula (Pascoe, 1968). These mainly show foliation joints, transverse joints and sub-horizontal sheet joints. As these rocks are rich in aluminous silicates, these are highly susceptible to disintegration and decomposition by the agents of weathering. Thickness of zone of weathering is more in the area of low relief in comparison to the areas of high relief. Thickness of weathered zone varies from a few centimeters to as much as 30 m or even more.

The Effusive Lava Flows

The basaltic lava flows of Deccan trap, occupying an area of about 500,000 km^2, represents sub horizontal to horizontal lava flows (Fig. 2). These are massive and fine-grained as well as highly vesicular and amygdular. Quite often these include Inter-Trappean formations like sandstone, limestone and clay. The thickness of individual flow may vary from less than a meter to over 30 m. The opening includes joints, vesicles and cooling cracks, faults and shear planes. Depth of weathering is controlled by individual flow and it may vary from less than a meter to about 20 m.

Compact Sedimentary Formations

Cuddapah and Vindhyan systems represent a vast area of highly compact sedimentary formations, comprising a variety of quartzite, sandstone, shale, and limestone. Due to their bedded nature and alternation of layers of varying compactness, the types of joint systems that developed in these formations are difficult to describe. Being themselves the product of weathering and transport, sedimentary rocks are usually less susceptible to weathering than igneous and metamorphic rocks. As such the depth of weathering in these rocks is relatively small.

Carbonate Rocks

In India, carbonate rocks, comprising limestone and dolomites, are known in the Archaeans, in the Cuddapah and the Vindhyan formations as well as in Mesozoic and Tertiaries. In Karstic tracts, large openings in the limestone are created by enlargement of fractures and fissures by solvent actin of groundwater. However, presence of large solution channels in these has been reported from very few places, e.g. Kurnool rocks in Andhra Pradesh, in Jaisalmer, Rajasthan, Mirzapur, in U.P. and Kopili limestone in Assam.

OCCURRENCE OF GROUNDWATER IN HARD ROCKS

Regime of groundwater in hard rock areas is strikingly different from the unconsolidated and semi-consolidated sediments. Hard rocks possess secondary porosity which are of two types, firstly, joints, fissures and fractures as a result of tectonic activities and secondly inter-granular porosity due to action of weathering agents. Occurrence of groundwater varies from shallow to deep and its movement is controlled largely by the topography. The flow pattern gets modified due to presence of natural barriers like dykes and fresh quartz veins while faults and shear zones may act either as conduits or barriers, depending on their location in relation to groundwater flow paths. In weathered zones, groundwater occurs generally under unconfined conditions and movement is restricted to drainage divide to valley base. In Karstic limestone it is the nature of solution channels that control groundwater movement rather than the surface topography.

GROUNDWATER MODELLING IN HARD ROCK TERRAINS

Aquifer modelling in general, aims at representing the natural groundwater regime by an equivalent system which may be effectively used for the prognosis of aquifer response to probable stresses. The initial stage of modelling involves the collection, analysis, interpretation, and conceptualization of the vital parameters of the hydrogeologic system. The conceptualization is necessarily based on the simplification and abstraction of available data. This is inescapable in view of the inadequacy of data on the one hand and requirements of mathematical tractability of the resultant model on the other. In case of the fractured formations, the process of conceptualization is difficult. Abrupt discontinuities and wide variations in hydrogeologic properties, even in the same formation defy, at times, even an approximately correct physical description of the system. Quite often one does not have any quantitative information on density, disposition, size and connectivity of fractures, which primarily determine the utilizable groundwater resources in a fractured aquifer.

Despite these difficulties, there has been an increasing awareness of the need to study and assess the fractured aquifers in view of their growing importance as potential source of water for various uses. Specially, in the Indian context where more than two-thirds of the land is covered by hard rock formations, such studies assume even greater significance. Large chunk of information on fluid flow through fractured rocks comes from petroleum industry as many oil wells are located in these rocks around the world.

Streltsova (1976) has broadly classified the fractured formations into the following four categories (Fig.3) for the purpose of modelling:

- Purely fractured formations wherein the porosity is entirely due to fractures and the matrix is impervious.
- Fractured formations whose conducting properties are associated mainly with fracture permeability while storage properties are related to the primary porosity.

- Doubly porous formations when the hydraulic properties of the blocks and fractures are of the same order.
- Heterogeneous formations wherein the fractures are filled with silty clays or fine sands and the flow domain consists of multiple pervious saturated blocks separated by interconnected passages of relatively low permeability.

There has been tremendous progress in numerical modelling of groundwater flow since the late 1960's, which has facilitated study of regional groundwater problems involving, non-homogeneity, anisotropy, pumping, recharge and interaction with streams and canals. While these analytical and numerical models have been successfully applied for a number of field situations, there has been a constant and inconclusive debate on the applicability of porous media flow concepts for hard rock aquifers (Streltsova, 1976; Sridharan *et al.*, 1980). The obvious difference between hard rock formation and the simple grains-pore picture and the presence of fracture, which act as planes of mechanical discontinuity have raised basic questions on the validity of continuum approach based on concepts of flow through porous media.

Conceptual Models

Broadly, there have been two approaches in the study of groundwater flow in hard rock areas. The first approach concentrates on the effect of fractures on the flow assuming that all the flow practically occurs through the fractures. One extreme view of this approach is the network model wherein the system is treated as a network of fractures surrounded by impervious blocks. This is perhaps the most impracticable of all hard rock aquifer models as it requires data on geometry of the fracture system and friction factor of the individual fractures. Besides, the blocks surrounding the fractures may rarely be impervious.

The second approach for modeling hard rock aquifers is the continuum approach similar to the classical study of flow through porous media. However, an attempt is made to incorporate the specific features of flow through a fissured rock. This lies in explicit recognition of the existence of two interconnected media, namely the fractures and the surrounding pervious blocks. Models of this category include the double-permeability-storativity model developed by Barenblatt *et al.* (1960), combined continuum-discrete fracture model of Shapiro and Andersson (1983), and adoption of classical porous media flow models. In the later category, leaky aquifer and unconfined aquifer models can be used for modelling the fractured rock system and weathered zone aquifer, respectively. There is a great deal of similarity between the double-permeability-storativity model and the classical leaky aquifer model. Thus, in reviewing hard rock aquifer models developed from considerations of local groundwater flow, one should consider the compatibility of the model for regional applications.

Fracture Based Models

Fracture based models concentrate on the study of fracture distribution and its properties. Snow (1969) used a model based on parallel plate openings to simulate real fractures. Some properties of permeable fractures are arrived at based on this idealization. Kiraly (1971) used a two dimensional electric analog model to simulate heterogeneous, anisotropic, fractured media. Models of fractured media, consisting of single fracture of given extent and orientation have been developed to predict a fractured reservoir performance (Scott, 1963; Russel and Truitt, 1964). Russel and Truitt (1964) have studied the transient pressure behavior of a well through a single plane vertical fracture, based on finite difference technique. The analysis neglects effect of pressure drop within the fracture and flow into the well bore other than from the fracture. Type curves are presented for different values of (lateral) fracture penetration. It is concluded that in a vertically fractured system, flow in the region nearest to the fracture is practically linear, whereas farther away from the fracture essentially radial flow prevails. These solutions for a single fracture through the abstraction well are more relevant to oil wells as hydraulic fracturing is used as a completion and stimulation technique in low permeability oil reservoirs. The case of linear flow towards a fracture surface, as against the normally assumed radial flow towards the pumping well, was also studied by Jenkins and Prentice (1982). In all these solutions, the permeability of the fracture is assumed many orders of magnitude greater than the block.

Summers (1972) gave an empirical equation for specific capacity of wells in crystalline rocks in terms of fracture frequency, depth of well and maximum depth of fracturing. In general, fracture based models are of a restricted nature and site specific and have not reached a stage where these can be applied widely.

In situations where explicit knowledge exists about the location and geometry of each fracture, discrete fracture approach has also been used . This is particularly appropriate to analyze flow regime close to the source of perturbation. Studies by Baker (1955), Huitt (1956), Snow (1968), Wilson and Witherspoon (1970), Gringarten *et al.* (1974), and Gale

(1977) are some of the significant ones devoted to the analysis of fluid flow adopting discrete fracture approach. Neuzil and Tracy (1981) have studied flow through fractures by treating these as a set of parallel plate openings, generally with different apertures. Raghavan (1977) has given a review of studies based on this approach.

Double-Permeability-Storativity Model

A schematic diagram of the double-permeability-storativity model is shown in Fig.4. In this model (Barenblatt *et al.*, 1960), the fractured rock system is represented by two overlapped continua of fractures and the surrounding pervious blocks. The permeability of the blocks is small in comparison to that of fractures. During pumping, water is first released from fractures and a pressure difference is created between the fractures and the surrounding blocks. Consequently, water moves from the blocks to the fractures, similar to leakage from aquitard to aquifer in a semi-confined aquifer. Barenblatt *et al.* (1960) handled the problem by introducing mean characteristics of storativity and hydraulic conductivity for the fractures and blocks *at a point,* the point being sufficiently large compared to the dimensions of the blocks. Also at each point in space two pressures are considered, viz., pressure in the fractures and in the blocks. Under pumping there is transfer of water from the blocks to the fractures. Each elementary block volume is conceptualized as containing a large number of fissures and a large number of solid blocks. The interaction at any point between the two continua is defined by a non-linear fluid transfer function, which depends upon the potential difference between them at the location of interest and the hydraulic conductivity and geometry of porous blocks. It should, however, be clear that the existence of two potentials at a single point should be regarded mainly as a mathematical artifice and not a physical reality.

The approach known as double porosity model has been employed by several workers in analyzing well test data from naturally fractured reservoirs (e.g. Warren and Root, 1963; Odeh, 1965; Kazemi *et al.*, 1976). This approach has also been applied to general aquifer studies in fractured rocks, among others, by Duguid and Lee (1977) and O' Neill (1977) using finite element technique and by Kent Thomas *et al.* (1983) using finite difference technique.

One of the important studies among the finite element technique was provided by Huyakorn *et al.* (1983). A brief introduction of the technique is given below. The vertically averaged equation of flow in a fractured continuum can be written as:

$$\frac{\partial}{\partial x_i}\left[T_i \frac{\partial h}{\partial x_i}\right] S\frac{\partial h}{\partial t} - Q_t - q = 0 \qquad (1)$$

where i=1,2, h is the hydraulic head in the fracture, T_i and S are the fracture transmissivity and storativity respectively, Q_t is the volumetric rate of fluid transfer from porous matrix blocks to fracture per unit area, and q is the volumetric rate of fluid flow per unit area via sinks (or sources).

The term Q_t which represents the interaction between porous matrix and the fractures needs to be calculated. For a simple quasi steady-state fracture model, it is not an explicit function of time and can be expressed as:

$$Q_t = Q_L \sigma^2 (h'-h) \qquad (2)$$

Where h' is the average head in the rock matrix, σ is the surface area of fractures per unit volume of the porous medium and Q_L is the leakage parameter assumed to be constant. This, in turn, is governed by the mass balance equation as:

$$S'\frac{\partial h'}{\partial t} = Q_L \sigma^2 (h'-h) \qquad (3)$$

where S' is the storativity of the rock matrix. The other models considered by Huyakorn *et al.* (1983) are unsteady parallel fracture model and the unsteady blocky fracture model. The latter is an ingenious representation of the discrete matrix blocks by a series of spheres. The number of these spheres is chosen in such a way that the secondary fracture porosity is the same as that of the actual fractured porous medium. The fluid transfer function Q_t is calculated in terms of a convolution integral, which may be substituted in equation (1). The resultant equation is solved using Galerkin finite element approximation. Another numerical method given by them is to use the Galerkin finite element approximation in conjunction with a one-dimensional finite difference approximation; the former to handle the flow in the fractures while the latter in matrix blocks. They showed that a greater accuracy is achieved by the combined finite element-convolution integral technique.

The integral finite difference technique originally developed by Edward (1972) for heat transport problems was applied by Narasimhan and Witherspoon (1976) to analyze groundwater flow problems. Narasimhan (1983) has used it to study a number of fracture configurations. The starting governing equation in the integro-differential form are derived from the law of mass conservation. Under this scheme the entire flow region is discretised in N domains; each sub-domain will have a volume element in the fracture continuum and another in the porous matrix. Thus, there will be a total of 2N volume elements and correspondingly, there will be 2N simultaneous equations. These equations have been solved by using a mixed explicit-implicit approach.

Narasimhan (1983) has tested this technique for a number of simple models, which are analytically tractable and found the method yielding correct results. He has also simulated a hydraulic fracturing experiment and horizontal fractures separated by porous blocks.

Solutions for draw down in the fractured aquifers in the vicinity of a well pumped at a constant discharge have been obtained by Warren and Root (1963) and Kazemi *et al.* (1969) using double permeability-storativity model. Their solution is based on the following assumptions:

- Darcy's law is valid in both the blocks and the fractures.
- The transfer of water from the blocks to the fractures is proportional to the pressure difference between the blocks and the fractures.
- The fluid is considered slightly compressible so that the relationship between density and pressure is linear.
- Flow through the blocks (other than the transfer of water from blocks to the fractures) is considered negligible.
- Radial flow is valid.

Based on these assumptions, the solution for draw down in the fissures is obtained for a confined aquifer (Kazemi et al, 1969). It is shown that for large values of time, the draw down is identical for a homogeneous aquifer with an equivalent transmissivity, $T_1 = T_2$ and storativity $S = S_1+S_2$. Here subscript 1 refers to the blocks and 2 refers to the fractures. The transmissivity and storativity are defined as in the case of porous media flow. During early stages of pumping, the solution for the fractured rock system depends on two additional parameters ω and λ defined by:

$$\omega = S_2/(S_1+S_2) \qquad (4)$$

$$\lambda = \alpha[T_1/T_2] \qquad (5)$$

where α refers to the leakage parameter for flow from blocks to fractures.

Based on similar concepts, Streltsova (1976) discusses the hydrodynamics of groundwater flow in a fractured formation by distinguishing fissure flow and pore flow. Boulton and Streltsova (1977) have considered two models of double-permeability-storativity system (Figs. 5a and 5b) and obtained solutions for draw down in the blocks and the fissures. In both the models, the fracture and pervious blocks are taken to be aligned horizontally. In the first model (Fig. 5a), the well is screened along both the block and fissures, so that there is lateral contribution in the block also. The discharges per unit length for block and fissure zone are assumed to be proportional to the respective permeability. In the second model (Fig. 5b), the well is taken to be cased along the block, so that flow in the block may be treated to be vertical. In both the cases, vertical gradient in the fracture is ignored as the fracture thickness is treated very small compared to the block thickness. Darcy's law is assumed to be valid both for fissure and block flows.

A natural extension of the double porosity model is the multiple continuum approach where in a fractured formation is represented by a number of interacting continua. In other words, the porous matrix continuum and the fractured continuum can each be divided into several sub-continua for a better description of the spatial variations in each primary continuum (Narasimhan, 1982). A multiple continuum approach may, however, need a formidable computational effort.

Leaky Aquifer Model

While there has been an extended debate on the applicability of classical well field solutions to hard rock areas, simultaneously some of the simplest of these solutions have been used to interpret field observations in hard rock areas (Zdankus, 1974; Adyalkar and Mani, 1974;

Uhl and Sharma, 1978; Deolankar, 1980). It appears that the Theis and Jacob solutions or their anisotropic counterparts for draw down and recovery, are still the most widely used for analyzing field data in hard rock areas in India. Considering the heterogeneity in hard rock areas, it may be surmised that these solutions oversimplify the picture. Among the classical models, it is the leaky aquifer concept, which might be most suited for application to hard rock aquifers.

The double-permeability-storativity model of Boulton and Streltsova (1977) shown in Fig. 5b is practically identical to the leaky aquifer model of Hantush (1964) with a confined, compressible aquitard. The assumptions listed in the previous section for Warren and Root (1963) solution for the fractured rock system also confirm the conceptual similarity between the double-permeability-storativity model and leaky model. The leaky aquifer model proposed for hard rock areas is shown in Fig. 6. It may be seen that this differs from the schematization of Boulton and Streltsova (1977) shown in Fig. 5b, in that the aquitard is treated as unconfined. Thus, the weathered zone above the fracture is treated as a composite unconfined aquitard, while the deeper fracture zone is treated as an aquifer.

Cooley (1972) has shown that Boulton's convolution integral can be used as a source term in the aquifer differential equation to represent the influence of water table aquitard on the aquifer. These findings perhaps explain why the draw down curve in hard rock aquifer fits well with Boulton's type curves. The latter can be looked upon as a solution for unconfined or leaky aquifers.

Mohan Kumar (1984) obtained a rigorous numerical solution for the aquifer-water table aquitard problem. His model is of a quasi three-dimensional nature, which takes into account vertical variations of head in the aquitard. The water table is treated as an unknown boundary. The compressibility of the aquitard is also considered. Mohan Kumar (1984) compared the results from the rigorous numerical analysis with those from an approximate model for the water table aquitard (Sridharan *et al.*, 1980) and concluded that for regional modeling, the approximate model is acceptable and saves computer time very significantly. The approximate model ignores aquitard compressibility and takes the leakage from aquitard to aquifer directly proportional to the difference between the water table head and aquifer head.

Dug Well Model

In many hard rock areas of India, groundwater utilization is essentially through dug wells, which tap the upper weathered zone. Even in situations where bore wells have been successful, groundwater extraction from dug wells can not be ignored. Thus, modelling the shallow weathered zone aquifer is of practical interest. An unconfined aquifcr model may be suitable for this purpose if well storage factor is taken into account.

Boulton and Streltsova (1976) obtained an analytical solution for the draw down in the vicinity of a large diameter pumped well in an unconfined aquifer. However, as in all analytical solutions for unconfined flow, the free surface boundary condition is approximate. The solution of Boulton and Streltsova (1976) indicates that for aquifers with very low vertical hydraulic conductivity, the type curves for the unconfined aquifer are indistinguishable from those for a confined aquifer developed by Papadopulos and Cooper (1967). Boulton and Streltsova (1976) suggest that the type curves for confined aquifer may be used for unconfined aquifer also for analyzing early time draw down data. The unconfined aquifer model for dug wells is shown in Fig. 7. The aquifer contribution to total pumping varies during pumping depending upon the permeability of the aquifer. The typical variations in aquifer contribution are given in Fig. 8. The solutions of groundwater flow to a large diameter well under different hydrogeological situations presented by Chachadi (1989) can be used to solve many of the flow problems in the hard rock terrain.

Combined Continuum-Discrete Fracture Model

An integrated approach by suitably combining the two representations viz., the discrete fractures and the continua has been put forth by Shapiro and Andersson (1983). In regions where fractures can be explicitly defined, one should take full advantage of the available geologic information and incorporate the same in the model study. In other areas where interconnected fractures are known to exist but cannot be explicitly located and described, continuum representation of the medium is adopted by employing dual porosity model.

Shapiro and Andersson (1983) have used a boundary element method (Brebbia, 1978) in handling a coupled discrete fracture-continuum model. They have shown that highly complex fracture geometry may be considered by this approach, since fluid responses in the porous rock are described with a set of linear equations written only in terms of the hydraulic and fluid mass flux at the boundaries between the porous rocks and the fractures. Discretisation is required only along the fractures alleviating the need of internal discretisation of the host rock, which is required while using either finite difference or finite element methods.

Single Continuum Model for Regional Flow Simulation

For a large-scale area flow simulation, assumption of an equivalent single continuum, which could be treated as a porous medium, seems to be justifiably reasonable (Huyakorn *et al.*, 1983). The underlying assumptions are that the various heterogeneties and discontinuities smooth out over sufficiently large blocks of rocks and the flow velocities obey Darcy's law. These assumptions are tenable if the fractures are numerous and they are randomly oriented and scattered. One can regard the single continuum representation to be valid in the same statistical sense as the pore space interlacing soil and rock formations are represented by a porous continuum.

Once such an equivalent continuum is defined, the existing techniques developed for simulation of porous media can be applied for its modeling. It should, however, be borne in mind that the use of such a model will be restricted to finding aquifer response in terms only that property for which the equivalence has been defined (Sagar and Runchal, 1982). Long *et al.* (1982) have dealt with porous media equivalent for networks of discontinuous fractures. They have carried out a numerical study to find various conditions viz., fracture density, aperture distribution, fracture orientation, and sample sizes, under which a fractured rock system may be regarded to behave as homogeneous, isotropic media. Using single continuum approach Gupta *et al.* (1980) have carried out a regional aquifer modeling study in a granitic terrain in Andhra Pradesh where groundwater is known to occur in the unconsolidated weathered zone as well as in the underlying fractures in the granites.

CONCLUSIONS

An overview of the groundwater flow models for hard rock terrain indicate that there exist potential methods for simulation of groundwater flow in fractured aquifers. However, there has not been a matching developments in techniques for the collection of hydrogeologic data. Estimation of hydrogeologic parameters through pump tests are required to be made more meaningful through numerical analysis. A continuum approach is useful for the study of groundwater flow regime on a regional scale. However, in problems like waste disposal where one requires a more deterministic model, explicit data on the fractures are to be collected. It is shown that the double porosity and leaky aquifer models have considerable similarity and either of these models may be used to describe thc weathered zone and fractures. For modelling dug wells tapping the weathered zone, it is proposed that the confined aquifer model can be used for an unconfined aquifer.

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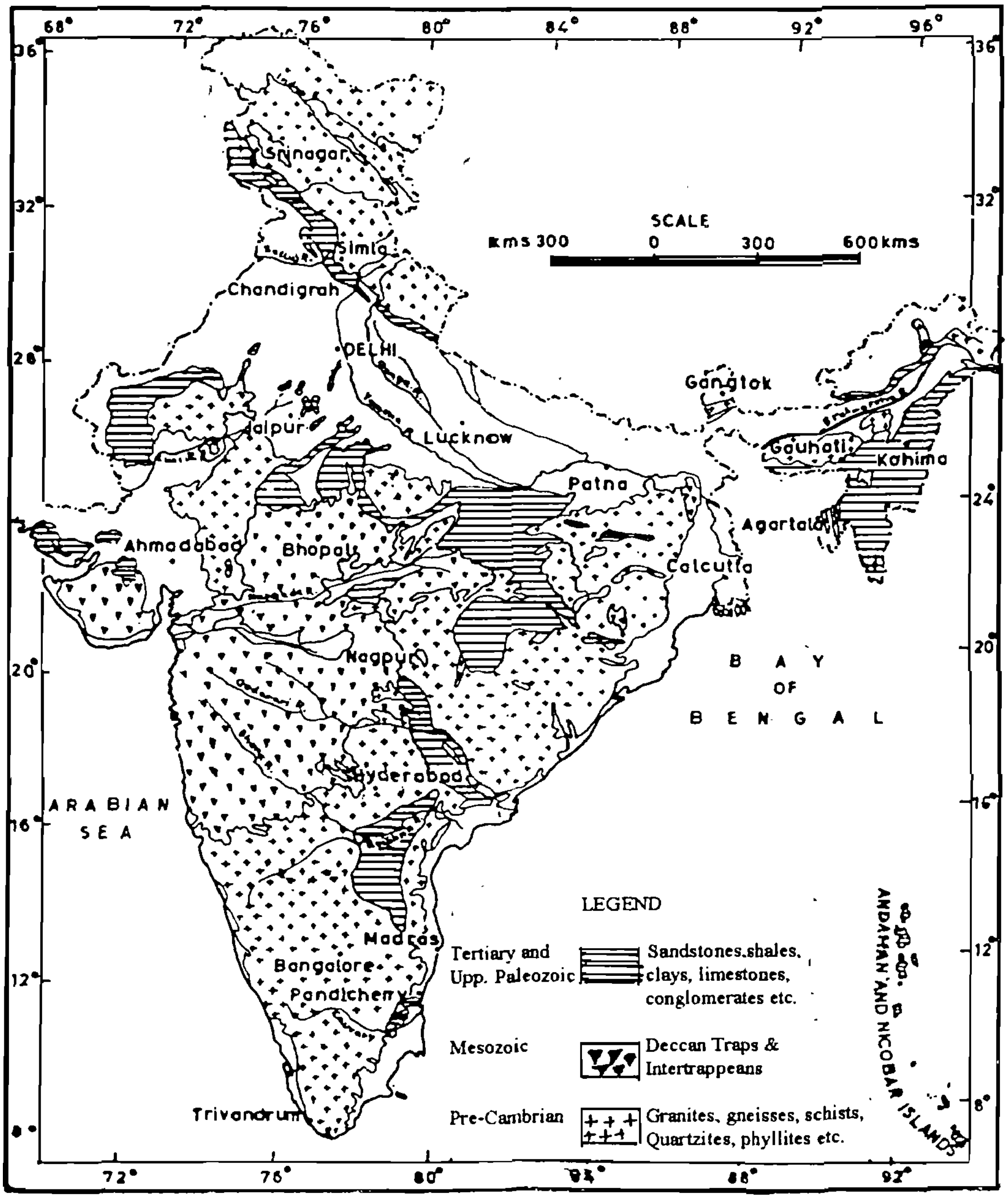

FIG.1 MAP OF INDIA SHOWING HARD ROCK GEOLOGICAL FORMATIONS

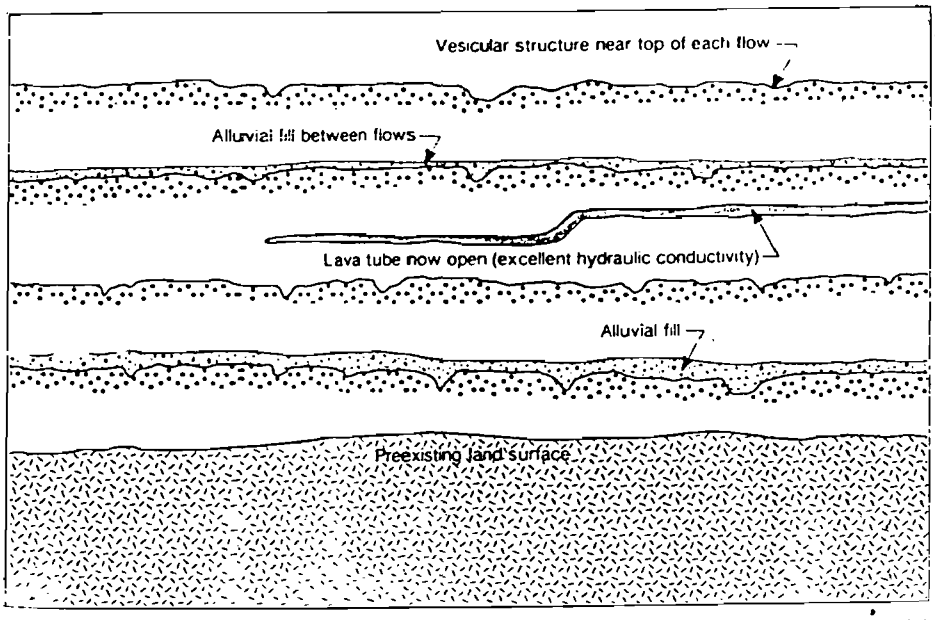

Figure 2 . Basaltic lava flows possessing a vesicular structure can be highly permeable. Any alluvial deposits laid down between flows can also store and transmit significant volumes of water.

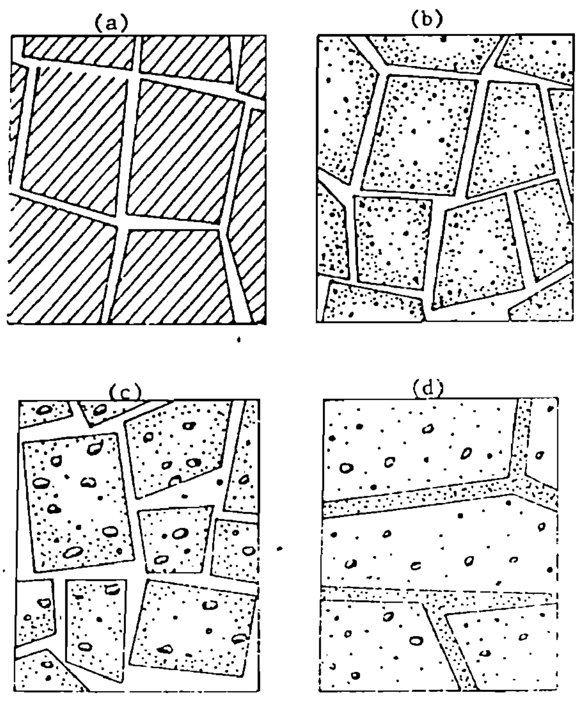

Fig. 3 . Schematic representation of fractured aquifers (After Streltsova, 1976)

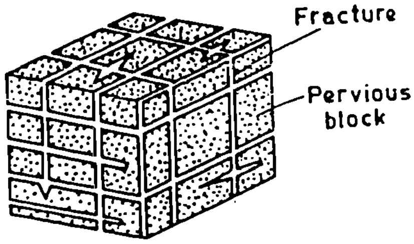

FIG.4 DOUBLE PERMEABILITY-STORATIVITY MODEL

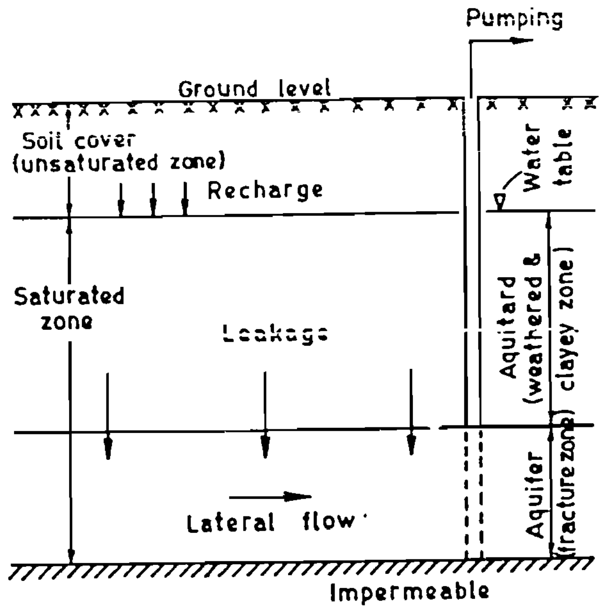

FIG. 6 LEAKY AQUIFER MODEL

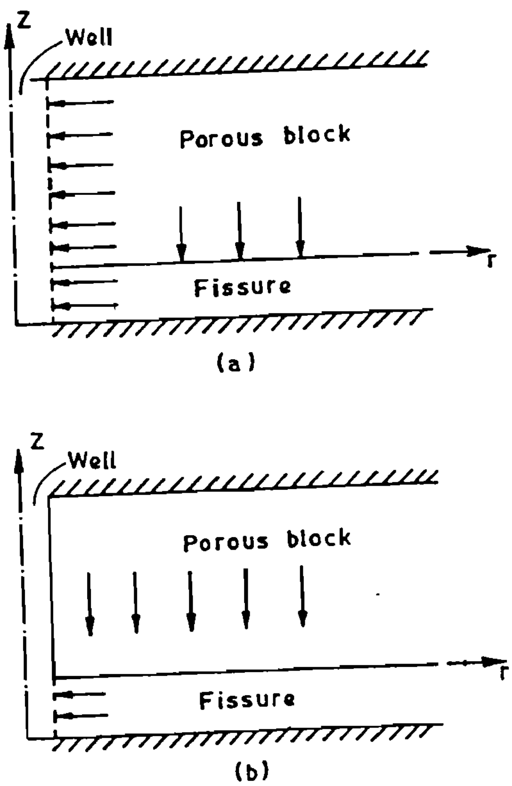

FIG. 5 HORIZONTALLY ALIGNED FISSURE BLOCK MODEL

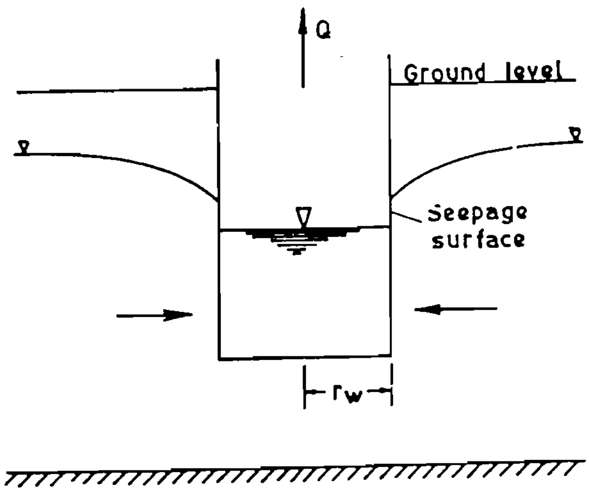

FIG. 7 SCHEMATIC DIAGRAM OF DUG-WELL MODEL

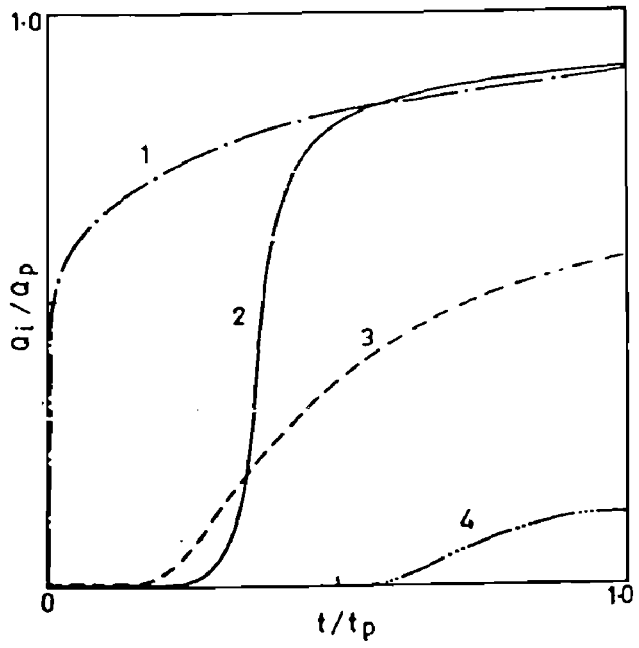

FIG. 8 RELATIVE CONTRIBUTION OF AQUIFER

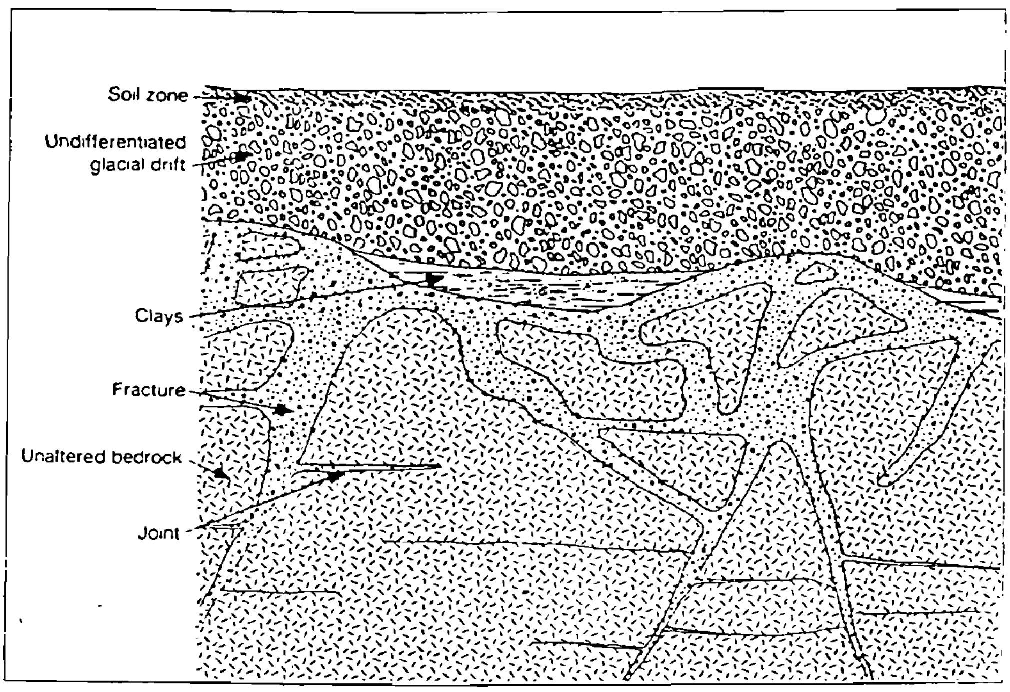

Figure 9 Stratigraphic relationship of deeply weathered igneous or metamorphic rock overlain by glacial drift. Clays are weathered from bedrock and collect on the surface as residual products.

APPROACHES FOR MODELLING OF HARD ROCK AQUIFER SYSTEM

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ABSTRACT

The groundwater flow models represents the porous media having continuous interconnected pore spaces. The flow problem in the fractured rocks has always been and will continue to be of interest to hydrologists. Evolving conceptual model of a fractured system requires either a gross simplification or a detailed description of the aquifer properties controlling the groundwater flow. At present, there is only a basic conceptual understanding of flow in the vicinity of weathered and fractured hard rock aquifers. Normally this conceptual understanding is not translated in to the quantitative interpretation procedures; often, simple continuum models are applied to analyse pumping test data, and the results then used to produce quantitative calculations on a regional scale. Even if the regional system can be represented using the continuum equivalent approach, it is unlikely that the results of applying continuum models at the local scale have any general validity, and also aquifer parameters so derived, may be different to the aquifer parameters appropriate for describing regional flow in quantitative terms. Hence, there is a need to develop appropriate methods for analysis of pumping test data and appropriate simulation technique to improve the success rate and yield of wells in fractured rock. The analysis should provide cost-benefit analysis for new and / or in-fill wells. To do this, it is necessary to investigate the flow in the vicinity of a pumping borehole, and to apply appropriate non-continuum models. Fractured systems are typically using one or more of the following conceptual models: (i) equivalent porous medium, (ii) dual porosity medium, (iii) discrete fracture network model, and (iv) stochastic continuum model. This paper deals with the different approaches used to simulate the fractured aquifer system.

INTRODUCTION

India, being a monsoon climatic country, is beset with a special meteorological situation in the form of monsoon rainfall. The long-term average annual rainfall is in the order of 1100 mm, but it is highly uneven in space and time. It is received in short spells during few months in a year. The rainfall is also intense with only short duration and thereby it is lost as runoff;

evapotranspiration is also high. Due to the above factors, the actual precipitation entering into the groundwater system is limited. The groundwater is the major resource, which meets the demand for drinking, agriculture, and industries throughout the year. Moreover, the spurt in the industrial activities during last two decades has led to groundwater pollution due to discharge of untreated industrial wastes. This situation warrants concerted R & D efforts to evolve appropriate strategies and methodology for maximising the availability of hazard-free water resources. Over the last five decades, the exploitation of groundwater resources in the country was increased many fold. Due to indiscriminate exploitation of aquifer in many parts of the country, groundwater levels have been progressively declining. However, reliable estimates of safe dynamic potential of groundwater resources in hard rock aquifer system are limited. Even at places, where efforts are made to assess this potential, the methodology is empirical and quite often leading to erroneous results.

Hard rocks are all those crystalline hard and massive rocks, which have no intergranular porosity. The most common types are the granite and basalt. The distribution of hard rocks in India is shown in Fig. 1 (Radhakrishna, 1970). The crystalline limestone, quartzite, sandstone, and many schistose rocks formed as a result of metamorphism are also called hard rocks (Radhakrishna, 1970). However, due to tectonic disturbances, secondary porosity in the form of fissures, fractures, and joints have higher permeability. Number of fractures, if they connect to form networks, can be expected to form the principal pathways for fluid flow and mass transport. The hydraulic conductivity of individual fracture in granitic rock can vary over several orders of magnitude, and the geometry of interconnection of the fracture is generally irregular. For these reasons, the properties of the fractured rock mass with respect to groundwater flow are, on a local scale, extremely heterogeneous. Hydrological testing methods that are commonly used to characterise less heterogeneous rocks is of questionable value for characterising rock masses. Traditional methods for interpretation of hydrological test results are based on assumption of flow through an approximately homogeneous porous medium with simple flow geometry (e.g., radial or spherical flow). In fractured rocks, the test results are, in general, controlled by fracture properties on a localized scale, and the flow geometry can be very irregular.

It is, thus, imperative to develop more reliable techniques for estimation of aquifer parameters in hard rock region and assessment of these resources for their hazard-free optimal exploitation. The ultimate objective would be to evolve an appropriate methodology for a rational management of groundwater resource and thereby find lasting solutions to the problems of water scarcity and water quality.

MODELLING APPROACH

Groundwater flow is expected to occur in crystalline rocks mainly through networks of interconnected fractures and joints. Discrete-fracture networks (DFN) models provide a means of explicitly representing flow path geometry in such cases. The geometry of interconnection among fractures determines the locations and pathways. The statistical geometry of fractures can be deduced directly from observation of fractures in borehole and at outcrops on the surface. Thus, the flow paths in DFN models arise as a direct consequence of observed fracture geometry, rather than as the result of conditioning on cross-hole hydrological data. The applicability of this model is limited in terms of scale of the area and volume to be simulated. The maximum volume (3D) that can be modelled depends upon the intensity of fracturing and the resolution (in terms of minimum fracture conductivity) that is desired. Due to these limitations, DFN models must be used in conjunction with Stochastic Continuum (SC) and Channel Network (CN) models. SC model is used to model fluid flow on the larger scale by making use of probability distribution of fracture properties (i.e., given a definite location, size, transmissivity, etc). In practice, it is extremely difficult to characterise all hydraulically significant fractures in a block of rock, in which case, stochastic modelling allows uncertainty to be represented explicitly. Monte Carlo simulations resulting in multiple model realisations achieve this. Dual porosity stream tube modelling is used to predict mass transport. CN models are used as an alternative model for transport within the dominant flow pathways. The DFN model is used to provide information required for the other two modelling approaches.

The comparison between DFN, SC and CN modelling approach is shown in Fig. 2. The data analysis and the conceptual model of the system are explained in Fig. 3. The model validation and prediction is shown in Fig. 4.

Equivalent Porous Medium

Fractured system is represented as an equivalent porous medium (EPM) by replacing the primary and secondary porosity and hydraulic conductivity distribution with a continuous porous medium having equivalent or effective hydraulic properties. The parameters are selected so that the flow pattern in the EPM is similar to the flow pattern in the fractured system. An EPM approach assumes that the fractured material can be treated as a continuum and that a representative elementary volume (REV) of material characterised by effective hydraulic parameters can be defined. Simulation of flow in fractured system using this concept requires definition of effective values for hydraulic conductivity, specific storage, and porosity, which are, in turn, determined by aquifer testing (Gingarten, 1982), estimated from water balance or inverse models, and /or calculated from field description of fracture apertures, lengths and interconnections, and unfractured rock volumes and permeabilities (Cacas *et al.* , 1990 a). When EPM is considered, then standard Finite Difference Method (FDM) or Finite Element Method (FEM) may be applied to simulate groundwater flow in fractured system. This approach can be applied, only if the system has high intensity of fractures, otherwise this concept is not valid. Many research workers, however, have concluded that EPM approach may adequately represent the behaviour of regional system, but poorly reproduces the local conditions.

Dual Porosity Medium

If the rock mass contains significant primary permeability, a dual porosity may be used. This concept was proposed by Barrenblatt *et al.* (1960). In this conceptual model, flow through the fractures is accompanied by exchange of water to and from the surrounding porous rock matrix. Obviously, the fracture network as well as the properties of the porous blocks must be described prior to modelling. Exchange between the fracture network and the porous blocks is normally represented by mass transfer function (Huyakorn *et al.* , 1983). The double porosity approach is primarily applicable to sedimentary formations such as sandstone, but may also be of interest in the inverse interpretation of the hydraulic properties of hard rock formations.

Discrete Fracture Network

A discrete fracture network model assumes that water moves only through the discrete fracture network. This approach is typically applied to fractured media with low primary permeability such as crystalline rocks. The flow through single fracture may be identified as occurring between two parallel plates with a uniform separation equal to the fracture aperture. The parallel plate fracture flow equation is derived from the Navier-Stokes general equation for fluid flow in three dimensions of space as:

$$\rho\frac{\partial u}{\partial t} + \rho u \nabla u = \rho g - \nabla P_T + \mu \nabla^2 u \qquad (1)$$

where ρ is fluid density; μ is viscosity of fluid; u is groundwater flow velocity; P_T is total pressure.

Flow through a single fracture may be idealised as occurring between two parallel plates. For the parallel plate situation, the relationship can be simplified to 1-dimensional equation. This is because the aperture is assumed infinite by perpendicular to flow. This condition is illustrated in Fig. 5.

From these simplifications, the relationship becomes:

$$\frac{\partial^2 u}{\partial z^2} = -\frac{G}{\mu} \qquad (2)$$

where dP/dx = -G; u is the groundwater velocity in x direction

Integrating equation (2) twice with respect to z gives:

$$U = -\frac{Gz^2}{2\mu} + Az + B \qquad (3)$$

where A and B are arbitrary constants eliminated by applying boundary conditions: when z=0, u=0 and z=d, u=0 Where, d is the aperture size. Substituting these boundary equation into equation (3)

$$U = \frac{G}{2\mu}(dz - z^2) \qquad (4)$$

Thus, the velocity profile across the fracture is parabolic, the maximum is located at z=d/2. Given the symmetry of the system, it is possible to integrate this relationship with respect to z in order to obtain a discharge per unit length of the fracture.

$$Q = \frac{Gd^3}{12\mu} \qquad (5)$$

Where, G is pressure gradient. When using head gradient, the following relationship must be used:

$$Q = \frac{d^3 \rho g}{12\mu} i \qquad (6)$$

where i is the hydraulic gradient; ρ is density of fluid and μ is the viscosity of fluid. By Darcy's law:

$$Q = -Aki \quad \text{-----------(7)}$$

Equations (6) and (7) show an analogy in terms of flow. Transmissivity is defined as hydraulic conductivity multiplied by saturated thickness, so that equation (7) can be rewritten as:

$$Q = -T_i \quad \text{------------(8)}$$

for discharge per unit length in x direction. Thus, transmissivity of fracture can be written as (Alex Bond, 1998):

$$T = \frac{d^3 \rho g}{12\mu} \quad \text{..........(9)}$$

Discrete-Fracture Network (DFN) Models are applied for

(i) Small scale modelling.

(ii) Explicit representation of flow path geometry.

(iii) Process of flow and mass transport assumed to take place primarily or entirely through network of discrete fractures.

Advantages of DFN Model

(i) Explicit representation of the geometry and physical properties of fracture and fracture zones.

(ii) Ability to incorporate fracture-geometry data in the model, and thus give a basis for extrapolation from packer tests of uncertain flow geometry.

(iii) Possibility of modelling fracture zones on various scales, including undetected zones and other heterogeneities, based on observations of structural patterns.

Disadvantages of DFN Model

(i) The approach is relatively new, so the modelling tools are not as sophisticated as continuum tools. They have generally been developed for specific applications e.g., deep repository or reservoir studies, treatment of water table, unconfined aquifers, and surface water features. Need for fracture geometrical data at sampling location distributed throughout the region to be modelled, including data at depth. When sampling locations are not well distributed, extrapolation is required.

(ii) Need to simplify fracture patterns and / or restrict the range of fracture transmissivity modelled to simulate large-scale region.

This methodology is applied in advanced countries for identification of sites to dispose nuclear wastes. Models based on DFN approach are computationally complicated. To date, applications are to the oil industry, mining industry and restricted nuclear waste disposal sites.

Stochastic Continuum Approach

The stochastic continuum theory treats the parameter heterogeneity in the context of a statistical (probabilistic) framework. It is assumed that an effective hydraulic conductivity tensor K exists on some averaging scales, and that it forms a continuous random tensor field i.e. :

$$K_s \quad = \quad K_s(x) \qquad \text{----------(10)}$$

The assumed hydraulic conductivity field $K_s(x)$ is described by the expected value, the variance and the co-variance function, but possibly by trends. The following steps are involved in SC approach:

(i) Estimate the population statistics i.e., expected value, variance and co-variance.
(ii) Divide the flow domain into blocks.
(iii) Generate multiple realisation of the conductivity field
(iv) Solve the flow problem for each realisation.
(v) Carry out statistical analysis of the results from the simulations.

Normally the conductivity is transformed so that the resulting value field will satisfy the theory of Regionalised Variables i.e., stationarity and Gaussian behaviour. In general, it is assumed that K_s is isotropic at each point in the log-conductivity field:

$$Z(x) = l_n(K(x)) \qquad \text{-----------(11)}$$

The hypothesis of a multivariate normal distribution Z implies that the entire statistical structure of the stationary Z(x) is defined with the aid of μ and $\sigma_{ij} = C_z(x_i,h, x_j)$ where, μ denotes the mean and C_z the two point co-variance. Thus, we may write:

$$Z(x) = l_n(k(x)) \in (N(\mu, \sigma, \lambda_z(orI_z))) \qquad \text{-----------(12)}$$

Where N $((\mu,\sigma,\lambda_z$ (or I_z))) denotes normal (Gaussian) distribution.

Advantages of SC Model

(i) An extensive theory and statistical procedure for analysis.

(ii) Ability to model site scale regions.

(iii) The possibility of conditional simulation.

(iv) A tendency to produce more structure than a purely random field.

Disadvantages of SC Model

(i) Simplistic structure of the conductivity field produced by these models.

(ii) Inability to model discrete, heterogeneous connection.

(iii) Uncertain relation of model parameters to the varying support scales owing to the differing influence of radii when performing pumping tests.

A major problem with numerical simulation using stochastic continuum-approach is that of framing representative model blocks in which the heterogeneous equivalent conductivity is spatially varying parameter for which spatial conductivity is defined in geostatistical terms. This problem is relevant to hard rocks, where the amount of test data is by far too small compared to the size of the regional flow domain to be modelled.

It is, therefore, proposed to use DFN model to characterise the discrete fractures and use this as an input to stochastic continuum model to simulate regional flow. Some research work has been started in UK in this direction. It is high time to initiate an integrated modelling technique (DFN & SC) to simulate groundwater flow in fractured aquifer system in India also.

NUMERICAL SOLUTION METHODS

Though analytical methods provide error free solution, it is applied only to simplified flow conditions with regard to the physical and geometrical aspects of the aquifer system. Therefore, one has to resort to numerical methods. Groundwater modellers are using both finite difference (FD) approximation and finite element (FE) techniques to solve groundwater flow equation. Computationally, FD is easier than the FE method. Since the flow problem is heterogeneous in fractured rock, it is preferred to use FE technique.

Finite Element Technique

In this method, the continuous flow field is discretized into a number of elements, which are used for interpolation of the field parameters such as the piezometric head and hydraulic conductivity. The basic idea is to transform the governing equations to integral form and to carry out piecewise integration over the elements. The elements may have both different spatial dimensions and shapes. The order of the underlying interpolation scheme may typically be linear, quadratic or cubic. Continuity may be prescribed not only for the variables themselves but also for their derivatives. The procedures to be followed are as given below:

(i) Discretization of the flow domain into a set of elements, where each element is defined by a number of nodes, for instance 3- or 6- node triangles, 4-, 8- or 9- node quadrilaterals in 2D or 4-node hexahedrons in 3D, etc.

(ii) Expression of field parameters such as piezometric head, hydraulic conductivity, etc., in the following form:

$$h(x,y,z) = \sum_{1}^{N} h_j \psi_j \qquad \text{-----------(13)}$$

where h is piezometric head, N is the number of nodal points in the discretized element grid and Ψ is the interpolation function called test function.

(iii) Formulation of the groundwater flow equation (PDE) in integral form

(iv) Element-wise integration of the integral form of the groundwater equation

(v) Assembly of the algebric matrix equation that result from the integration step into global system of linear equation of the form:

$$[M]\{\frac{dh}{dt}\} + \{K(h)\}[h] = [f] \qquad \text{........(14)}$$

where [] denotes a matrix; {} denotes column matrix

(vi) Time integration

(vii) Solution of the global system of linear equations.

PROCEDURE FOR MODELLING DISCRETE FRACTURE NETWORK

(i) Preliminary geological and geophysical investigations for selection of suitable sites.

(ii) Geological assessment [scan surveys on outcrops, borehole logging (fluid logs, formation logs, calliper, CCTV, ideally acoustic televiewer), surface geophysics, coring and trenching].

(iii) Selection of an appropriate conceptual model for discrete-fracture network geometry.

(iv) Testing (core material / trench material, pumping tests, packer tests and tracer tests).

(v) Derivation of statistics for fracture properties from site characterisation data to conceptualise a preliminary DFN model for the rock mass.

(vi) Constant (pressure) head packer tests will be analysed using fractional dimensional methods to estimate effective transmissivities and flow dimension for the packer test intervals.

(vii) Discrete fracture data on orientation, size, shape, and location along with hydrologic data will be used to evolve preliminary conceptual model for the conductive fractures at the site.

(viii) The variability of fracture properties will be expressed by probability distributions.

(ix) The preliminary conceptual model will be used to simulate 3-dimensional population of conductive fractures in a cube of rock.

(x) Transient packer tests will be simulated in these fracture populations, and the simulated results will be used to validate the preliminary conceptual model.

(xi) The calibrated model will, then, be used to estimate the components of effective conductivity tensors for the rock by simulating steady state groundwater flow through cubes in three orthogonal directions.

(xii) Monte Carlo stochastic simulation will be performed for alternative realisations of the conceptual model.

(xiii) Adaptation of software for discrete fracture network (DFN) flow model (FracMan or NapSac) based on observable, geometric, and hydrologic characteristics of the fracture population, that can be used to predict groundwater flow through fractures of the crystalline rock.

DATA REQUIREMENTS FOR DISCRETE FRACTURE NETWORK MODEL

Due to fundamental limitations of site characterisation technology, the data needed to model the exact geometry and property is limited to a few boreholes and outcrops. Although major conductive features can perhaps be identified within the rock mass by geophysical methods such as borehole radar and skin depth effects but the interference limits the resolution of these techniques. Since the locations and properties of most of the fractures in the rock cannot be measured by any available means, an approach is needed, which is based on some form of statistical characterisation of the fractured population. The following data are required to characterise the discrete fractures through the DFN model.

Fracture Property	Data Source
1. Orientation	Lineament and Fracture Maps, Core Logs
2. Conductive Fracture Intensity	Core Logs and Packer Tests
3. Location	Lineament and Fracture Maps
4. Size	Lineament and Fracture Maps
5. Shape	Fracture Maps, Generic Information
6. Transmissivity	Steady and Transient Packer Test Data
7. Dimensionality	Transient Packer Test Data
8. Storativity	Transient Packer Test Data and Generic Information
9. Transmissivity Variability	Generic Information

The following give definitions of specific fracture properties:

Orientation

The orientation of conductive fractures can be analyzed from borehole televiewer data for each section of the borehole. It is possible to analyze images of fracture intersections on bore hole walls to determine the relative orientation of the fracture where it intersects the bore hole. The fracture orientation also can be represented stochastically by the statistical process of "bootstrapping" directly from the bore hole data. This process chooses the orientation of simulated fractures by sampling from the measured orientation set, corrected for sampling bias by applying a Terazaghi correction (Terazaghi, 1965). The bootstrapping approach ensures that the data are honoured in the model simulation without a requirement for further interpretation to derive distributions.

Fracture orientation is also expressed in terms of fracture pole orientations or fracture dip directions. The fracture pole is the direction normal to the place of the fracture. The variability of fracture orientation can be expressed in terms of either parametric or non-parametric distribution for either pole or dip directions. Examples of parametric distributions for orientation are univariate Fisher distribution, the bivariate Bingham distribution (Bingham, 1964), and bivariate Fisher distribution (Dershowitz, 1979). Non-parametric characterisation of orientation data can be based upon bootstrap or jackknife re-sampling methods. The oriented core logs and comprehensive scan line or trace-plane maps will provide both the strike and dip of each fracture plane.

Intensity

The DFN modelling approach is simplified by modelling only the conductive fracture population. In general, only a fraction of the fractures present in the rock are significantly conductive. This can be identified through packer test, although core logs show multiple fractures in those intervals. By modelling only the conductive fractures, a realistic prediction can be obtained with considerably less computational effort than would be required to model all the fractures. For this approach, the total area of the conductive fractures in a unit-volume of rock is taken and related to conductive fracture frequency f_c which is defined as the number of conductive fractures per unit length of line sample (borehole or scanline).

Location

Location of individual fractures is expressed in terms of probability density function f_z (x) for fracture centres in 3D space. The simplest case is the purely random case, referred to as the Baecher conceptual model as shown in Fig. 6, in which fracture centres are located by a uniform Poisson process in three dimensions, i.e., f_z (x)=constant. Model was introduced in rock mechanics by Baecher *et al.* (1977).

Size

The size of a polygonal fracture is expressed in terms of the equivalent radius r_e of the fracture. This is defined as the radius of a circle that has the same area as the polygonal fracture.

$$r_c = \sqrt{A_f \pi} \qquad (15)$$

where A_f is area of the fracture and r_c is radius of the circle.

This definition holds good for both terminated as well as un-terminated fractures. Fracture size (radius) probability density functions, f_r (r_e), are obtained from fracture and lineaments trace length data. Traces are assumed to represent the lines of intersection between circular fractures and the trace plane. The length of these lines may be truncated due to the finite extent of the trace plane, or censored due to their being overlooked, or due to their being shorter than the minimum length considered by the survey. Analytical methods are used for deriving f_r (r_e) from trace length data are available, based upon simplifying assumptions about:

(i) The forms of distribution (generally assumed to be normal)
(ii) The forms of the orientation distribution, usually constant or uniform on the sphere
(iii) The type of censoring
(iv) Type of truncation at the boundaries of the trace plane

Shape

Normally, fractures are assumed to be planar and approximately polygonal. Population of random oriented fractures and non-planarity of the fractures is not believed to be of sufficient importance in terms of fracture connectivity, to justify the added difficulty of calculating intersections among undertaking fractures. Polygonal fractures are used to allow in terms of fracture shape. When a planar fracture terminates at an intersection with another fracture, the resulting edge is linear. As the percentage of fractures terminating at intersections, fracture shape converges to be polygonal.

Transmissivity

The transmissivity at a point density ψ, hydraulic on fracture is defined as the constant of proportionality between flux density and hydraulic head gradient. Darcy velocity is expressed as:

$$q = -T(\psi)\frac{\partial h}{\partial \psi} \quad \text{.....(16)}$$

where q_I is Component of flux per unit width of plane in the direction ψ_I; $T(\psi)$ is transmissivity at the point ψ in the fracture plane; ψ_I is i^{th} component of the local co-ordinate vector ψ.

This is a phenomenological definition having relationship between transmissivity and the assumed local fracture. This definition is applicable to fractures with or without infilling. The local transmissivity is assumed to be isotropic (in two-dimension) and independent of head gradient. In the simplest model, transmissivity is assumed to be constant throughout any given fracture plane. But this is not true. Field observations by many research works show that flow distribution through individual fractures is irregular due to channelling effects.

However, the inaccuracy can be neglected within the network if details of flow in the fracture can be neglected and the flow between two connected fractures is characterized by an average cross-fracture transmissivity. In a more detailed model, transmissivity is considered to vary as a fractal process within the plane of each fracture. Each fracture is recursively discretized into a number of sub-fractures of approximately equal size and the transmissivity of each fracture is assigned a distinct transmissivity.

Storativity

The storativity at a point ψ on a fracture describes the change in the volume of fluid contained per unit area of the fracture, in response to a unit increase in pressure.

$$S(\psi) = \lim\left[\frac{1}{A}\frac{\partial V_{\psi}(\psi)}{\partial h(\psi)}\right] \qquad (17)$$

where, A is area in the fracture plane; S (ψ) is storativity at point ψ in the fracture plane; $V_w(\psi)$ is volume of water contained within an area A around the point ψ.

The storativity is related to the fracture normal stiffness and the fluid compressibility. If infilling is present, then the storativity is also related to the porosity and compressibility of the infilling material.

Packer Test Data

The aquifer test provides information about fracture intensity, transmissivity, and storativity, which can be used to conceptualise DFN model. Transient test data will help to validate the DFN model. The packer testing methodology, known as Fixed Interval Length (FIL) testing as described by Osnes *et al.* (1988), provides the necessary data for statistical derivation of the relevant fracture model parameters.

A discrete fracture interpretation of FIL packer test involves three main steps:

(i) Evaluation of individual packer test results to estimate interval transmissivity for each test.

(ii) Estimation of variation on bore hole measurements of fracture transmissivity.

(iii) De-convolution of packer interval transmissivity data to estimate the conductive fracture frequency, f_c and the single fracture transmissivity distribution.

The purpose of the packer test analysis is to determine the number of conductive fractures within a hard rock mass. Packer testing works by scaling a length of borehole using two inflatable seals. The head can, varied within the sealed zone and the flow response is measured. The response can be used to obtain a hydraulic conductivity for that interval. The packers can, then, be moved to test another zone. In this way, the profile of hydraulic conductivity with depth can be plotted. Each borehole also should have a CCTV fracture log. Often the log will discriminate between sizes and orientation of fractures. The criteria by which fractures were added to the log are unknown, but it is be assumed that they are representing the realistic situation of fractures.

Combining these two logs, it is possible to correlate the presence of fractures and elevated hydraulic conductivity. If the fracture is active, one would expect to see an elevated hydraulic conductivity. If a fracture is not active, it will not conduct water significantly, as the hydraulic conductivity of the test zone will be dominated by the rock matrix. Thus, percentage number of conductive fractures can be determined. Note that it does not matter whether the fracture tested is actually connected to the rest of the network. All that is required is a percentage of the total number of fractures that can potentially sustain the flow, if they were connected to a network. This value can be used to correct the field observation of fracture densities, which can be used to model the conductive fracture system.

Monte Carlo Analysis

The most straightforward way of carrying out an uncertainty analysis for a given hydrological problem is by means of the Monte Carlo method. The basic steps in a Monte Carlo analysis are as follows:

(i) Establish a probabilistic description of the input parameters

(ii) Generate a large number of realisations e.g. with hydraulic conductivity as a random variable and solve the groundwater transport problem for each realisation.

(iii) Compute the statistics of the result parameter of interest i.e., the travel time or flux on the basis of the results from each of the computed realisations.

The generation of random fields of hydraulic conductivity may be carried out using one of the following methods:

(i) Choleski factorisation (LU – decomposition) by the co-variance matrix (V = LLT), and multiplication with a vector Z or independent random members drawn from a normal (Gaussian) distribution

(ii) Turning bands methods

(iii) Spectral techniques

The Choleski factorization technique is the simplest to program, but becomes inefficient for large data sets. In this, it is recommended that either of the other two methods be used.

Information Needed for SC Modelling

(i) The minimal scale [the representative volume (REV)] if any, on which the rock mass can be said to behave as an equivalent porous medium.

(ii) The variability of (average) rock mass effective hydraulic conductivity (K).

(iii) The variability of anisotropy, expressed in terms of the ratio of the principal components of the (presumed) hydraulic conductivity tensor (Kx, Ky and Kz) to the average hydraulic conductivity K.

(iv) The form of spatial correlation of rock mass conductivity that results from fracture network effects.

(v) The relationship between apparent hydraulic conductivities measured by borehole testing and the effective hydraulic conductivities of the rock mass on the scale of blocks used in SC modelling.

Information Needed for CN Modelling

(i) The spatial intensity of channel (number per unit volume) as a function of channel length and channel conductivity, based the observable geometric characteristics of the fracture population.

(ii) The interconnectivity of flow channels (number of intersection with other channels per unit length of channel) in three dimensions.

The spatial intensity of channels can be estimated directly from packer test data, but DFN models may provide independent ways for deducing the same data.

All fracture properties can be viewed as stochastic variables, the variability of which is characterised in terms of probability distributions. Because the quantity of data is limited, and because a finite degree of error is associated with any single data measurement, the estimated forms and parameters of probability distributions for fracture properties have an associated uncertainty.

COMPUTER CODES TO SOLVE DFN MODEL

NAPSAC Software

This code was developed jointly by Scientists from UK, Germany, Sweden, and Canada for identifying suitable sites to dispose nuclear wastes. Presently, M/s Atomic Energy Company, UK, markets this code.

Due to the extreme difficulty of quantifying actual fracture networks within a given rock mass, a stochastic approach was taken with NAPSAC. Rather than the user explicitly models actual fractures, statistical data on the dips, dip azimuths, and fracture lengths is collected from the field.

Using this data set, NAPSAC will generate a network of rectangular planar fractures with properties specified by the field statistical data. According to Poisson Point Process, this is done for each set by distributing the fracture centres in space (a volume specified by the user). Each generated fracture centre will then have a rectangular fracture placed around it. Once all the fractures have been generated, those outside test volume are discarded. For those that remain, the intersections between fractures are calculated and the finite element nodes are assigned across the network. Flow can then be simulated at steady state, transient condition and particles tracked through the network. The random network, that is generated, will be controlled by a 'random number seed', a value that is to be specified in the input data set.

NAPSAC can simulate flow either in parallel plate flow mechanism (each fracture is characterised by a single 'aperture' value) or specified distribution of local apertures (aperture variation over the entire plane). The most practical way is to follow the first one, though it is unrealistic. The other is more realistic but it is difficult to measure local aperture.

FRACMAN Software

The FracMan software developed and marketed by Golder Associates Inc., Redmond, USA provides an integrated set of tools for simulation of discrete fracture network (DFN) analysis i.e., fractured and non-fractured heterogeneous rock masses. FracMan includes tools for discrete fracture data analysis, geologic modelling, spatial analysis, visualisation, flow and transport, and geomechanics.

The following modules are incorporated in this software:

(i) FracSys (Data Analysis)

(ii) FracWorks (3D DFN Structural Modelling and Visualisation)

(iii) Mafic (Finite Element and Transport Modelling)

(iv) PA Works (Pathways and Analysis)

(v) FracCluster (Cluster Analysis)

(vi) FracView (Visualisation and Software Linkage)

FracSys provides a unique set of tools to transform geological and well testing data into quantitative parameters necessary for discrete feature network modelling.
FracWorks generates 3-dimensional realisation of discrete feature geology using the parameters derived with FracSys. Fifteen different spatial models are supported. FracWorks also includes the ability to validate model through simulated exploration.
Mafic (Matrix and Fracture Interaction Code) uses the finite element method to solve the flow and transport through FracWorks geological models. Mafic idealises fractures using triangular finite elements and provides a dual porosity interaction using either quadrahedral finite elements approximation. Mafic uses a pre-conditioning conjugate gradient solver, and has applied for network of up to 100,000 fractures.

PA Works and FracCluster are powerful tools to support analysis of the flow behaviour of discrete feature network, without requiring the solution of flow equations. PA Works determines flow pathways within a FracWorks model using graph theory methods, to identify most important pathways and their properties. FracClusters defines the geometry and properties of fracture network cluster, and the block defined by fracture and fracture network.

FRAC 3 DVS Software

Frac 3 DVS is a 3-dimensional finite element model for simulating steady state or transient, variably – saturated groundwater flow and advective – dispersive solute transport in porous or discretely fractured porous media. The code was marketed at Waterloo Hydrogeologic Inc, Waterloo, Canada.

Frac 3 DVS can use either an 8-node block or 6-node prism finite element or 7-point finite difference discretization of the porous medium and rectangular or triangular elements to represent fractures, if present. Block elements can be sub-divided into tetrahedron so that grid, composed of non-orthogonal block elements can be accommodated. A separate pre- and post-processors are included for ease inputting and output analysis.

Frac 3 DVS uses numerical approach which can be either a control-volume finite element, Galerkin finite element or finite different method. The flow solute has the following features: An exact treatment of the saturation term using a mixed, mass-conservation formation and full Newton-Raphson interaction for robustness in handling non-linearities in Richard's equation describing variably saturated flow.

Variability and Uncertainty

The variability and uncertainty are inherent in modelling a heterogeneous system. Variability in the model arises from the heterogeneity of the system. In the case of DFN Model, variability is expressed in terms of probability distribution for fracture properties (orientation, transmissivity etc.), the forms and parameters which, can be estimated from field data.

Uncertainty in a model of the heterogeneous system exists whether the simulations are based on a SC, CN or DFN approach. The uncertainty arises from problems inherent to data collection, such as sample size, sampling bias, sampling accuracy and analysis limitations.

Case Study in south-west Ireland (by Mark A. Jones *et al.* 1999)

A discrete fracture network model has been applied to increase the probability of sinking a successful groundwater production borehole at a well field in carboniferous rocks in South-west Ireland. The model employs the FracMan software to explicitly represent fractures. Model construction is based on a synthesis of data from a variety of geological and hydrogeological sources. The model is verified and calibrated against borehole measurements and multi bore hole pumping tests. The process of model construction indicates that the intensity of flowing fractures is controlled primarily by fracture zones running through the well field, and that there is also a relationship between flowing fractures and zones of weathered dolomite. Simulations allow the optimal orientation of any production bore hole to be determined, and suggest that the most favourable orientation increase the mean number of flowing fractures intersected by up to 30%. The likely yield for different bore hole locations can be assessed by conducting flow simulations. Within fracture zones, the probability of a successful production well is high. Flow simulations are also used to quantify the degree of hydraulic interference between bore holes. The results of modelling can be used to assess the most significant uncertainties and to develop a programme of future site characterisation that addresses them.

Equipment Required to Estimate Fracture Parameters

(i) CCTV with data logger
(ii) Fluorimeter with data logger
(iii) Acoustic Televiewer
(iv) Packer test equipment
(v) Tensiometer, piezometer etc.
(vi) Sun Workstation (to run Napsac)
(vii) ABM Geo-resistivity meter

CONCLUSIONS

Assessment of the dynamic potential of groundwater resources through mathematical modelling (discrete fractured network modelling) in a hard rock region will be the first of its kind in this country.

The combined DFN and SC Model will be a potential tool to get answers for:

(i) Bore hole optimization – orientation, location pumping regime, artificial recharge, etc.
(ii) Yield estimation from a single borehole and / or a sub-basin
(iii) Contaminant prediction

It is suggested to establish a National facility to carry out research work on Characterisation of Fracture geometry and Modelling of Fracture aquifer system.

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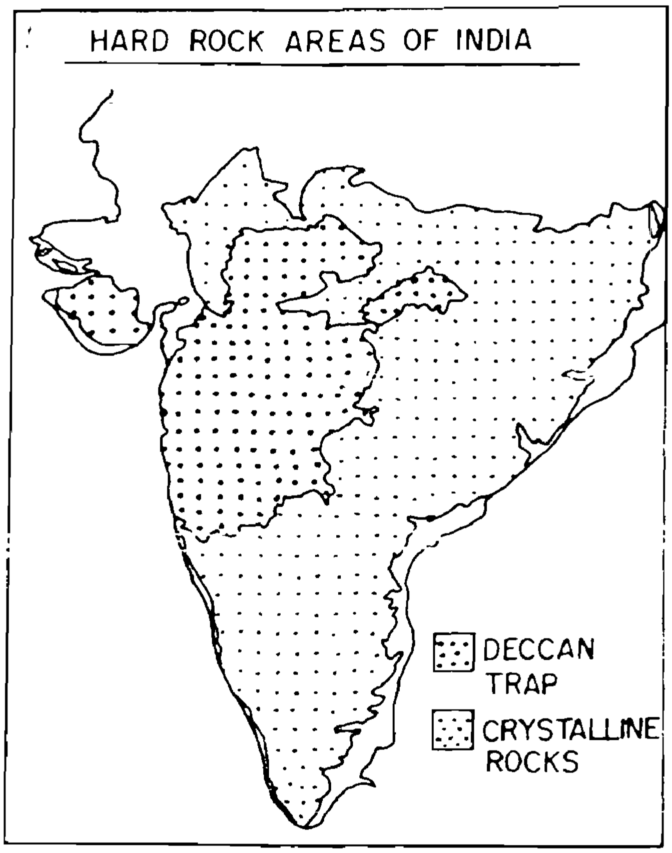

Fig 1 Hard Rock Regions of India (after B.P.Radhakrishna)

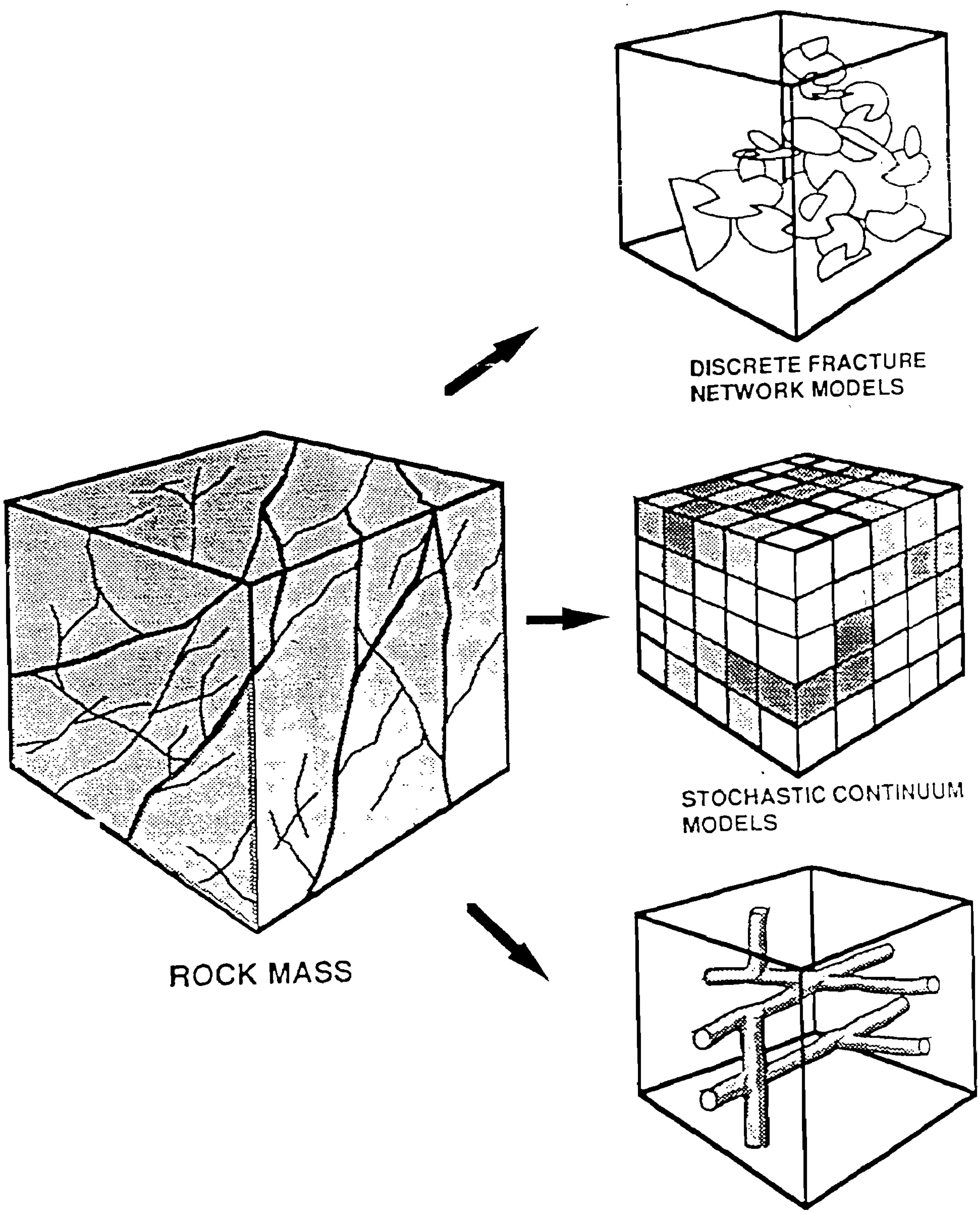

Fig. 2. Comparison of DFN, SC and CN Models (after Golder Associates Inc.)

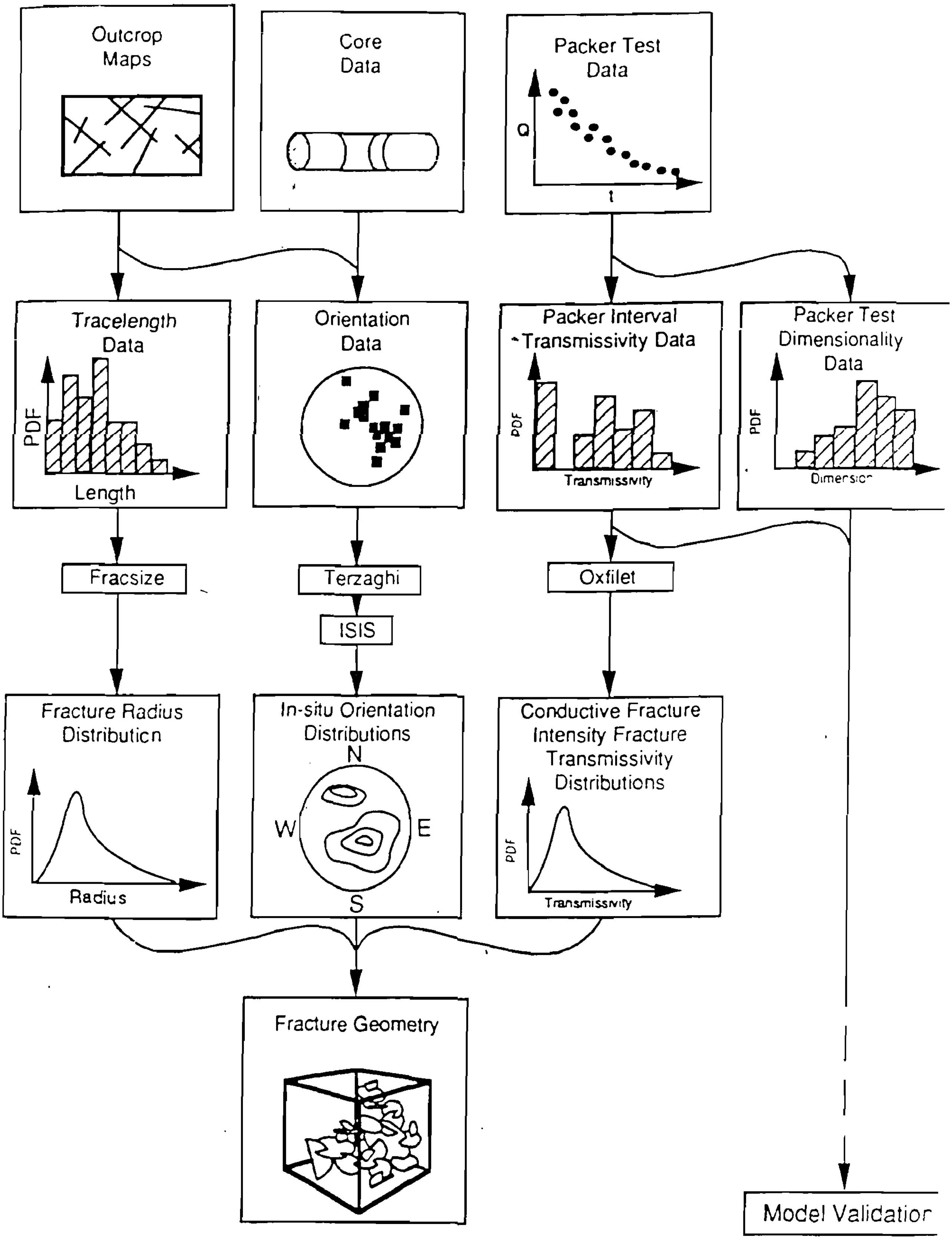

Fig. 3. Conceptual Model of the Flow System (after Golder Associates Inc.)

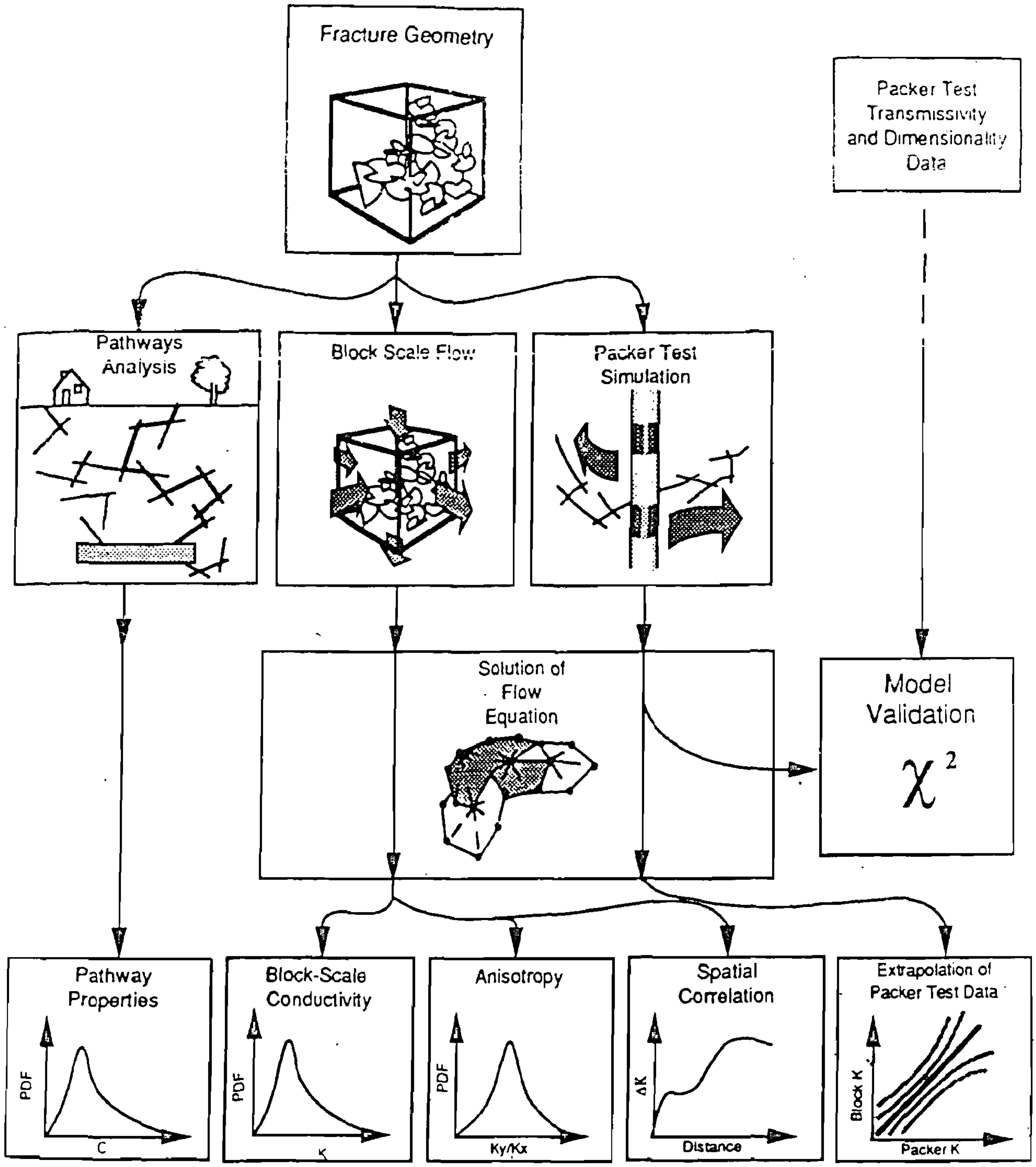

Fig. 4. Model Validation and Prediction (after Golder Associates Inc.)

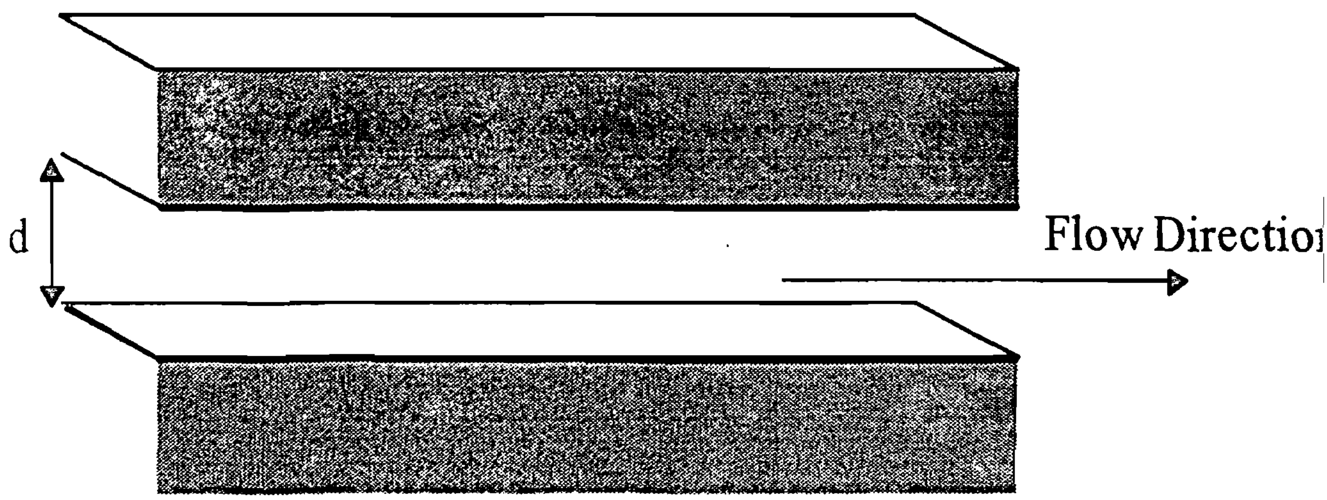

Fig. 5: Parallel Plate Flow Approximation

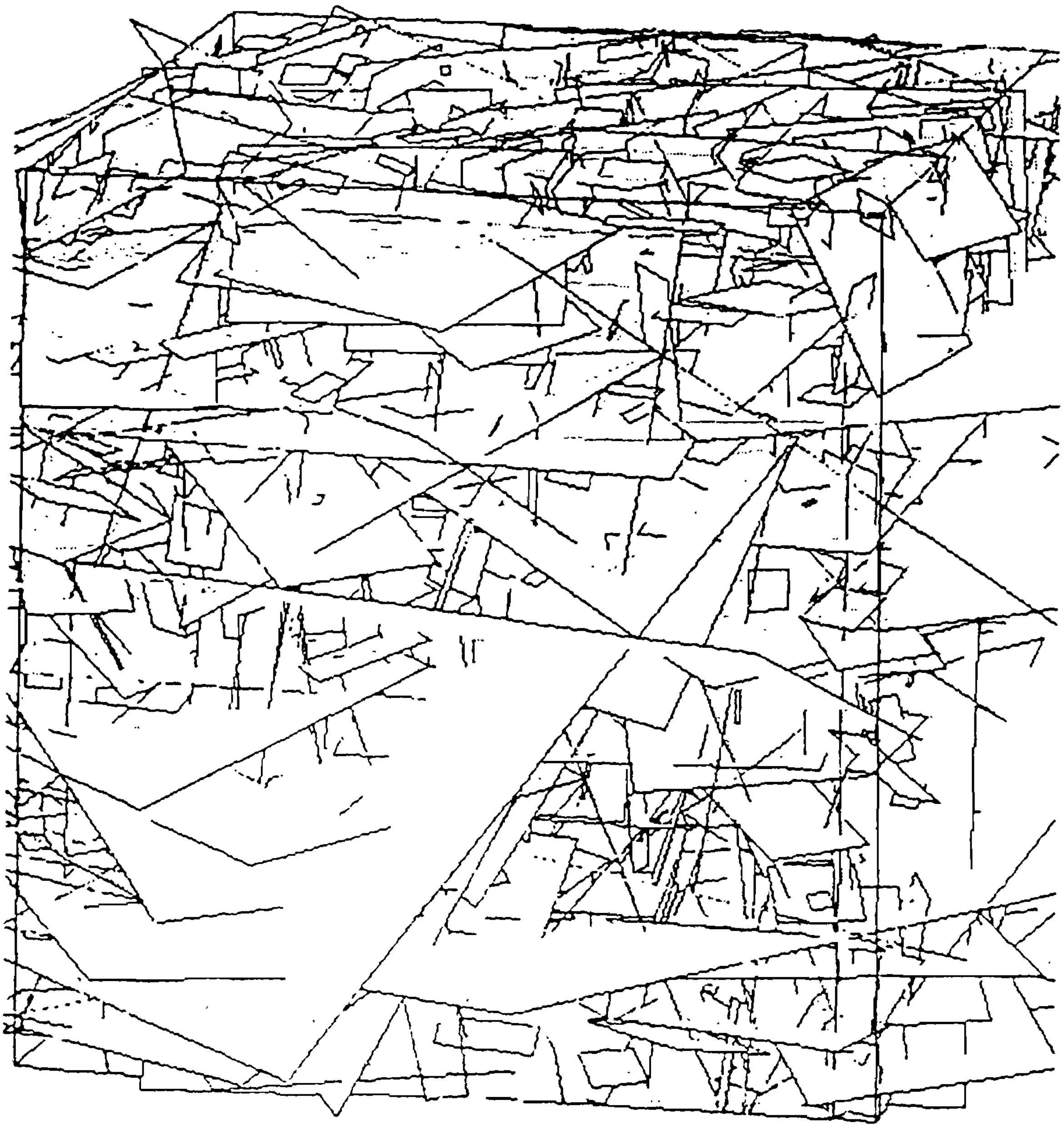

Fig. 6: Oblique View of Fractures Generated in a 5 m cube at Helsby using NAPSAC Computer code (after Allex Bond)

GROUNDWATER MODELLING: FLOW AND MASS TRANSPORT MODEL CASE STUDIES

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ABSTRACT

Groundwater pollution due to discharge of domestic sewage and industrial effluents is increasing day by day in different parts of the country. Mass transport modelling is a tool to assess the status of groundwater pollution as well as predict the contaminant migration in groundwater. A groundwater flow model is required to compute the hydraulic heads, which in turn is used to compute the groundwater velocity. The processes of advection and dispersion are accounted in mass transport modelling. Two examples of flow modelling and three examples of mass transport modelling are presented to demonstrate the utility of these models for assessment of groundwater potential as well as groundwater pollution.

A groundwater flow model is developed to assess the interaction of seepage losses on the groundwater regime and river-aquifer interaction in Ganga-Kali inter-stream region, U.P. The second case study deals with assessment of impact of water harvesting structures on groundwater regime in a basaltic terrain. Quantification of contaminant migration in groundwater due to discharge of industrial effluents from Hindusthan Polymers Plant in Venkatapuram area formed a mass transport case history. The second and third mass transport case studies covered the problem of contamination of drinking water supply well in the Sabarmati river bed near Ahmedabad and contamination of groundwater in Patancheru industrial development area from effluents of chemical and pharmaceutical industries.

INTRODUCTION

Water is a part of the natural environment with many complex parallel roles and functions. Water as a landscape element, and as a chemically active mobile substance is always on continuous move through the surface and sub-surface. Frequent handling of polluting substances on the ground surface involve interventions with water quality in view of the fact that water is an excellent solvent, chemically active and always on the move according to the laws controlling the hydrodynamics of the water cycle. Once caught by the moving groundwater, pollutants tend to move along with the groundwater, unless chemical reactions along the groundwater pathways influence mobility of the pollutant.

Water carries pollutants through invisible and visible landscapes. On the local scale, water soluble compounds used in agriculture (fertilisers), industrial refuse, solid waste deposits, etc., may be caught by water and produce groundwater pollution, which will remain undetected until the polluted water passes through a local well. Similarly, refuse disposed on land surface may be leached by water, and ultimately transferred to the river Effect of pollution may show up further downstream where the river water is being used for some vulnerable purpose like irrigation. On regional scale, pollutants emerging from land use activities in upstream areas of a river basin are being transferred into lakes along the river and finally to the downstream area. Environmental management and protection would mean that decisions have to balance dependencies against threats in the region.

Groundwater modelling has become an important tool for planning and decision making process involved in groundwater management. For managers of water resources, models may provide essential support for regulations and engineering designs affecting groundwater. This is particularly evident with respect to groundwater protection and aquifer restoration. Assessment of the validity of modelling-based-projections is difficult and often controversial. The success or failure of a model depends on the availability of field information (quality and completeness of data) and the type and quality of the mathematical tools (software). The natural starting place for groundwater contamination is with the mass transport processes. These processes determine the extent of plume spread and the geometry of the concentration distribution. Advection is by far the most dominant mass transport process in shaping the plume. Hydrodynamic dispersion is usually a second order process. The magnitude and direction of advective transport is controlled by:

- the configuration of water table or piezometric surface,
- the presence of sources or sinks,
- the permeability distribution within the flow field, and
- the shape of flow domain.

All these parameters are important in controlling the groundwater velocity, which drives advective transport. Adding dispersion to advective transport can cause important changes in the shape of a plume. Other important process is sorption and irrespective of the model describing sorption, the process is of paramount importance in controlling contaminant transport.

MATHEMATICAL MODELLING

The partial differential equation describing three-dimensional transport of contaminants in groundwater can be written as:

$$\frac{\partial C}{\partial t}=\frac{\partial}{\partial x_i}\left[D_{ij}\frac{\partial C}{\partial x_j}\right]-\frac{\partial}{\partial x_i}(v_i C)+\frac{q_s}{\theta}C_s+\sum_{K=1}^{N}R_k \quad \text{.......(1)}$$

where C is the concentration of contaminants dissolved in groundwater; t is time; x_i is the distance along the respective Cartesian co-ordinate axis; D_{ij} is the hydrodynamic dispersion coefficient; v_i is the seepage or linear pore water velocity; q_s is the volumetric flux of water per unit volume of aquifer representing sources (positive) and sinks (negative); C_s is the concentration of the sources or sinks; θ is the porosity of the porous medium; R_k is chemical reaction term.

Assuming that only equilibrium controlled linear or non-linear sorption and first order irreversible rate reactions are involved in the chemical reactions, the chemical reaction term can be expressed as :

$$\sum_{k=1}^{N}R_k=-\frac{\rho_b}{\theta}\frac{\partial\bar{C}}{\partial t}-\lambda\left[C+\frac{\rho}{\theta}\bar{C}\right] \quad \text{.......(2)}$$

where ρ_b is the bulk density of the porous medium; $\bar{C}$ is the concentration of contaminants sorbed on the porous medium; λ is the rate constant of the first-order rate reactions.

Rewriting:

$$\frac{\rho_b}{\theta}\frac{\partial\bar{C}}{\partial t}=\frac{\rho_b}{\theta}\frac{\partial C}{\partial t}\frac{\partial\bar{C}}{\partial C} \quad \text{.......(3)}$$

We can rewrite equation(1) by substituting equation (2) and (3) as:

$$\frac{\partial C}{\partial t}=\frac{\partial}{\partial x_i}\left[D_{ij}\frac{\partial C}{\partial x_j}\right]-\frac{\partial}{\partial x_i}(v_i C)+\frac{q_s}{\theta}C_s-\frac{\rho_b}{\theta}\frac{\partial\bar{C}}{\partial C}\frac{\partial C}{\partial t}-\lambda\left(C+\frac{\rho_b}{\theta}\bar{C}\right) \quad \text{.......(4)}$$

Rearranging terms we get:

$$R\frac{\partial C}{\partial t}=\frac{\partial}{\partial x_i}\left[D_{ij}\frac{\partial C}{\partial x_j}\right]-\frac{\partial}{\partial x_j}(v_i C)+\frac{q_s}{\theta}C_s-\lambda\left(C+\frac{\rho_b}{\theta}\bar{C}\right) \quad (5)$$

where R is called the retardation factor, defined as:

$$R=1+\frac{\rho_b}{\theta}\frac{\partial \bar{C}}{\partial C} \quad (6)$$

Equation (5) is the governing equation underlying the solute transport model.

The transport equation is linked to the flow equation:

$$v_i=-\frac{K_{ii}}{\theta}\frac{\partial h}{\partial x_i} \quad (7)$$

where K_{ii} is a principal component of the hydraulic conductivity tensor; H is hydraulic head.

The hydraulic head is obtained from solution of three dimensional groundwater flow equation through MODFLOW software (McDonald and Harbaugh, 1988)

$$\frac{\partial}{\partial x_i}\left[K_{ii}\frac{\partial h}{\partial x_j}\right]+q_s=S_s\frac{\partial h}{\partial t} \quad (8)$$

where S_s is the specific storage of the porous material.

The hydrodynamic dispersion tensor for isotropic media is defined as:

$$D_{xx}=\alpha_L\frac{v_x^2}{|v|}+\alpha_{TH}\frac{v_y^2}{|v|}+\alpha_{TV}\frac{v_z^2}{|v|}+D^*$$

$$D_{yy}=\alpha_L\frac{v_y^2}{|v|}+\alpha_{TH}\frac{v_x^2}{|v|}+\alpha_{TV}\frac{v_z^2}{|v|}+D^*$$

$$D_{zz}=\alpha_L\frac{v_z^2}{|v|}+\alpha_{TH}\frac{v_x^2}{|v|}+\alpha_{TV}\frac{v_y^2}{|v|}+D^*$$

$$D_{xy}=D_{yx}=(\alpha_L-\alpha_{TH})\left[\frac{v_x v_y}{|v|}\right]$$

$$D_{xz}=D_{zx}=(\alpha_L-\alpha_{TV})\left[\frac{v_x v_z}{|v|}\right]$$

$$D_{yx} = D_{xy} = (\alpha_L - \alpha_{TV})\left[\frac{v_y v_z}{|v|}\right]$$

where α_L is the longitudinal dispersivity; α_T is the transverse dispersivity; D^* is the effective molecular diffusion coefficient; v_x, v_y, v_z are components of the velocity vector along the x,y,and z-axes. Where

$|v| = \left(v_x^2+v_y^2+v_z^2\right)^{\frac{1}{2}}$ is magnitude of the velocity vector

NUMERICAL APPROACHES

The numerical approaches for solving the mass transport equations are based on computer based particle tracking methods. These are approximate forms of the advection-dispersion equation (5) as a system of algebraic equations or alternatively simulating transport through the spread of a large number of moving reference particles. These numerical approaches deal with variability of flow and transport parameters (hydraulic conductivity, porosity, dispersivity, etc.). One of the first steps in developing computer model is to sub-divide the region in terms of cells. This process makes it possible to account for variable nature of parameters involved in controlling groundwater flow and mass transport. Second step is to provide boundary conditions at a large number of node points and assign values. of concentration or loading rates defining various boundary conditions for all nodes located along boundary of the domain. Continuity consideration of numerical solutions of solute transport requires a smooth and accurate representation of velocity field, which can be obtained by simulation with a flow model. Velocity values are computed by applying Darcy's equation with calculated hydraulic heads and porosity values. The transport model is coupled to the flow model by the velocity terms. There is no requirement to solve the flow and transport equations simultaneously and in many cases concentration does not influence the flow by changing the fluid density. Flow is then assumed to be independent of mass transport.

The finite difference method replaces the governing differential equations of groundwater flow and solute transport by a set of difference equations applicable to the system of nodes. The difference equations approximate the first and second -order derivatives in the transport equation by concentration differences between node points. When each node in the grid is considered, the result is a system of algebraic equations, which can be solved with the matrix methods. The method of characteristics (MOC) takes the advection-dispersion equation and breaks it down into a set of simpler differential equations. This formulation in effect provides a frame of reference that is moving with the mean groundwater velocity. The transport of contaminants is simulated by adding reference particles and moving them in a prescribed manner. By varying the number of particles added at the source during any one-time step, it is possible to simulate complex loading functions. Advection is accounted by moving each particle by a distance in the direction of flow that is determined by the product of the magnitude of the groundwater velocity and the size of the time step. With a small time step, this particle motion traces a path line through the system (Konikow and Bredehoeft, 1978). Dispersion is accounted for in the particle motion by adding to the deterministic motion a random component, which is a function of the dispersivities. The mean concentration for each grid block is calculated as the sum of the mass carried by all the particles located in a given block divided by the total volume of water in the block.

Reliability of groundwater model predictions typically depends on the correctness of the conceptual model, availability and quality of model data and the adequacy of the prediction tools. Conceptualisation and characterisation are sufficiently understood to meet project objectives, and then the conceptual model may be translated into a mathematical model. Such a mathematical model typically consists of a set of governing equations and boundary conditions for groundwater flow and transport simulation. Relating such a mathematical model to a particular system requires specific values for system parameters, stresses and boundary conditions as well as rate coefficients. The application of geo-chemical and transport models requires simplifying assumptions with respect to system processes, stresses and geometry, a procedure referred to as model schematisation. Efficient model schematisation starts early during conceptualisation and characterisation process and continues into the code selection, model design or construction and model attribution and calibration phases of a modelling project. Determination of site boundaries is based on (a) natural site characteristics (topography, soils, geology, hydrology, biota, and chemistry) (b) current and past land use and (c) known or suspected extent of site-related contaminants. Investigations of groundwater contamination should include areas of potential source up-gradient and potential migration paths down-gradient from a vulnerable source location. Data from existing sources are gathered by identifying data sources and collecting and organising relevant data into a manageable database.

Transferring data into a conceptual model is rather intuitive process consisting of (1) qualitative and quantitative data interpretation of individual data elements and grouped data within a particular data type, (2) analysis of spatial and temporal relationships between various data types, and (3) relating data types and interpreted data to elements of specific system (i.e. processes, structure, state and stresses). The source, transport, fate and resulting distribution of each targeted chemical (e.g. inorganic and/or organic chemical constituents, tracers or isotopes) in the transport phenomenon are conceptualised in the second step. In the case of unknown sources, source locations and strengths are hypothesised from the conceptualised transport and fate processes and actual distribution of chemicals. The conceptual models are described and visualised using cross-sections and regional maps. Surface characterisation at the near ground-surface is made considering vegetation related (including plant releases and uptake) and rainfall related chemical exchanges with subsurface system.

Geological and geomorphologic and geo-chemical characterisation considers petrologic, mineralogical and geo-chemical factors and composition with respect to their spatial and temporal variations. Geological maps and cross-sections, sub-surface investigation logs, and stratigraphic columns are used in conjunction with surface characterisation, geophysical data and geochemical data and analysis to develop a part of the geological and geochemical framework that represent the distribution of lithological units and mineralogical and geochemical compositions as transport system materials. The groundwater system is characterised and quantified by determining the type, amount, temporal variation and spatial distribution of groundwater recharge and discharge using surface, subsurface and hydrogeological analysis. Further more, reaction and flow paths of indicative chemical species are analysed for information regarding the groundwater flow system. The groundwater system is quantitatively defined in terms of boundary conditions, flow paths and potentiometric surfaces and groundwater regime budget. Transport system characterisation analyses the presence, transport and fate of the chemical species in both space and time. At this stage relevant physical and chemical processes of the transport system are mathematically described and quantitatively attributed. Transport processes include advection, dispersion, adsorption, volatilisation, ion exchange and bio-transformation. The final result of this analysis is a characterised mass transport process model. An adequate computer code is chosen to simulate groundwater flow and mass transport processes.

The distribution of contaminants in the sub-surface is a manifestation of mass transport processes. Establishing this link is vital for understanding of how a particular contaminant plume has developed, how it can be expected to behave in future and how effective a remedial measure might be if implemented. The attributes distinguishing sources of groundwater contamination are:

- the degree of localisation,
- the loading history, and
- the kinds of contaminants emanating from them.

A point source is characterised by the presence of an identifiable small-scale source, such as a leaking storage tank, which produces a reasonably well defined plume. The loading history describes how the concentration of a contaminant or its rate of production varies as a function of time at the source. The concentration of chemical wastes added to storage pond at an industrial site can vary with time due to changes in a manufacturing process, seasonal or economic factors.

GROUNDWATER FLOW MODEL

Slice successive over relaxation is a method for solving large systems of linear equations by means of iteration. This method is implemented in the SSOR package of MODFLOW by dividing the finite difference grid into vertical slices and grouping the node equations into discrete sets, each set corresponding to a slice. In every iteration, these sets of equations for each slice are processed. They are first expressed in terms of the change in computed head between successive iterations. The set of equations corresponding to the slice is then solved directly by Gaussian elimination treating the terms for adjacent slice as known quantities. The values of head change computed for the slice are then multiplied by an acceleration factor, ω generally taken between 1 and 2. The computed heads are taken as the final values of head change in that iteration for the slice. This procedure is repeated for each slice in sequence until all slices in the three-dimensional array have been processed, thus completing a domain iteration. The entire sequence is then repeated, until differences between the computed head values in successive iterations is less than the chosen criterion at all nodes in the grid. The solver checks for the maximum change in the solution at every cell after completion of every iteration. If the maximum change in the solution is below a set convergence tolerance then the solution has converged and the solver stops. Otherwise a new iteration is started (McDonald and Harbaugh, 1988).

Ganga-Kali sub-basin, a part of central Ganga basin, Uttar Pradesh

The Ganga-Kali sub-basin forms a part of central Ganga basin and lies in the Bulandshahr district, western Uttar Pradesh (Fig. 1). Varanasi Older Alluvial Plain, Aligarh Older Alluvial plain, Terrace zones and Ganga recent flood plain are the geomorphic units and abandoned channel of Ganga river, channel scars and meander scars represent various land forms. The aquifer extends up to 120 m depth except at places where it is intercalated with 5 to 10 m thick lenticular clay beds. The transmissivity, storativity and permeability values are varying from 522 m^2/day to 2500 m^2/day, 1.13 x 10^{-3} to 1.5 x 10^{-3}, and 20 m/day to 50 m/day, respectively. The seepage from upper Ganga canal, lower Ganga canal and their network is playing a vital role in controlling the groundwater regime. The terrigenous clastic deposition system of the river Ganga in the area was an index of the complex hydrodynamic behaviour of groundwater regime in the Ganga basin.

Table 1. Groundwater balance (mcm) in Ganga-Kali sub-basin

Input stresses		Output stresses	
Recharge due to rainfall	110	Lateral outflow	14
Seepage from Ganga canal and its distributaries	62	Pumping through wells	123
		Outflow to Chhoiya and Nim rivers	12.8
		Outflow to Kali river	1.6

Note: Net pumping was considered, so irrigation return flow was not shown separately (36 mcm i.e. 30% of net pumping)

The permeability is varying from 32 m/day near Ganga river to 20 m/day near the western boundary (Fig. 2). The average recharge due to rainfall (95 mm/year) estimated elsewhere for alluvial tracts of Ganga basin was initially assigned as input. The seepage from the upper Ganga canal and its distributaries was simulated as additional recharge spread throughout the year by deploying Recharge package in the model (Fig. 3). The lateral outflow across the southern boundary from the second and third layers has been simulated as constant head boundary. The western boundary was considered as no flow boundary except the Kali river. The Ganga, Chhoiya, Nim and Kali rivers are represented by assigning appropriate river stages, river bed elevations and connecting intervening hydraulic conductance between river bed and the aquifer system in the River package. The draft has been simulated by assigning appropriate pumping rates at individual pumping centres. The pumping rates are varying at pumping centres varying from 50 -100 m^3/day at wells taping top aquifer whereas pumping rates are in the range of 800-1000 m^3/day for deeper wells. Temporal variation in pumping rates depended on monsoon or non-monsoon seasons and were was taken care while assigning pumping schedules during 10 year period of simulation. The water level in June 1986 was selected as initial water level for steady state model calibration. The computed water level contours and groundwater velocity vectors indicate that different flow patterns observed in the sub-basin, viz. outflow towards Ganga river, groundwater effluence to Chhoiya and Nim rivers and a little contribution from Kali river (Fig. 4). The influence of seepage from upper Ganga canala, lower Ganga canal and other canal network could also be seen from the groundwater flow directions originating from the canals. The groundwater balance has been worked out (Table 1). The transient simulation has been carried out from June 1986 to May 1996.

Water Harvesting Structures in Wagarwadi Watershed, Parbhani District, Maharashtra

Wagarwadi watershed (564 hectares) is a micro-watershed of Purna river basin located in Parbhani district, Maharashtra (Fig. 5). The physiography is undulating to rolling in upper parts of topo-sequence with a slope of 8 to 10%. The slope is 2 to 5% in the central part whereas towards lower parts the land is almost plain having a slope ranging between 0.5 to 2% with flat gullies formed due to erosion. The soils are of basaltic origin. The predominant group is of light type of soil having a depth of about 5 to 15 cm covering about 47% of the area. Medium and heavy soils comprise about 23 and 20% of the area, respectively. The afforested and pasture area of the watershed was treated with staggered and contour trenches. Two *nala* bunds, one cement plug and a stone (loose boulder) check dam are constructed at different places across slope on two ephemeral stream courses joining the main channel of Aundha tank during 1992. The depth of impounding water behind the embankment was fixed as 4 m based on contour map of *nala* bunds stage capacity relationship. The catchment area for *nala* bund 1 is 59.6 hectares. The silt deposited on the upstream side of *nala* bund was measured. The height of impounded water was kept as 4 m for which total length of bund was 195 m. The height, bottom width and top width were kept as 5.33 m, 33.64 m and 2.5 m, respectively. The measurements of 1997-98 were as follows:

- Length and width of impounding water in *nala* bund no. 1 was found to be 100 m and 150 m, respectively with a storage capacity of 22,500 m^3.
- Length and width of impounding water in *nala* bund no. 2 was found to be 140 m and 130 m, respectively with a storage capacity of 36,400 m^3.
- Cement plug no.1 has 3 m width and a water spread area extending upto 300 m with a depth of 1 m and a storage capacity of 6,880 m^3.

A groundwater flow model of the micro-watershed was constructed to assess the impact of impounded water in the *nala* bunds on the groundwater regime. The water table configuration of June 1997 was assumed to be under equilibrium and was considered as the initial water level for steady state condition. The nodes falling on the stream channel may have relatively larger thickness of weathered zone owing to stream flow in the channel and thus, may have higher permeability. The permeability distribution was estimated from pumping tests and is varying from 1 m/day to 1.6m/day in the area. Groundwater recharge was worked out from a separate water balance model and was estimated as 91 mm during 1997-98. The groundwater abstraction from the wells was given appropriately based and field measurements. The balance of the recharge goes as outflow to the stream. A specific yield of 0.01 was arrived from model calibration under transient condition. Water was stored in these structures for about 9 months during the year. The stored water could artificially recharge the groundwater regime, thereby resulting in rise of water levels in the observation wells situated downstream of these structures.

The two *nala* bunds and cement plug structures have been simulated as lake interaction in the model by simulating the ponding levels and connecting hydrualic conductance between the beds of *nala* bunds/cement plug and groundwater levels. The hydraulic conductance of 20 m^2/day for *nala* bunds and 10 m^2/day for cement plug ponds was simulated in the model. Thus, the additional input has been appropriately simulated as artificial recharge from the water harvesting structures. The additional input was arrived from the model calibration by matching the computed hydrographs with the observed water levels. Maximum rise of water table of 2 m has been observed in wells located about 200 m on the downstream of *nala* bund no.2. There has been an overall increase in water table elevation owing to the artificial recharge from the ponding of water in the water harvesting structures (Gore *et. al*, 1998). The artificial recharge has been worked out from the model was 8,274 m^3 for *nala* bund no.1, 18,083 m^3 for *nala* bund no.2 and 4,452 m^3 for cement plug pond. The artificial recharge has been worked out as 36.7%, 49.6% and 64.7% of surface water storage for *nala* bund no.1, *nala* bund no.2 and cement plug no.1, respectively during 1997-98. The *nala* bunds and cement plug structures are effectively contributing for artificial recharge through harvested water in the Wagarwadi watershed.

MASS TRANSPORT MODEL

Mass transport in three dimensions (MT3D) is a computer model for simulation of advection, dispersion and chemical reactions of contaminants in three-dimensional groundwater flow systems (Zheng, C., 1990). The model is used in conjunction with a block-centred finite difference flow model, MODFLOW, and is based on the assumption that changes in concentration field will not measurably change the flow field and uses a mixed Eulerian-Lagrangian approach to the solution of the advection-dispersion equation, based on a combination of method of Characteristics (MOC) and the modified method of characteristics (MMOC). Longitudinal dispersivity is specified as a characteristic of the soil type (related to the tortuosity of interconnected pores) which tends to spread out contaminant mass along the advective path of the plume. The horizontal transverse (plume width) and vertical transverse (plume thickness) dispersivities are assigned as ratios (fractions) of the longitudinal dispersivity as required by MT3D. The molecular diffusion coefficient is also to be given as input. The hydrodynamic dispersion coefficient is computed as the product of the dispersivities and velocity (mechanical dispersion) plus the molecular diffusion coefficient. The MOC uses a conventional particle tracking technique based on a mixed Eulerian-Lagrangian method for solving the advection. The dispersion, sink/source mixing and chemical reaction terms are solved with the finite difference method (Zheng, C., 1990).

Contaminant migration in groundwater due to industrial effluent in Venkatapuram area, Andhra Pradesh

Untreated industrial effluent from the Hindusthan Polymers is being discharged into a stream which joins two small tanks in Venkatapuram, Visakhapatnam, Andhra Pradesh (Fig. 6). The groundwater and water quality monitoring has been carried out since 1981 in 33 observation wells covering an area of 15 km^2. The water quality measurements during 1991-92 indicated elevated Total Dissolved Solid (TDS) concentration (as high as 4,500 mg/l) in a few observation wells as compared to 1981-82. The TDS concentration of the effluent was observed as 6,500 mg/l at the outlet of the plant during the same period. The transmissivity and storativity of the Khondalitic aquifer system were estimated from 3 pumping tests carried out on large diameter wells. The lithologs indicated a 30 - 40 m thick unconfined aquifer. The regional water table configuration in May 1981 was used for steady state model calibration. Transient model was calibrated for three years period from 1981.

Conceptualisation of the groundwater regime from above information formed the basis for mathematical modelling of groundwater flow. Two different versions of the groundwater flow models were made using MODFLOW (McDonald and Harbaugh, 1988) and FLOWPATH computer codes (Franz and Guiger, 1990). The models use a block centred finite difference grid. Initial conditions, the flow parameters as obtained flow model, were fed as input to the mass transport model. Solute transport modelling was carried out using the MOC computer code. The effective porosity and dispersivity values were assigned conforming to the values estimated for similar hydrogeological formations elsewhere. The effective porosity of 0.2, longitudinal dispersivity of 40 m and transverse dispersivity of 10 m were used uniformly for the entire area. The source concentration of 4,000 - 4,500 mg/l at the water table was estimated from the analysis of surface water and groundwater quality data. It was assumed that the effluent reaching the water table source nodes are located just below the stream course and two tanks. Thus, sources concentration was distributed at 8 nodes in the model. It was assumed that the quantum of fluid effluent seeping to the groundwater system was about 20 - 30 % of that discharged at the surface and solute reaching the water table would be about 70 - 80% of TDS concentration of the effluent at the surface (Subbarao and Gurunadha Rao, 1999).

Flow paths and advective travel times for specified periods of time were determined with the help of particle tracking computer code FLOWPATH by computing particle movement through a velocity field. The groundwater velocity field consists of velocity vectors resolved from inter-cell flow rates computed for individual grid cells in a mathematical flow model.

The computed path line of a particle can be displayed graphically as a trace of discrete points (x, y, z, t) viewed in the x-y, x-z and y-z planes of a Cartesian co-ordinate system. Imaginary particles released at source node points, track the movement of particles in groundwater as path lines. Path lines in this case were predicted for 30 years (Fig. 7).

Calibration and prognosis of the solute transport model was also made for the same period for quantifying the migration of TDS concentration. Areal migration of TDS concentration for 30 years was computed from transport model and compared with predicted path lines from FLOWPATH model (Fig. 8). The computed TDS concentration of contaminant is found matching satisfactorily with the observed TDS concentrations during 1992. Prognosis of migration of contaminants indicated that the effected area increases by 20% of the present level with elevated concentrations in the range of 200 to 1500 mg/l in a period of 10 years (Subbarao *et al.*, 1998).

Contamination of a water supply well in the Sabarmati River bed aquifer in Ahmedabad

French wells are radial collector wells with several horizontal radial infiltration pipes emanating from a central caisson (also called jack well). Under favourable hydrogeologcial conditions these are convenient means of groundwater recovery. Five such wells are supplying drinking water from the Sabarmati River bed aquifer during last decade. Each well was pumping at a rate of 4,000 m^3/day. Bacterial and fungal contamination was detected in the French well water near Sabarmati Railway Bridge in Ahmedabad during September, 1992 (Fig. 9). National Environmental Engineering Research Institute (NEERI), Nagpur and Physical Research Laboratory (PRL), Ahmedabad had jointly investigated the contamination problem (Draft Final Report (DFR), 1994). The contamination problem could have been due to infiltration of the river water containing sewage effluent discharged in this reach of Sabarmati River. They have carried out three types of investigations:

- a tracer test designed to ascertain if there existed a rapid channel type of flow between the sewage discharge points and any of radials of the collector wells
- a step draw-down pumping and recovery test to understand process of the French well-river bed aquifer interaction, and

- physico-chemical and bacteriological analyses of the river bed aquifer soil samples to ascertain the extent of river bed contamination.

It was reported that observed contamination of water pumped from the collector well was not caused by any channel type of flow. It may be due to slow and steady migration of contaminants through years of persistent sewage effluent discharge from river banks. The groundwater flow, path line and mass transport models were developed to analyse reported concepts and to verify results of field experiment carried out by computing groundwater velocities and studying migration of contaminants from sources in the river bed aquifer. The hydraulic gradient in the river bed aquifer was assumed as 0.5 m/km and porosity as 0.2. The permeability of formations on either side of Sabarmati river course was assumed 20 m/day. The thickness of first layer was 18.3 m and second layer as 10.0 m. TDS concentration of Sewage effluents was in the range of 800 - 1000 mg/l and at the source locations groundwater TDS concentration has reached about 500 mg/l. Groundwater TDS concentration at the source nodes was kept constant at 500 mg/L throughout mass transport simulation. The longitudinal dispersion coefficient of 30 m and a horizontal transverse dispersion coefficient of 10 m was assumed to account dispersion processes. Predictions were made to determine capture zone of the French well under two Scenarios:

- when the river bed was dry with only later groundwater inflow /outflows across the river bed cross-section under Scenario I
- under controlled release of surface water from upstream Dharoi reservoir to keep a minimum water column of 0.2 m in the Sabarmati river (Scenario II).

Comparison of path lines and iso-concentration contours of TDS under both scenarios indicate that capture zone of the French well under Scenario II was much less than under Scenario I (Fig. 10). The scenario II indicated the necessity of providing controlled release of surface water from Dharoi reservoir to maintain a minimum level of 0.2 m surface water around the French well. The scenario could be implemented through appropriate planning of controlled release of surface water from Dharoi reservoir. The significant role of river-aquifer interaction controlling pollutant migration from sewage source was also evident. Thus, it became imperative for the government to implement a scheme of controlled release of surface water from Daharoi reservoir throughout the year to reduce contaminant migration from sewage source in this reach of Sabarmati river (Gurunadha Rao and Gupta, 1999). The computed radius of influence of French well as 150-200 m in the model, when there is flow of surface water in the river, confirmed pumping test results.

Patancheru Industrial Development Area and its Environs, Medak District, Andhra Pradesh

The Patancheru Industrial Development Area (IDA) forms part of catchment of Nakkavagu, a tributary of Manjira River. The area covers about 120 km^2 under Patancheru, Mandal of Medak district, Andhra Pradesh, India (Fig. 11). The industries are located around Patancheru village on both sides of National Highway from Hyderabad to Mumbai. More than 400 industries are functioning dealing in production of pharmaceuticals, paints and pigments, metal treatment and steel rolling, cotton and synthetic yarn and engineering goods since 1977. Most of these industries use various inorganic and organic chemicals as raw material in the manufacturing and processing units. The effluents contain appreciable amounts of these chemicals and their bye products. These effluents (mostly untreated) are discharged into various unlined channels and streams. The Common Effluent Treatment Plant (CETP) of Patancheru was situated adjacent to Peddavagu and treats various untreated effluents from a number of industries. The wastewater from the CETP is let out into Peddavagu. The wastewater discharged from the CETP contain total dissolved solids (TDS) concentration ranging from 4000 to 5000 mg/l.

The Pamulavagu, Peddavagu and Nakkavagu streams while carrying effluent contributes as a diffuse source of contamination all along its course up to confluence with Manjira River near Gowdcherla village. The alluvium around Nakkavagu is a result of paleo-channel course of Manjira River and forms a potential groundwater bearing zone. Contaminants on reaching groundwater table through stream-aquifer interaction migrate in the aquifer system mostly through advective dispersion. The rate of movement and consequent spread of pollutants depends upon the hydraulic gradient and groundwater velocity. To determine the groundwater velocity distribution a groundwater flow model was constructed. The computed velocity distribution was used to analyse advective and dispersive transport to determine contaminant migration in the area.

Estimation of aquifer parameters is essential for quantifying the groundwater resources and also to determine well characteristics. Pumping tests were carried out on 10 wells including bore wells, filter points and dug wells. High transmissivity values were obtained in alluvial formations, despite limited aquifer thickness. The pumping test data were interpreted using GWW computer software. The transmissivity was found to vary from 140 m^2/day in granites to 1300 m^2/day in alluvium (Fig. 7). The permeability values as high as 50-75 m/day are found in the alluvium around Arutla village. Intensive groundwater irrigation has resulted in stream aquifer interaction around this village.

The surface water while seeping through bed of Nakkavagu carries effluent to groundwater regime thereby contaminating groundwater up to a distance of 600-800 m on the East of Nakkavagu. The well inventory and lithologic data collected from tube wells indicated that top weathered aquifer having 10-12 m thickness was underlined by a fractured layer. The most important process contributing to the mass transport in groundwater is advection. Longitudinal dispersion is relatively significant but transverse dispersion could be negligible. The total dissolved solids (TDS) concentration in contaminant was selected for a detailed model study because (a) it's concentration remained relatively constant in effluent ranging between 1000-4000 mg/L along different reaches of Nakkavagu, and (b) it showed a uniform background level of about 300 mg/L in native groundwater. The initial stage in developing the flow and TDS concentration solute transport models was to define the region of interest and establish boundary conditions for flow and solute transport.

The simulated model domain of Patancheru IDA and environs consist of 51 rows and 88 columns and 2 layers covering an area of 22000 m x 8000 m. The top layer consists of 10-15 m thick alluvium along Nakkavagu or a weathered zone in granite and was underlain by 10-15 m fracture zone. The simulated vertical section has a total thickness of 30 m in the model. The outflow from groundwater flow model was estimated in terms of a constant head node at the confluence of Nakkavagu with Majira river by assuming outflow towards Manjira river. The groundwater recharge @ 110 mm/year has been fed to simulate distributed recharge to aquifer system from the first layer in the recharge package. Continuous seepage from Peddavagu, Pamulavagu and Nakkavagu streams was simulated as additional input in the model as there was always some effluent flow in Nakkavagu at Ismailkhanpet bridge even during summer months.

The values of dispersivity in longitudinal and two transverse directions (Y and Z) were assumed to be 50 m, 5m and 0.05 m respectively. The tendency for α_L to be about 10 times larger than α_{TH} and for α_{TZ} to be much smaller than either of them is in line with the concentrations determined in the area. The relatively smooth decline of TDS concentration away from the Nakkavagu suggests a relatively constant rate of loading. Thus a constant TDS concentration at different nodes on Nakkavagu was assigned varying from 3500 mg/L at source near Patancheru and 1000 mg/L away from the source at about 18 km downstream of Nakkavagu near Ismailkhanpet. The computed iso-concentration contours indicate that the plume is expanding and follows the hydraulic gradient implying that advection is the dominant mechanism of spreading. Qualitatively shape of the plume indicates that longitudinal dispersion is more significant than transverse dispersion. The contaminant migration was to be found extending up to 500-600 m from Nakkavagu on the eastern part during last 20 years (1997) (Fig. 12). The modelling study has helped in gaining a better insight of the hydrogeologic set up and assessment of contaminant migration due to mass transport processes. Over-exploitation of groundwater in the alluvial parts of Nakkavagu has resulted in decline of water table, resulting in further contamination of groundwater through stream aquifer interaction. Remedial measures like reduction of concentration of effluent in waste water let out into streams from CETP and individual industries has been suggested to contain elevated concentration of TDS (Gurunadha Rao *et al.*, 1999).

CONCLUSIONS

The groundwater modelling is a prognostic tool for assessment and management of groundwater potential as well as pollution due to discharge of effluents on ground surface. The case studies illustrated the applicability of flow and mass transport models for assessing the contaminant migration. These studies will help in planning creation of organised geohydrologic and water quality database for construction of reliable groundwater flow and mass transport models for understanding and prediction of likely contamination of groundwater from effluent sources and designing of necessary remedial measures.

It is fairly common for comprehensive and intensive hydrologic investigations to include the development, application and calibration of simulation models of groundwater flow and to use them to make predictions. Data collection and monitoring in a study area tend to be curtailed after the project has ended. This inevitably results in deficiency of future data relating to prediction period. The collection of new data after a prediction was made provides the basis for a strict test of model accuracy - post audit. If a model is to be used for prediction of responses in a system, subject to continuing water management constraints, it should be periodically post audited and re-calibrated to incorporate new information such as changes in imposed stresses or revisions of the assumed conceptual model. There is no sure way to reliably predict the future, but because management decision must be made, predictions of future conditions needed and will be made in one or the other manner. To make the most reliable prediction for a given groundwater problem, all relevant information should be considered and evaluated in order to arrive at the best estimate of the future behaviour of system. Additional pumping tests are recommended to characterise the deeper aquifer. Regular monitoring of water level as well as water quality should be continued to assess the changing water quality due to waterlogging in canal command areas. In view of occurrence of large amount of outflows to the rivers from the basin, it was suggested to reduce the amount of outflow by development of additional groundwater resources from deeper aquifers for irrigation purposes in future.

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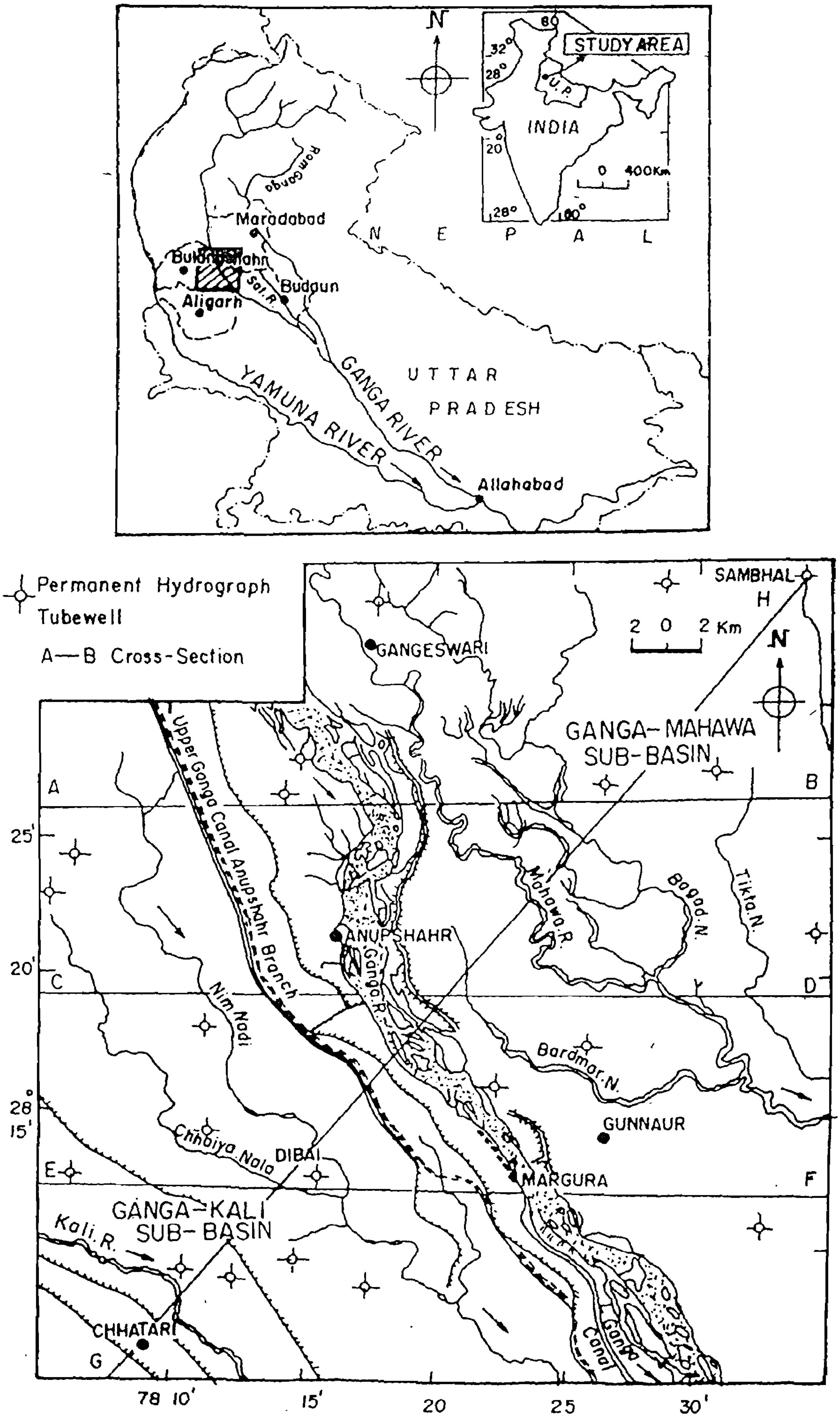


Fig. 1 Ganga-Kali-Sub-basi

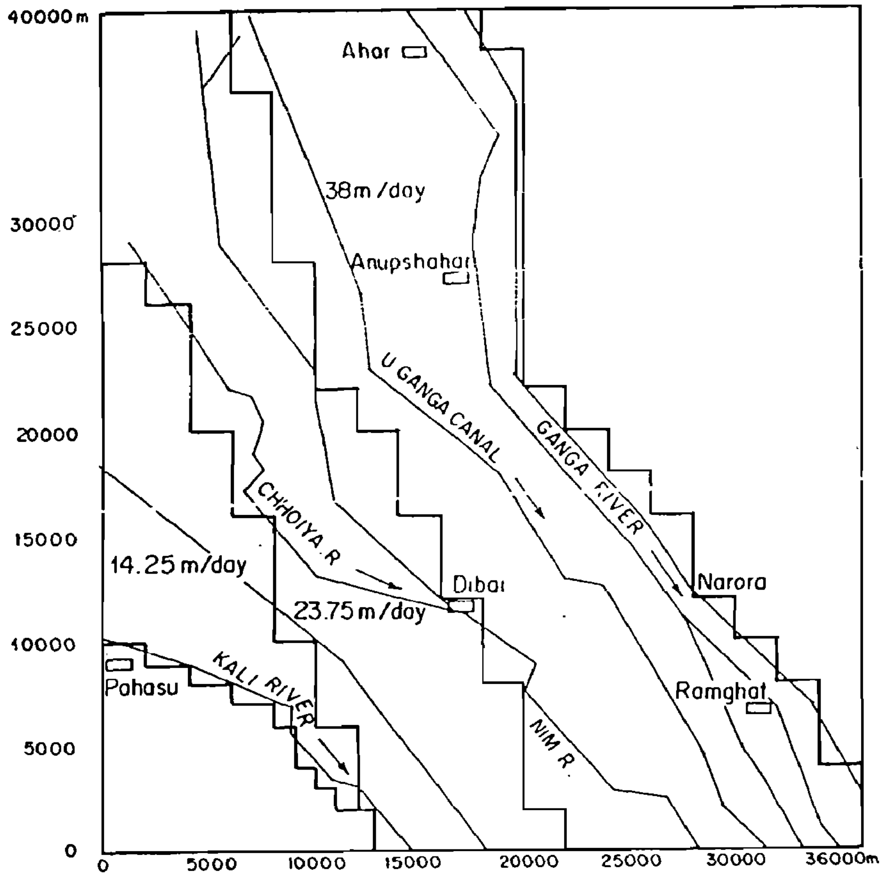


Fig. 2 Block-wise permeability in Ganga-Kali sub-basin

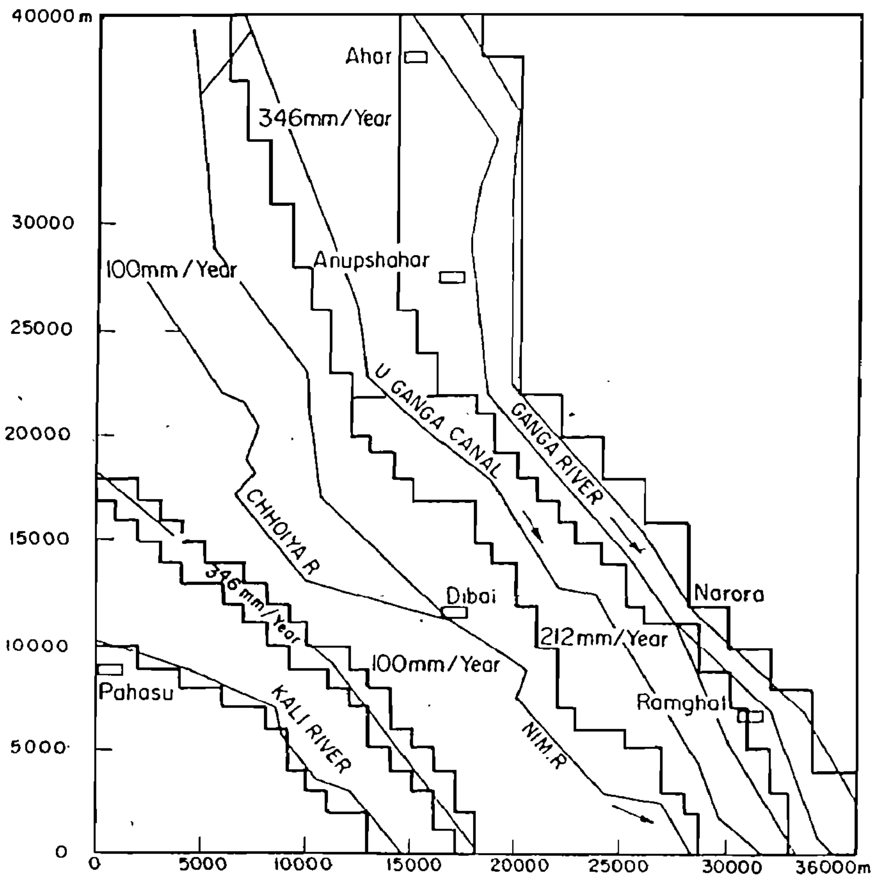


Fig. 3 Distribution of recharge, seepage losses from Upper and lower Ganga canals

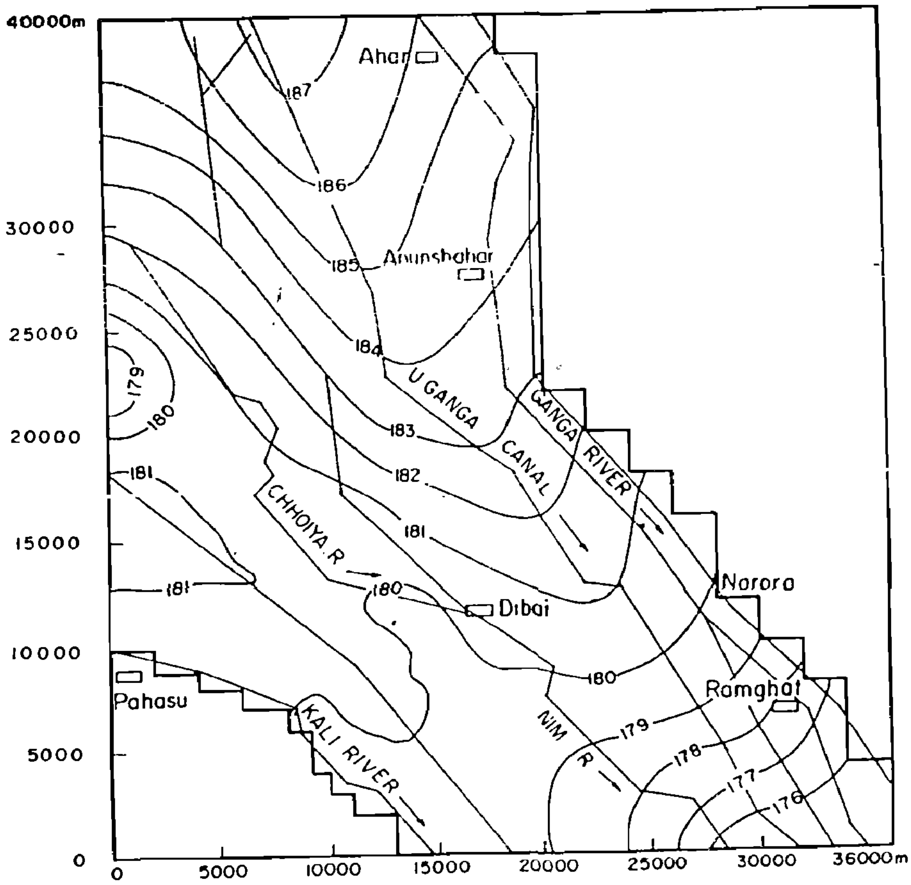


Fig. 4 Computed water table contours in m (amsl) during June 1986

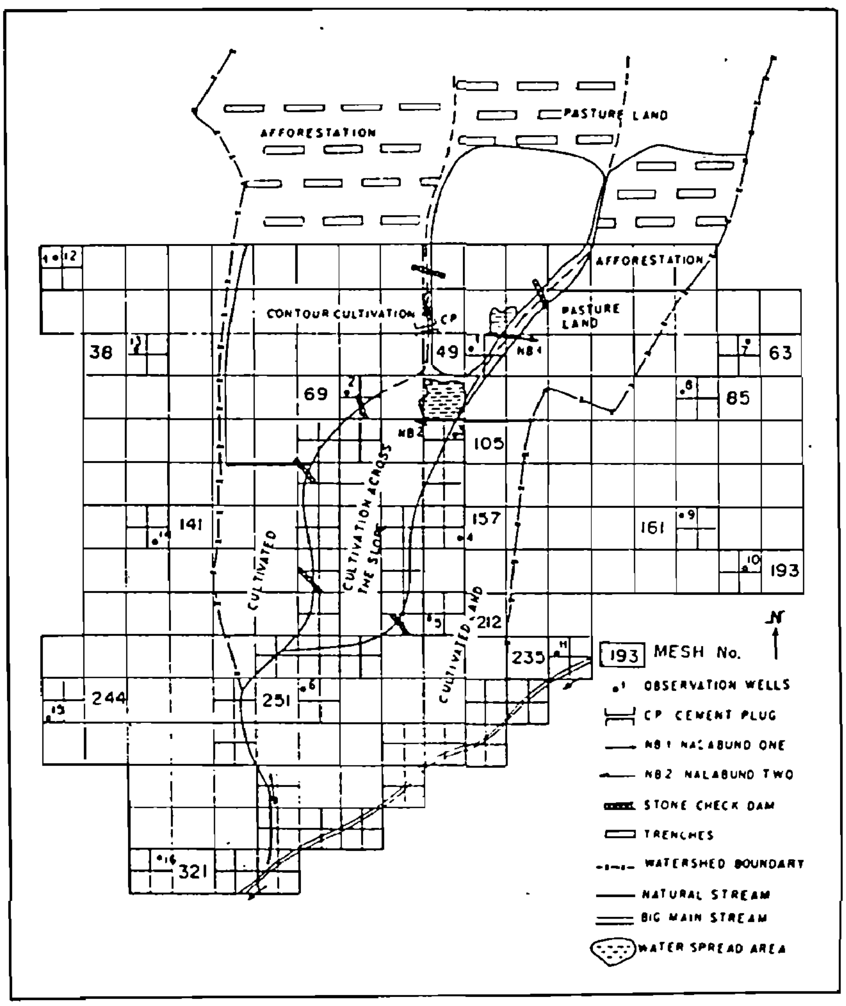


Fig. 5 Water harvesting structures in Wagarwadi watershed, Parbhani district, Maharashtra

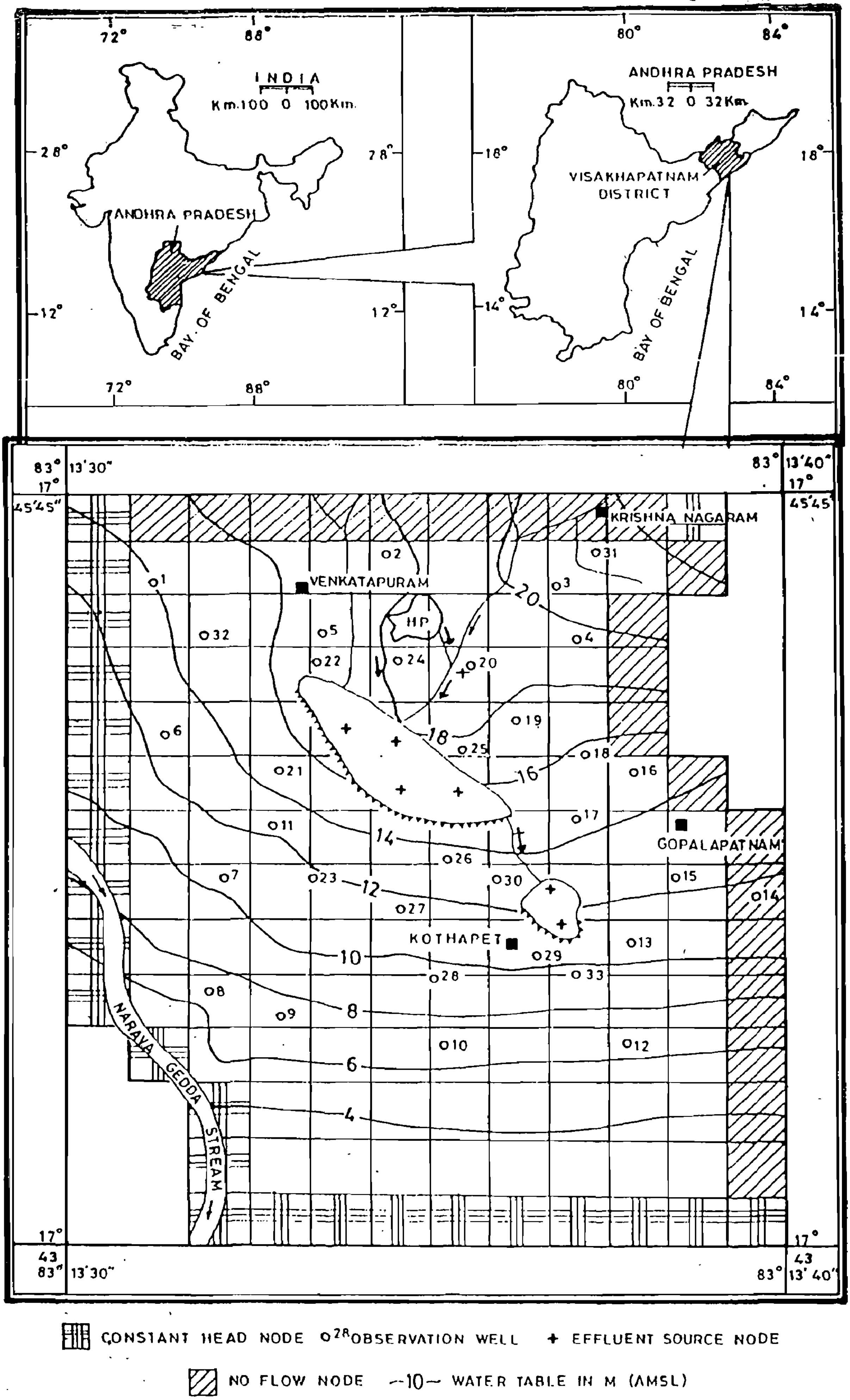


Fig. 6 Grid map of Venkatapuram area, Visakhapatnam and boundary conditions

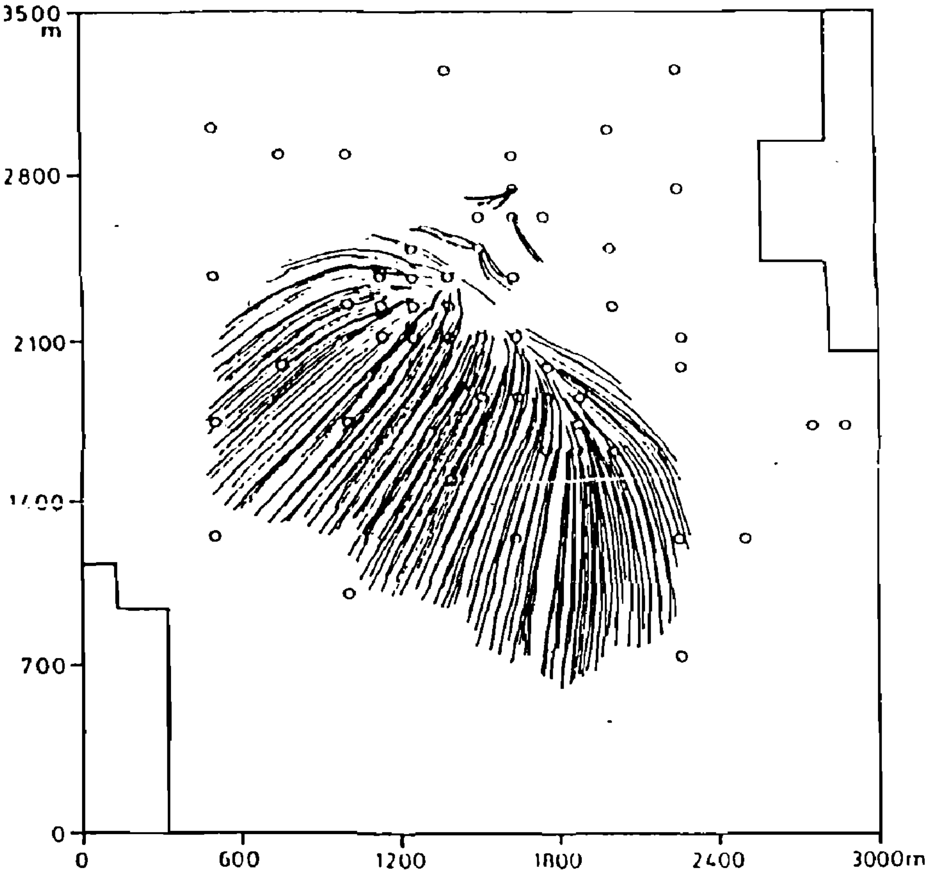


Fig. 7 Pathlines of contaminant migration for 2002 (30Years)

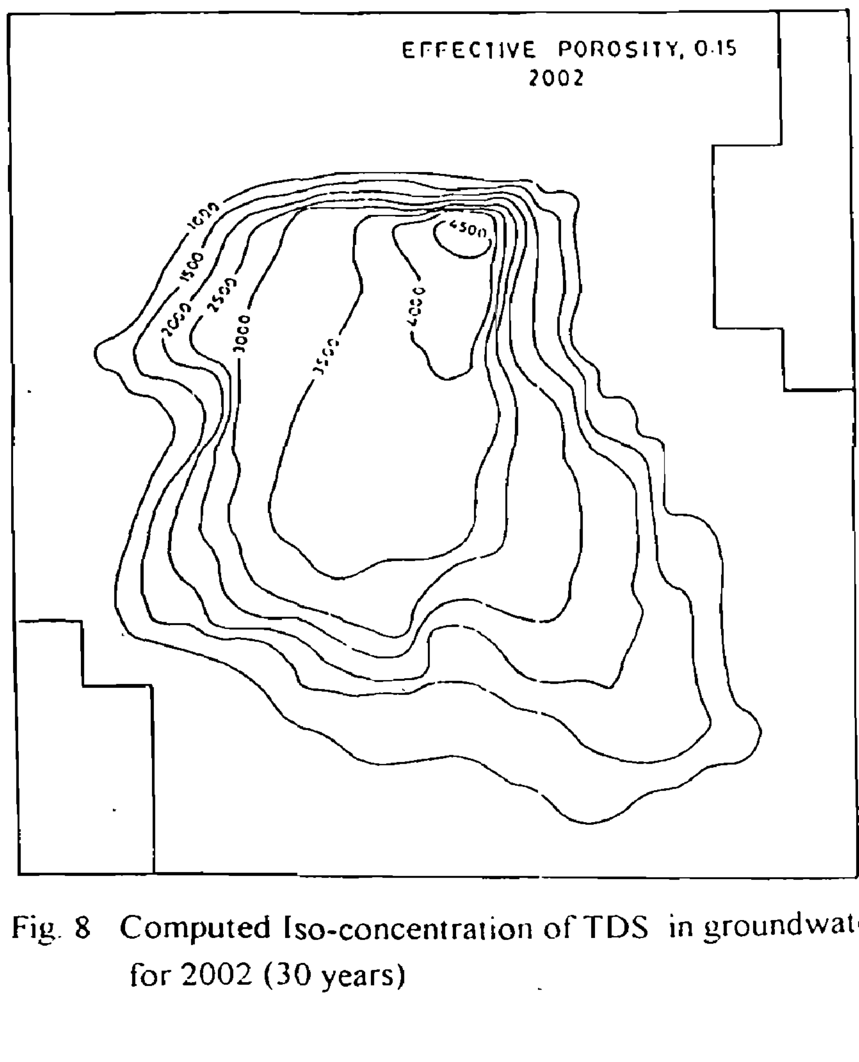
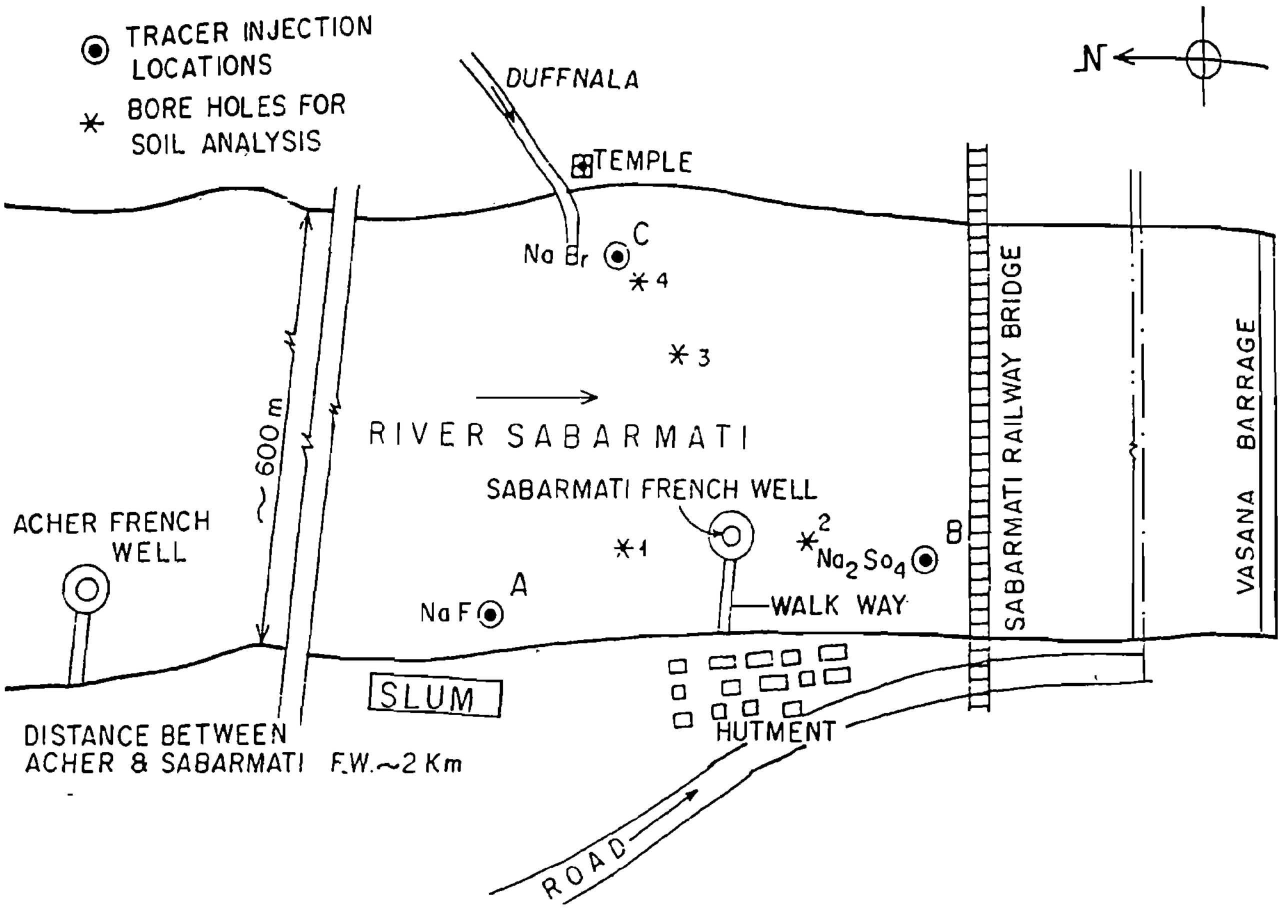


Fig. 8 Computed Iso-concentration of TDS in groundwater (in mg/l) for 2002 (30 years)



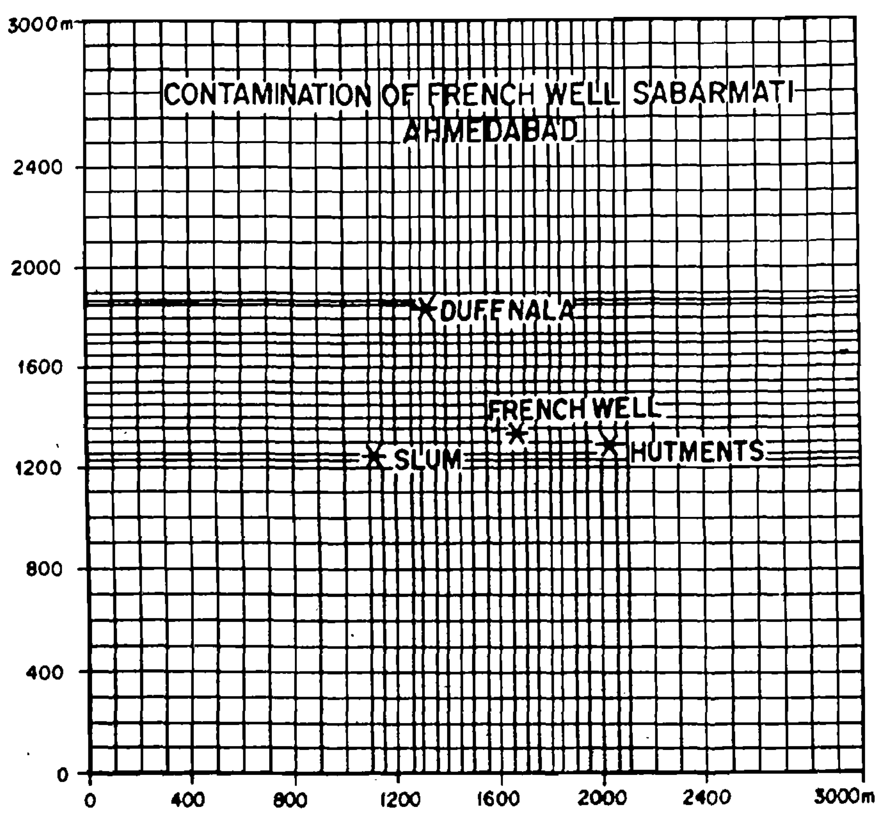


Fig. 9 Water supply well and sources of pollution in Sabarmati river bed, Ahmedabad

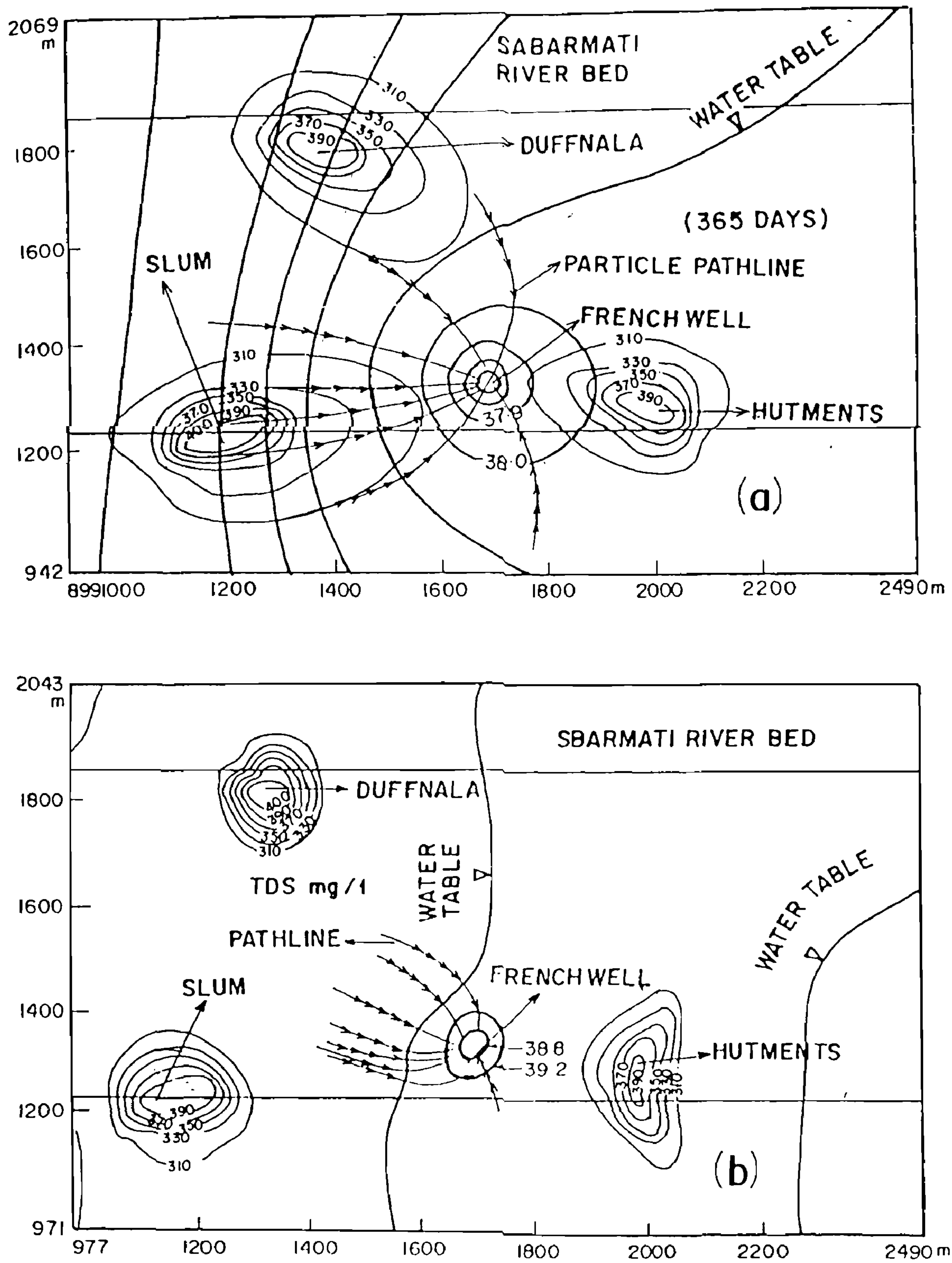


Fig. 10 Computed contaminant migration from sewage sources and capture zone of French well under (a) Scenario I - Dry river bed; (b) Scenario II- Flow in river

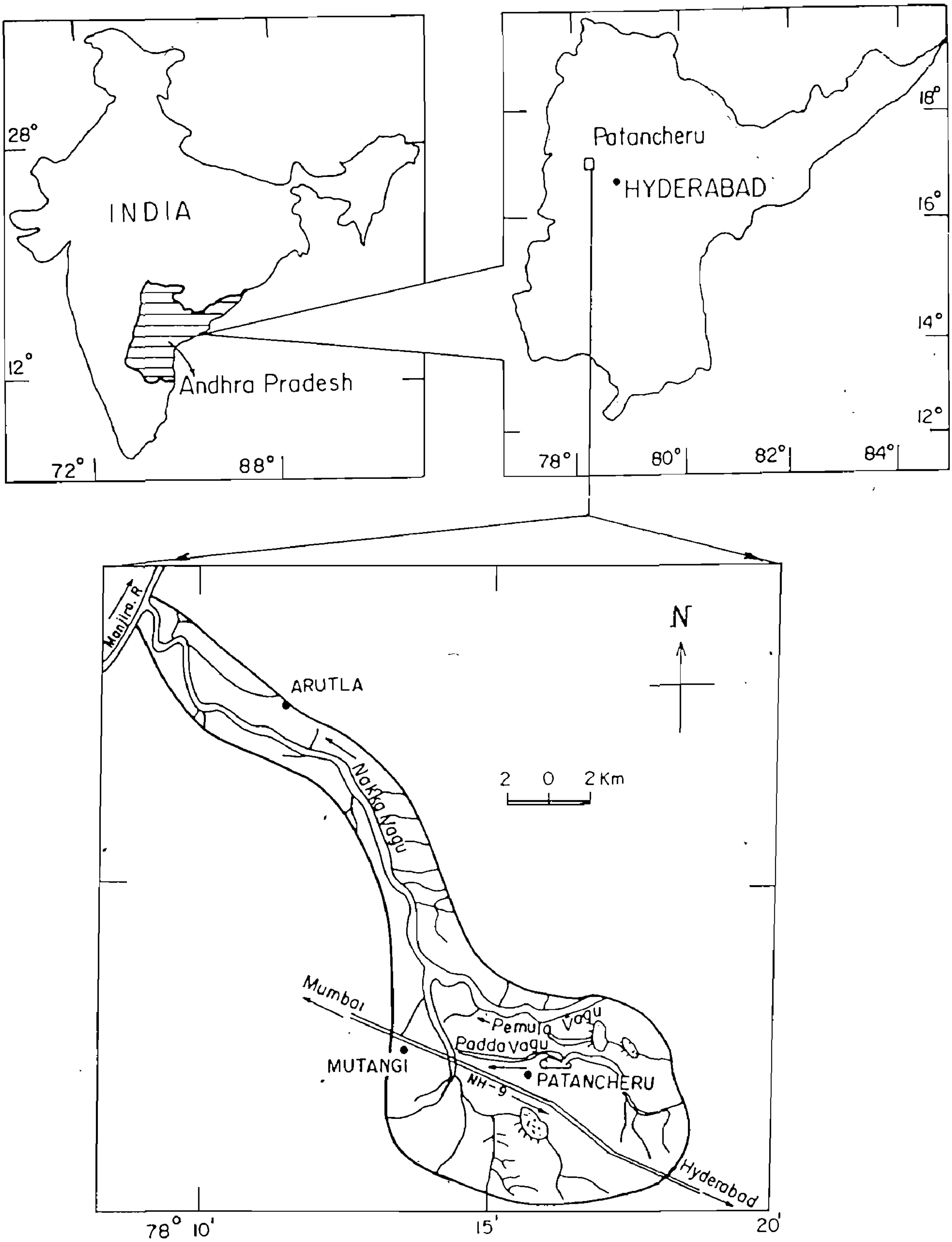


Fig. 11 Patancheru Industrial Development area near Hyderabad, A.P.

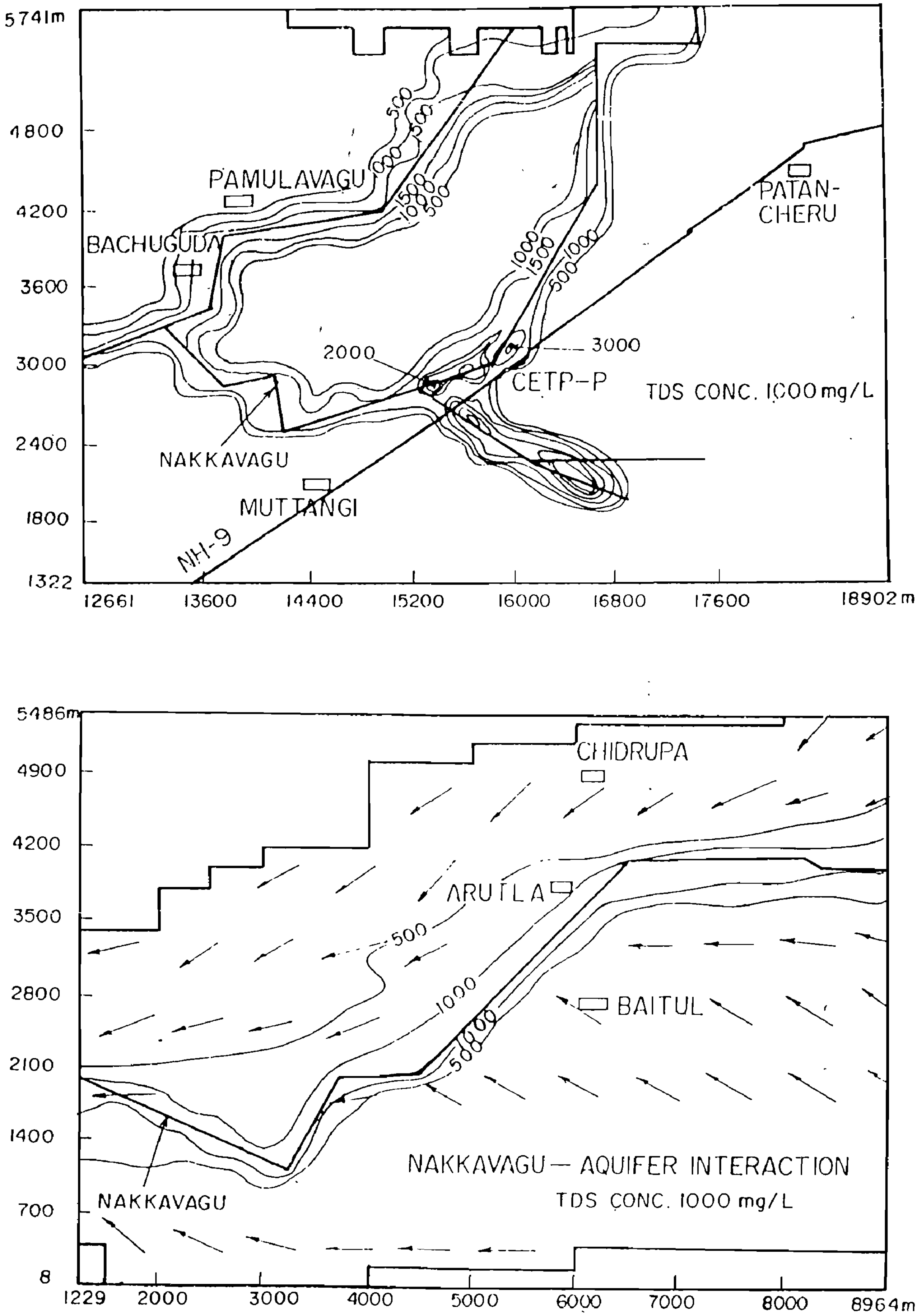


Fig. 12 Computed TDS concentration (mg/l) of groundwater in Patancheru IDA for 1997

REMEDIATION OF CONTAMINATED GROUNDWATER

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INTRODUCTION

Groundwater is a very important source of water and several instances of groundwater contamination have illustrated the adverse impact that contaminated groundwater has on human health and the environment. When the groundwater contains contaminants at concentrations that may be harmful to humans and the environment, it needs to be remediated. A lot of research work has been done to identify ways by which remediation work could be carried out and a review of the literature (NRC, 1994; Brusseau, 1996; Cohen and Miller, 1983; Johnson *et al.*, 1993; and Schnoor *et al.*, 1995) shows that newer techniques are being evolved to achieve these goals.

REMEDIATION GOALS (NRC, 1994)

It is very important to define the remediation goals in any groundwater remediation program. Some of these can be listed as:

- Complete restoration. This procedure involves the complete removal of all the contaminants from the aquifer, a task which is quite impossible to achieve. However, if it is possible to restore the aquifers, it could eliminate all risks.
- Non-degradation. This procedure involves the removal of contaminants that exceed either the detection limits of available analytical equipment or background concentrations. It is extremely expensive, difficult and time consuming for many contaminants and hydro-geologic settings to achieve.
- Containment. This involves the use of engineered systems for preventing the migration of other locations in the aquifer. This is a very reliable and predictable way that also costs less than most of the remediation methods, however it may result into migration of the contaminants in the subsurface environment in case the system fails.
- Technology based standards. Involve the use of the best available technology to remove as much of the contaminants as possible. However, it may not be possible to reduce risk to a level that is not harmful to human health and the environment.

- Remediation to health based standards. This involves the removal of contaminants so as to prevent measurable impacts to human and environment, however, such standards are very difficult to define and may fail to address all possible health impacts of exposure to contaminated groundwater.
- Government control. This involves the imposition of legal restrictions on the use of groundwater in those areas that have been identified as contaminated by using physical barriers like a fence etc., which really does not work unless the restrictions are stiff.

Thus, the degree to which the groundwater needs to be remedied is important when deciding on the remediation goals. In the past, especially in the USA, a simple procedure of 'pump-and-treat', has been very popular. However the recent studies of the USA, EPA has shown that the success of this method is very low. A look at all the goals mentioned above suggests that for most circumstances the best available technologies are incapable of restoring the quality of water, but on the other hand many remediation systems now are being designed with the goal of either containment or remediation to health-based standards. To ensure the success of the remediation goal, it is important to first estimate the risk associated with the exposure to the contaminated groundwater and then to design the system.

GROUNDWATER REMEDIATION SYSTEM DESIGN

To design an effective system for groundwater remediation, it is important to understand the nature and extent of contamination, the remediation objectives and an evaluation of the remedial technologies and their ability to meet the objectives, at the same time ensuring that the system is both efficient and cost effective. A stepwise approach can simplify the entire design procedure and minimize the chances of failure of the system to achieve the remediation goals. (NRC, 1994)

Step 1. Define the Problem

The problem needs to be defined in adequate detail and parameters like extent of contamination (both horizontal and vertical), the risk associated with the contaminated groundwater, the regulations that apply to the problem, the degree of remediation required, and the detailed subsurface conditions are needed. To achieve all this requires extensive site exploration and monitoring program with field exploration data collected to complete the evaluation. Some of the hydraulic properties that are important for groundwater cleaning are as follows:

Property	Description	Importance for Groundwater Cleanup
Porosity	Volume of pore space relative to total volume	Pores store water and contaminants
Effective porosity	Interconnected pore space that transmit contaminants with fluid	Water and contaminant flow through interconnected pores
Groundwater velocity	rate of fluid movement	Influences the direction and velocity of dissolved contaminant movement
Hydraulic gradient	Elevation and pressure differences that cause fluid flow	Influences the direction of contaminant movement
Hydraulic conductivity	Ease with which water moves through geologic formation	Influences rate of migration and rate at which fluid can be pumped for treatment
Transmissivity	Product of formation thickness and hydraulic conductivity	Influences rate of migration of plume and rate at which fluid is pumped for treatment
Storage coefficient	Volume released during pumping by pressure changes per unit area	Influences quantity of fluid that can be obtained by pumping
Specific yield	Fraction of total pore volume released as water of gravity drainage during pumping in an unconfined aquifer	Influences quantity of fluid obtained by pumping
Specific retention	Fraction of total aquifer volume retained as water above water table after pumping in unconfined aquifer	Influences quantity of contaminant that remains in the subsurface after pumping

Some of the mechanisms that influence the fate of contaminants in the environment are given in the table below (NRC, 1994):

Process	Environmental conditions	Contaminant
Movement(i.e, Advection)	Water flow rate, Formation Permeability, Water motion, Gravity, Surface tension	Amount of material, Physical State, Solubility, Viscosity
Retention (Physical- Processes affecting transport)	Soil/ Sediment, Organic matter content, Sorptive capacity	Type solubility, Ionic Character
Retention (chemical processes affecting transport)	PH, Redox status, Microbial communities	Chemical transformations, Biodegradation

Step 2. Define the Goal of Groundwater Remediation

This step involves identifying the remediation technologies that need to be implemented at that site. Various factors that affect the remediation process need to be identified. These factors can be listed under different subheads, namely; chemical properties of the contaminants, contaminant distribution, geology of the aquifer and hydraulic/flow properties. The various parameters, which needs to be addressed and that come under the subheads mentioned above are; the nature of release, the decay potential, volatility, contaminant retardation (sorption), contaminated phase, volume of contaminated media, contaminant depth, stratigraphy, texture of the un-consolidated deposits and the degree of heterogeneity, hydraulic conductivity, temporal variation and vertical flows, if any. Associated with each one of these factors a generalized remediation difficulty scale needs to be prepared.

Step 3. Screen Candidate Remedies

A list of the commonly used groundwater remediation technologies is shown in Table 1. These remedies need to be screened to identify the remedy that can most efficiently and cost effectively achieve the remediation goal. The various remediation goals and the corresponding remediation approaches are highlighted below:

Remediation Goals	Examples of Remediation Approach
Groundwater Restoration	Natural (intrinsic) Remediation
	Bioremediation
	Combination of conventional remediation approaches
Non-degradation	Source Removal
	Bioremediation
Return aquifer to health-based standards	Source removal
	Conventional pump-and-treat
	Bioremediation
Apply technology-based standards	Phytoremediation
	Electro-kinetics
	Solvent extraction
	Thermal Desorption
Containment	Physical barriers
	Hydraulic barriers
	Capping

Step 4. Prepare Detailed Design

Step 5. Implement the Design

Step 6. Confirm the Effectiveness of Design

This is the final step of remediation program to see and confirm if the remediation goals have been met. Data from a performance monitoring program needs to be reviewed periodically.

TREATMENT OF CONTAMINATED GROUNDWATER (NRC, 1994)

There are many techniques available for treatment of contaminated groundwater. A brief review of the most widely used standard treatment techniques and the most promising and innovative methods are presented. These technologies are categorized either as '*in situ*' or '*ex situ*' techniques. The *in situ* techniques are employed to make the contaminant non-toxic through treatment (e.g., Bioremediation) or to enhance extraction of contaminants from aquifer (e.g., air sparging), whereas the ex situ are employed only to treat groundwater that has been extracted from the aquifer. The following table lists most of the techniques that fall under the two categories:

IN SITU	Process Description
Bioremediation	Biological degradation of contaminants using naturally occurring microbes in soil
Soil vapor Extraction	Volatilization of contaminants that are present in the vadose zone
Air Sparging	Volatilization of contaminants in the saturated zone
Permeable reaction barriers	Physical or chemical treatment in a trench
Vacuum vapor extraction	Volatilization, within a well, of contaminants from saturated zone
Density driven convection	Enhanced bioremediation using single well driven convection system in aquifer
Phytoremediation	Engineered use of plants to remove or contain contaminants in groundwater or soil

EX SITU	
Bioreactor	Biological degradation of contaminants (activated sludge, fixed film reactors, biophysical treatment)
Air stripping	Volatilization of contaminants
Carbon adsorption	Adsorption of contaminants to activated carbon
Ion exchange	Exchange type attachment of contaminants to ion-exchange resins
Membrane	Separation of solids from water using membranes (reverse osmosis, ultrafiltration)
Wetland treatment	Uptake of contaminants by wetland features
Electrokinetic decontamination	Desorption of contaminants by acidic front of groundwater caused by hydrolysis of groundwater
Alkaline precipitation	Alteration of pH so that concentration exceeds compounds solubility limit causing precipitation

In Situ Treatment

Some innovative In Situ treatment Approaches have been developed in the past few years which provide a higher degree of permanence, a higher efficiency of contaminant removal and lower remediation costs.(USEPA, 1994). Some of these techniques are:

1. **Intrinsic Remediation**

This is also called natural attenuation and involves the evaluation and monitoring of naturally occurring processes that prevent the migration of contaminants to receptors e.g., Biodegradation of contaminants by naturally occurring microbes and physical or chemical process like adsorption which can very effectively prevent the migration of contaminants. In such cases, the natural forces are allowed to act on the contaminated groundwater without human intervention to remediate groundwater. Millions of microbes are naturally present in the soil water environment in aquifers and natural processes like sorption, complexation, precipitation etc. naturally occur to have a beneficial impact on the groundwater quality. These intrinsic remediation methods could be used alone or to supplement other conventional techniques.

2. **Phytoremediation**

Plants remediate groundwater or soils by direct uptake of the contaminants with water through the roots and accumulate the contaminants in the plant tissues, leaves or flowers. Plants also remediate by stimulation of biodegradation and enhancement of mineralization in the root-soil interface by fungi and microbes. Phytoremediation is best suited for cases where the contaminated groundwater is very shallow (less than 5 m deep), the pollutants are hydrophobic or chlorinated and excess nutrients are present in the soil. This method can be used to remediate soils that are contaminated with those heavy metals that have very low vertical mobility.

3. **Vacuum Vapor Extraction**

This is a common technique used to extract volatile matter and have proved successful in treating aquifers contaminated by DNAPL and LNAPL constituents. In this method groundwater is extracted from the extraction wells and re-circulated back into the wells after the VOC is volatilized.

4. **Wetland Treatment for Metal Contaminated Groundwater**

A wetland contains both an aerobic (shallow depth) and anaerobic zone (below the aerobic zone) that offer different opportunities for removal of contaminants. Contaminated groundwater is routed through a man-made wetland area and the water percolates vertically through and out of the wetland. This method was found to be very effective for treating acid mine drainage having low pH and high metal content. The plant matter in the wetland filters and adsorbs some dissolved metals. Oxidation and precipitation occur in the aerobic zone to remove metals as hydroxides and sulphides are produced in the anaerobic zone.

5. **Electro-kinetic Decontamination**

Charged electrodes are placed in soil and charged causing electrolysis of groundwater. As the electrolyzed water ions move towards the oppositely charged electrodes, an acidic environment is produced that accelerated the desorption of contaminants that are adsorbed to soil.

6. **Density Driven Convection (DDC)**

This technique is popular to remove petroleum hydrocarbons by supplying oxygen to enhance biodegradation process that naturally occurs in soils. Air is injected into a well that causes aerated water to rise and flows out into the aquifer, where oxygen-rich water enhances natural biodegradation

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Table 1. Summary of commonly used Groundwater Remediation Technologies (NRC, 1994).

Alternative Technology	Residual Groundwater Concentration	Residual Sorbed Concentration in Source Area	Cleanup time
Source Remediation			
Conventional pump and treat	Low to medium	Medium to high	Long
Vacuum extraction and bioventing	Not Applicable.	Low to medium	Short
Air sparging (vertical or horizontal wells)	Low to medium	Low to medium	Short to medium
In situ bioremedeation Hydrocarbons	Low to medium	Low to high	Short to medium
In situ bioremedeation chlorinated solvents	Low to medium	Low to high	Medium to long
Cosolvent and surfactant flushing	Low to medium	Low to medium	Short to medium
Steam Stripping	Low to medium	Low to medium	Short
In Situ thermal desorption	Low to medium	Low to medium	Short
In situ Chemical oxidation	Medium (?)	Medium to high (?)	Medium
In situ Bioremediation-metals	Low to medium	Low to high	Medium to high
Intrinsic Bioremediation	Low to medium	Low to high	Long
Plume Remediation			
Conventional Pump and treat	Low	Medium to high	Long
Air sparging (vertical or horizontal wells)	Low to medium	Low to medium	Medium to long
In situ bioremedeation Hydrocarbons	Low to medium	Low to high	Medium to long
In situ bioremedeation chlorinated solvents	Low to medium	Low to high	Medium to long
In situ reactive barriers	Low	Not applicable	Long
Intrinsic Bioremediation	Low to medium	Low to medium	Long

GROUNDWATER MODELLING – CASE STUDIES

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INTRODUCTION

Modelling is a technique used to predict the response of a physical system to a particular stress. Modelling becomes a particularly important tool if the physical process is governed by parameters, which are not directly measurable, either in the field or in the laboratory. In this sense, groundwater modelling plays an important role and among different areas of water sector, modelling has attracted maximum attention in the area of ground water. While in the early periods of modeling, alternate types of modelling such as physical models, analog models, numerical models etc were used, in present day context, modelling has come to mean mathematical modeling. The detail and complexity of a model should be related to two important aspects: a) the purpose for which the model is developed b) the data base available for use in the model. A model in which the focus is to estimate the annual replenishable recharge may be quite different from a model which is intended to predict the movement of a contaminant. Similarly, if data available is daily rainfall, a model which requires continuous rainfall data for a storm is not a suitable option.

Modelling studies may be broadly categorized into two types: (a) studies which are primarily of R & D nature where the focus is to develop a new model or modify an existing model to represent the physical system more realistically, (b) studies which apply a well established model to a particular problem. The latter studies represent specific case studies, which form the theme of this paper. However, in tune with the objective of the Brainstorming Session, the focus of discussion is not on the details of results of the case studies, but on the issues concerning case studies in groundwater modeling. With this focus, the paper leaves out equations, figures and bibliographical references assuming that the reader is familiar with applications of regional groundwater modeling.

LOCAL AND REGIONAL MODELING

Classical groundwater modelling has its roots in well field solutions, starting from the well known. This solution for draw down in the vicinity of a well in an infinite confined aquifer pumped at a constant discharge rate. There have been a number of analytical solutions for various types of well field models for confined, unconfined, leaky and double porosity systems. These models were directed towards better understanding of various porous and fractured media formations, besides providing a tool for well design and development in such formations. However, these analytical models were not directly extendable to represent regional groundwater systems.

In view of the non-homogeneity of a regional groundwater system, numerical models based on finite difference or finite element or other hybrid methods were necessary. However, the conceptual framework of the regional models are based on the analytical models developed for different well field situations. Generally, some simplifications in the parameter structure are used, either because of the difference in scales of the two types of problems (both spatial and temporal scales), or to make the problem computationally viable, or more commonly to reflect the limitation of data availability. Increasingly, the value of computational time is losing its importance and the primary concerns in deciding on the type of model are the purpose of application and the data limitations. It is almost certain that conceptual and computational modelling progress has far outpaced progress on data procurement. While this is true anywhere in the world, it is particularly true in India where researchers aim to be in touch with state of art work in modeling, which is vastly divorced from the quantity and quality of data that is available in the country. Further discussion in this paper is restricted to regional groundwater modelling only. Also, in view of the limitations of the writer's experience, the discussion is also restricted to flow and quantity issues only and water quality issues are not considered.

TYPES OF REGIONAL GROUNDWATER MODELS

Regional groundwater models may be broadly categorized as follows: (a) confined aquifer models (b) unconfined aquifer models (c) mixed confined - unconfined aquifer models (d) leaky or semi-confined aquifer models (e) double porosity models. Among these, pure confined aquifer models are not common except with regard to study of a local problem. A mixed confined - unconfined system, which may consider an unconfined recharge area can deal with the confined system as a particular case. The leaky aquifer model and double porosity model are conceptually and mathematically similar to each other. The double porosity concept was evolved to describe a fractured rock system with the fractures and weathered zones forming the two over lapped media. Among all the five types of models referred earlier, the unconfined aquifer model is the most commonly used model for case studies in regional groundwater systems. The nationally approved procedure for periodic assessment of groundwater resource is based on an unconfined aquifer system (Report of the Groundwater Resource Estimation Committee, Ministry of Water Resources, 1997). The unconfined aquifer model is commonly used for regional case studies in hard rock areas in different parts of the country. The writer was associated with a pilot study on groundwater assessment in Vedavati River Basin in parts of Karnataka and Andhra Pradesh. For this problem, both unconfined aquifer and leaky aquifer models were applied. It was found that with regard to estimation of annual recharge, both the models yielded comparable results. The leaky aquifer model requires estimation of two more set of parameters, corresponding to leakage coefficient and an additional storage parameter, and hence the associated data requirements are also more. Hence for the assessment of groundwater resource on a regional scale over a time period of an year or more, the unconfined aquifer model may be a better alternative for hard rock area. However, it must be noted that an unconfined aquifer model may not properly represent the flow near a pumped well in a hard rock area. In this context, the synthesis of results obtained from local pumping tests which may be based on double porosity model or leaky aquifer model with a regional unconfined aquifer model poses difficulties. In fact as the theme in this paper is developed, it will be seen that synthesis or fusion of information from different approaches and sources is a key issue for case studies in regional groundwater systems.

Another important issue in regional groundwater modelling is how to model the river or stream. There are several issues here. The river may or may not form a continuity with the groundwater domain. A river where there is such continuity or where vertical gradients below the river are negligible can be handled by Dirichlet boundary condition (with water level varying with time). It is possible that there is transfer of water from/to the river and groundwater by a leakage process. In this case, the hydraulic properties of the medium below the river are to be estimated. It will be seen later that more the number of unknown parameters, more the requirement of data for model calibration. An additional problem is in respect of non-perennial rivers, which may be dry for a good part of the year. There is another question regarding the use of base flow data where it may be available. Here, one has to ascertain the contribution within the region of study and the flow that may be transferred from an upstream region. In a hard rock area, if the model is applied for a watershed region and if a stream gauging site is located at the exit of the watershed, the data from the surface water discharge may be well utilized in a groundwater model.

There is one more significant complication associated with modelling streams, particularly in an irrigated area. The regional scale of the model may preclude the direct consideration of small streams in the model, but these streams if of adequate density, may drain a considerable amount of water. If its effect is ignored, one may predict an unduly severe waterlogging problem in an irrigated area, which may not be true in reality. This poses another problem of data fusion, in this case how to integrate into the model, the data of density of minor streams, which may be obtained from topographic sheet analysis.

DOMAIN OF MODEL

A problem of considerable interest in case studies of regional groundwater problems is the domain over which such case studies are properly applied. Hydrologists have always preferred the domain of study to be bounded by water divide boundaries, which mean that the region should be a river basin or watershed. In a hard rock area, the watershed boundary may also form the boundary defining groundwater flow divide, but this may not be true in alluvial areas. Mathematically, if the boundary of the region may be treated as a water divide for groundwater flow, no flow boundary condition can be applied which removes considerable uncertainty regarding boundary conditions. On the other hand, much of data is available in terms of administrative units such as blocks, taluks and districts. Similarly, the results of modelling study may also be required for administrative units as development plans are drawn based on such units. Another need based domain of study is an irrigated command area which may be served by a surface irrigation project. It may be a small area such as associated with a minor irrigation project or a large area associated with a major irrigation project. The groundwater regime in command areas are distinctly different because of the significant recharge from irrigation water, which may exceed the natural recharge from rainfall quite significantly.

The Report of the Groundwater Resource Estimation Committee (Ministry of Water Resources, 1997) suggests that for hard rock areas, the unit for groundwater assessment should be watershed. This requires that where necessary, the input data obtained from statistics for administrative blocks should be converted to the watershed region and similarly, the output from the model should be converted to administrative units for planning development activities. These are essentially mathematical interpolation/summation problems which can be handled by a software. However, if the purpose of a model is to develop a conjunctive use policy in a surface irrigation scheme, the command area of the scheme may be a more suitable domain than the watershed. The problem of dealing with the boundary condition in this case will be discussed with respect to a specific case study in Section 9. There is a proposal that for alluvial area, the "doab" (which is the land area bounded by two major stream courses) may be the unit for groundwater assessment. This also makes the specification of boundary condition straightforward. Case studies for different types of domain are discussed briefly in Section 9.

NUMERICAL MODELLING TECHNIQUES

Basically, the mathematical problem of modelling involves the solution of a two dimensional parabolic partial differential equation in a non-homogeneous domain. For an unconfined system, the equation is strictly non-linear, but linear approximations based on the concept that water level changes are small with respect to the saturated thickness are commonly used in case studies. The problem of solving a non-linear equation is not really difficult in the present case. The issue is whether one should choose to use a non-linear model and to what extent, a simpler linear model differs in its essential outputs with respect to the non-linear model. The non-availability of data regarding the non-homogeneous aquifer thickness may preclude the use of the non-linear model.

The two main options for numerical modelling for dealing with the non-homogeneous problem are the finite difference and finite element methods. Finite volume method has been discussed in the literature, but it has not really taken roots in regional groundwater modeling. The earlier models were based on the finite difference method, but later models use finite element method as well. Between the two approaches, the writer clearly prefers the finite element method. The finite element method has the following advantages: (a) It can conveniently represent irregular boundaries, internal (e.g. river or dyke) or external boundary. (b) It can elegantly handle the flux boundary condition. (c) Conservation of mass within the domain is achieved better than in the finite difference method. (d) There is a greater flexibility in discretisation in terms of a mix of coarse and fine elements than in the finite difference method.

Whether one uses the finite difference method or the finite element method, the low level computational problem reduces to the solution of a large number of linear algebraic equations. While earlier, several point and block iterative techniques were used (e.g. SOR, LSOR, ADI methods), now more powerful solvers such as SIP (Strongly Implicit Procedure) or conjugate gradient methods and sparse matrix solvers have become popular. In complex problems involving very heavy computations, multi-grid approaches are used with a mix of coarse and a fine grid.

Increasingly, the details of computation are becoming well established and are only of peripheral interest. The computational issues may now have to focus on the integration of information from different sources, utilization of qualitative information in modelling (e.g. from a map derived from remote sensed data), development of interface between different tools (e.g. data base software, GIS, core program in Fortran or C, etc.), graphical support to facilitate decisions, and development of software incorporating these options.

ASSESSMENT PROBLEM IN CASE STUDIES

The most important issue in regional groundwater studies in India is concerned with the estimation of recharge from rainfall and other sources. When modelling is used as the tool, the estimation of recharge is not done in isolation, but is combined with the simultaneous estimation of aquifer properties such as transmissivity and storage coefficient or specific yield. In the modelling context, the estimation problem is an inverse problem of simultaneous estimation of parameters and source terms. In order to make the discussion concrete, the most common regional model based on unconfined aquifer schematisation is used. The governing equation for this case is written as:

$$\frac{\partial}{\partial x}\left(T_x \frac{\partial H}{\partial x}\right)+\frac{\partial}{\partial y}\left(T_y \frac{\partial H}{\partial y}\right)=S_y \frac{\partial H}{\partial t}+Q_p-Q_{rf}-Q_{rs} \quad \text{.......................................(1)}$$

where T_x and T_y are the transmissivities along x and y directions (which are assumed to be along the principal axes), S_y is the specific yield, H is the piezometric head or water level, t is time, Q_p is the rate of pumping per unit area, Q_{rf} is the rate of recharge per unit area from rainfall and Q_{rs} is the rate of recharge per unit area from other sources. Among the three source terms in equation (1), the pumping term Q_p is usually taken as known in modeling, though there is a general awareness that the estimate of draft in groundwater has considerable uncertainties. The rainfall recharge term has to be handled as a functional relation involving rainfall and the simplest expression for this may be:

$$Q_{rf} = F_r R_f \quad \text{.......... ....(2)}$$

where F_r is a recharge factor and R_f is the rainfall. This introduces another parameter in eqn. (1), namely F_r. There may be other parameters introduced through the term Q_{rs}, the recharge term from other sources. This may be due to recharge from canal, surface water application on the field, recharge from rivers as leakage, etc. It is thus seen that assessment of recharge involves simultaneous estimation of a number of spatially distributed parameters.

One of the major issues in case studies concerns with the dimensionality to be used for these parameters. Strictly, the parameters T_x, T_y, S_y and F_r may vary non-homogeneously over the entire domain. However, for practical purposes, some parameterization is necessary, as even if computationally viable, we will not have adequate data for estimation of parameters for each node or element. One option is to specify a statistical distribution of the parameter and try to determine the associated statistical parameters. A common approach is to use a piecewise homogeneous discretisation where the domain is subdivided into a number of homogeneous sub-domains, with constant values of parameters within each sub-domain. This means that if the region is divided into N sub-domains, there will be M X N parameters to be determined, where M is the number of unknown parameters in each sub-domain (e.g. T_x, T_y, S_y, F_r).

There are several methods or approaches to determine these parameters. A heuristic trial and error approach is common, wherein the parameters are varied in a systematic way and the results of computed water level variations are compared with observed water level variations for the same period, and based on the comparison, the parameters are further adjusted. This approach requires an experienced hydrogeologist with a good 'feel' for the region of study. The quality of estimate also can not be ascertained as rms deviation usually used for this purpose is a poor index. A systematic optimization approach for the estimation problem is desirable. Two approaches are possible: (a) method based on equation error criterion, (b) method based on output error criterion. The output error criterion is the more common method and the writer has successfully used this method in several case studies. In this method, the parameters are estimated such that the following objective function is minimized.

$$E = \sum_{L=1}^{NS} \sum_{i=1}^{M(L)} W_i^L \left[s_{oi}^L - s_{ci}^L \right]^2 \qquad (3)$$

where NS = number of seasons or time periods for which measurements are made, M(L) = number of measurements in season or period L, s_{oi}^L = observed value of i^{th} variable for L^{th}

season or period, s_{ci}^L = computed value of i th variable for L th season or period and W_i^L = weight for i^{th} measurement in L^{th} season or period. Typical measurements used in quantity assessment studies are periodic water levels at specified observation wells.

The minimization problem may be solved by different techniques, but the Gauss–Newton method is commonly used because of its simplicity and robustness. The method requires evaluation of sensitivity coefficients, $\delta s_i/\delta p_k$ defining the variation of variable s_i with respect to the parameter p_l . If there are M X N parameters (N zones and M parameters for each zone), this requires (MN+1) simulation runs for the direct problem for each Gauss–Newton iteration to evaluate the sensitivity coefficients by finite difference approach. While this may appear to be unduly heavy computations, it is not really so and even desk top Pentium PC's can handle relatively large problems without undue computational time. .Further discussion on the choice of weights and assessment of the quality of parameter estimates is presented in Section 10.

DATA REQUIREMENTS

The simultaneous estimation of the aquifer parameters and the recharge requires field data for a period of one or more years. Normally, in case studies involving quantitative assessment of ground water, the field observations used are periodic measurements of water levels at observation wells. In some cases, pre and post monsoon water level contours may be available (generally in terms of depth of water level below ground) and such plots can be used to estimate zonal water level variations, which can also be used in parameter estimation process. In order to estimate the parameters without undue uncertainty, a reasonably adequate redundancy factor in data is necessary. This means that if M X N parameters are to be estimated, the combined data in time and space should be K X M X N, where K is greater than 1. For a satisfactory estimate, K value should be 2 or larger. The relative importance of spatial and temporal data and the effect of quality of data are discussed further in Section 10.

MODEL CALIBRATION, VERIFICATION AND APPLICATION

In general, data may be available for more than one year and in such situations, the question arises whether part of the data should be used for model calibration and the remaining used for model verification. In an academic exercise, this will be the preferred course. However, in a real life application, the position is not so clear. The principal purpose in split use of the data is to verify whether the choice of model is appropriate. If, however, the type of model is fixed from practical considerations including an assessment of the hydrogeology of the region, use of all the data for calibration may be desirable, particularly in situations where some of the data may be of poor quality. Except in well controlled pilot studies, data of doubtful quality is quite common in periodic groundwater monitoring. In case studies involving regional groundwater assessment, the writer has found it necessary to critically examine the consistency of each data before accepting it. An algorithmic approach to deal with poor quality data will be referred in Section 10.

The parameter estimation process gives a posteriori norms, which can be used for estimating the uncertainty in prediction for application studies based on the estimated parameters.

CASE STUDIES

As part of the work for the Groundwater Resource Estimation Committee, the writer with active cooperation of the Central Groundwater Board, compiled a list of case studies carried out in different parts of the country with a summary of results. These are listed in Appendix 3 of the 1997 Report of the Groundwater Resource Estimation Committee. As this list of 22 case studies were compiled in a very short time that was available, it is clear that there will be a number of case studies of varied rigour in regional groundwater assessment in different parts of the country. In this section, some of the case studies with which the writer was associated are briefly discussed. The focus will be on issues concerning the case study and its general applicability rather than details of results for the specific case.

Vedavati River Basin Project

This case study was undertaken jointly by the Indian Institute of Science and the Central Groundwater Board. It is perhaps the first large-scale regional model developed in the country for a hard rock area. The study region comprises of 24,200 km^2 area of the entire Vedavati River Basin in the states of Karnataka and Andhra Pradesh. It is a hard rock region with the principal rock types being granite, gneiss and schist. The modelling study was part of a pilot project taken up by the Central Groundwater Board. A finite difference simulation model was used, with two model options: a) unconfined aquifer model b) leaky aquifer model. In the leaky aquifer model, the upper weathered layer is treated as the aquitard and the lower fracture layer as the aquifer. For each zone, there are 6 parameters in the leaky aquifer model, namely transmissivities in x and y directions, storage coefficient of the deeper aquifer, specific yield of the upper aquitard, leakage coefficient and recharge factor. The region is divided into 96 zones and as a result, there are in all 576 parameters for estimation, which is indeed a very large number. Hence a mixed strategy was adopted for the estimation. The transmissivities were estimated based on a few long duration and several short duration pumping tests. These tests indicated that the granite/gneiss region may be taken to be isotropic while the schist region has pronounced anisotropy ($T_y = 5\ T_x$). The initial values for upper layer specific yield, lower layer storage and leakage coefficients were assigned based on analysis of a few long duration pumping tests. The parameters were estimated using the regional model based on a sequence of sensitivity studies involving a number of simulation runs.

Observations of piezometer nests in the region showed that in the dormant state (that is, when observations are not made in the vicinity of a well under pumping), there are no significant vertical gradients. In view of this, a simpler unconfined aquifer model was also developed. Here, the number of parameters for each zone is only 4 (Tx, Ty, Sy and Fr), which makes the estimation problem much simpler. As the transmissivities are estimated from pumping tests, basically there are only 2 parameters to be estimated for each zone from the regional model, that is in all 192 parameters for the 96 zones. The studies were suggestive that for a regional model in a hard rock area, an unconfined aquifer model may be well suited.

The observations of water levels at 508 key observation wells during the period November 1997 to November 1998 were used for the calibration. As the region of study was a river basin, no flow boundary condition could be specified on the external boundary. After calibration, the model was used to estimate safe and sustainable yield in the region.

Narmadasagar and Omkareshwar Composite Command

A groundwater modelling study for the composite command area of Narmadasagar and Omkareshwar Reservoirs was undertaken for the Narmada Planning Agency, MP. The principal scope of the study was to: (a) assess groundwater regime in the command area (b) predict effects of surface irrigation on groundwater levels (c) determine the increase in groundwater draft required to prevent waterlogging. The gross area of the region is 386,000 ha. The area comprises of Deccan trap basalt and Vindhyans. A finite difference model based on the unconfined aquifer system was used. The composite command was divided into 34 hydrogeological zones and for each zone, three parameters – transmissivity, specific yield and recharge factor were to be determined. The transmissivity values were estimated based on analysis of a number of dug well pumping tests. The specific yield and recharge factor were determined from the regional model by calibration using water level data for the two year period from June 1975 to May 1977. The specific yield and recharge values were obtained using a mixed strategy. An implicit relation between specific yield and rainfall recharge factor was obtained for each zone, by an analysis of pre and post monsoon water level for a number of years. Then the zonal specific yield values were determined by the calibration of the regional model, based on the observed water level decline during non-rainy seasons. Thus, only specific yield was directly obtained from the calibration process of the regional model. This approach is one example of data fusion from different sources, in this case results of pumping tests analysis, analysis of specific yield – recharge factor relation from pre and post monsoon water level change, and simulation results from the regional model.

Once the existing groundwater regime was determined, the effect of irrigation water application was studied by considering an additional recharge term from surface water application. For this, model of two existing tank command areas was used for estimation of recharge factor from surface water application. Based on this additional parameter for which a homogeneous value was used for all the 34 zones, an assessment of the effect of surface irrigation was made using the regional model. From these studies, a suitable conjunctive use policy was proposed.

Tank command areas

As a part of the study in Section 9.2, it was necessary to determine the recharge factor for surface water application. For this, modelling was done for two tank command areas, Satak and Kunda tanks, where irrigation was practiced for several years. The Satak tank command area was 5049 ha and the Kunda tank command area was 2510 ha. The areas comprised of basaltic rock and alluvium. The Satak study region was divided into three hydrogeological zones and the Kunda study region was divided into four hydrogeological zones. The calibration period was June 1982 to May 1983 for Satak command and October 1982 to September 1983 for Kunda command. The transmissivities were determined from analysis of pumping tests. The specific yield, rainfall recharge factor and surface irrigation recharge factor were determined simultaneously using the regional model. In the calibration process, advantage was taken of the fact that there were three distinct seasons – June to October when there is rainfall but practically no surface irrigation, November to February when there is surface irrigation but practically no rainfall, and March to May when there is practically no rainfall and no surface irrigation. Thus the groundwater balance in the summer season formed the basis for the determination of specific yield, the balance in the Rabi season for the determination of irrigation recharge factor and the balance in the Kharif season for the determination of rainfall recharge factor. But for this favourable situation, trial and error calibration procedure might have been too difficult. In Section 10, an automated procedure for handling such complex estimation problems will be discussed.

Bargi Diversion Project

This case study also involves modelling the command area of a major irrigation project. The Bargi Diversion Project involves trans-valley diversion of canal water from Narmada valley to Son sub-basin of Ganga basin. The command areas lie in both Narmada valley and Son valley, with a total service area of 245,000 ha. The modelling was done in two parts and the gross area for the model was 93,750 ha and 273,900 ha. The area was of Deccan trap rock and Vindhyan system comprising of stratified formations of sandstone, shale and limestone. A finite difference model based on unconfined aquifer system was used. The study area in the Narmada valley was divided into 16 zones and the study area in the Son valley was divided into 21 zones. For each zone, three parameters – transmissivity, specific yield and rainfall recharge factor were determined. The initial values of transmissivity were obtained from analysis of pumping tests. The parameters were determined in a heuristic sequential estimation process, wherein first the specific yield and rainfall recharge factor were determined, then these values were kept stationery and the transmissivity values were fine tuned, and finally the specific yield and recharge factor were fine tuned. In Section 10, the theoretical basis for this approach is indicated. Once the model was calibrated, the effect of surface irrigation application was studied for different conjunctive use policies.

Two adaptations were made in the model. The first concerns the effect of minor streams in draining excess water under irrigation. The scale of the model precludes the direct modelling of such minor streams and their effect was considered indirectly. Based on a detailed study of toposheets, the total length of minor drainage per unit area was determined for different parts of the study area. If the groundwater level rises to within a specified depth from ground level (1.5 m), water is 'drained out' in the model at such locations based on the drainage density, groundwater gradient and transmissivity. The second difficulty requiring adaptation was regarding specification of boundary condition for conditions of future irrigation. The purpose of simulation studies for conditions of surface irrigation was to predict groundwater levels with the additional recharge from irrigation water. At the edge of the command area, there may be some influence of surface water application and hence water levels obtained from observation wells for existing situation can not be given as boundary condition. This difficulty was solved by enlarging the study area outside the command by about 5 km from the command boundary and specifying water levels for existing situation on this outer boundary as the boundary condition. This assumes that the effect of surface irrigation is not felt at a distance of 5 km from the command boundary.

Chitradurga District in Karnataka

A study was sponsored by the National Drinking Water Mission to develop a water availability forecasting and allocation model based on an administrative unit of district. As a part of this study, a regional groundwater model was developed for the Chitradurga District in Karnataka (before the district was partitioned into two districts). The study area was 11,000 km^2 in a granitic/gneiss terrain. A finite element model based on unconfined aquifer system was used. The district area was divided into 9 taluks and each taluk was further subdivided into hydrological zones, yielding 25 zones in all. With three parameters for each zone (transmissivity, specific yield, rainfall recharge factor), there were 75 parameters in all to be estimated. Model calibration was done based on data for the two year period, December 1979 to December 1981.

Different types of boundary conditions were used along the district boundary in using the model for calibration and for forecasting. For calibration, boundary conditions were specified based on seasonal water levels as obtained from observation wells for the calibration period. For forecasting application, specified flux boundary condition was applied in the following way. The flux was calculated in the model itself based on the initial condition, using finite difference approximation for the gradient. There is an approximation in this approach as the flux is assumed to be constant over the period of simulation, as the gradients from the initial condition only are used. The method can be improved by using gradients calculated based on computed water levels for the previous time step. In hard rock aquifer conditions where the flow term is not dominant, such approximations may be acceptable.

The estimation process for the parameters was basically as explained in Section 9.4 using a sequential estimation process.

RECENT STUDY ON PARAMETER ESTIMATION

An extensive study was recently completed at the Indian Institute of Science on parameter estimation of regional groundwater systems based on weighted least squares (WLS) method (Nagaraj M K, Parameter Estimation of Regional Groundwater Systems, Ph D Thesis, Indian Institute of Science, April 1999). The Gauss-Newton method in combination with finite difference evaluation of sensitivity coefficients was used. Several significant conclusions were arrived at based on extensive testing on two synthetic aquifers, a piecewise homogeneous system and a bulk homogeneous system with a random heterogeneity. The conclusions arrived at from the synthetic aquifer study was verified on two real life problems. The first one was on a macro regional scale for Chitradurga District referred in Section 9.5. The second field application was on a micro regional scale for a watershed of 100 km^2. All the conclusions were found to be sustained in the field applications. A brief summary of the major conclusions from this study is given below.

The WLS algorithm is very robust and can form the basis for an automated procedure for groundwater assessment. There is no difficulty in dealing with different type of parameters and also relatively large number of parameters. There must be adequate data redundancy for proper assessment and in this respect redundancy in spatial measurements is more important than redundancy in temporal measurements. It is consistently seen that the regional model yields better estimates of specific yield and recharge factor compared to transmissivity. This conclusion is arrived at from uncertainty estimates based on a posteriori analysis of estimation. This conclusion is practically important as the focus on regional groundwater assessment is on the recharge. The choice of weights play an important role in the parameter estimation. It is found that a two step estimation process with mean measured values as weights in the first step, and elements of measurement covariance matrix obtained from the first step as weights in the second step, yields the best results. In addition, the use of iterative weights further improve the quality of estimates in the presence of some bad data. Where redundancy of data is inadequate or where there is some effect of parameter correlation, sequential estimation of parameters provide better results. In this process, the transmissivities are estimated in the first step, the specific yield and rainfall recharge factor are estimated in the next step, and the process is repeated for several iterations to achieve satisfactory estimates. It was mentioned in Sections 9.4 and 9.5 that a trial and error sequential estimation was heuristically used in case studies. The present study provides theoretical justification for the approach and guideline when to use it. A set of norms based on a posteriori covariance of parameters and measurements are found to be very useful in assessing the quality of estimates and in deciding any modification required in the estimation process. The commonly used rms norm is quite inadequate for this purpose.

FUTURE STRATEGY

In the previous section, a brief summary of results from recent studies at the Indian Institute of Science on regional groundwater modelling was presented. In this section, directions of further work being undertaken in this area are indicated. As stated in the previous section, several aspects of the WLS algorithm have been finalized. One generalization is under implementation wherein the discritisation of piecewise homogeneous zones is different for different parameters. Thus the division of zones for recharge parameter may not be the same as for specific yield. Similarly, the zonal pattern for data input may also vary depending on the source of information. For example, draft data may be available on administrative unit basis. Such multi-layer discretisation may benefit from the use of tools such as GIS, where information on different mosaics are processed together. Another area of progress is in the use of information from remote sensed (RS) data in the model. A joint study between the Indian Institute of Science and the Indian Space Research Organization is under progress with the specific objective of developing an integrated approach to groundwater assessment combining RS, GIS, and modeling. In this approach, the optimization problem in modelling may have to incorporate constrains which may be based on hydrogeological map prepared from analysis of RS and ground truth data. All these may require principally additional efforts on the software development, particularly in developing interface between data base, GIS and a Fortran or C core program dealing with the model. Considerable progress has been achieved in these areas recently. The overall objective in all these efforts is towards development of a software which can be used for regional groundwater assessment as envisaged under future strategy in the Report of the Groundwater Resource Estimation Committee (Ministry of Water Resources, 1997).

CONCLUSIONS

Issues concerning regional groundwater modelling with reference to case studies are summarized. The scope is restricted to flow, storage and recharge aspects only and water quality aspects are not covered. The objective of the paper is essentially to encourage discussion on issues concerning case studies of groundwater assessment and hence details of results from specific case studies are not presented. However, a summary of a few case studies is presented. For most of the discussions, the unconfined aquifer model is used as the basis, as this is the most common application in regional groundwater assessment. A brief summary of results from recent studies on regional groundwater modelling at the Indian Institute of Science is presented and directions of future work are also indicated. In summary, the writer feels that a focussed effort is needed on the following specific aspects in this area: (a) improvement in the quality of data, in particular on the estimate of draft and measurement and documentation of groundwater levels (b) fusion of data/information from different sources including use of qualitative information (c) integration of different techniques and tools such as RS, GIS and modelling (d) development of user friendly software which incorporates items (b) and (c) above, for direct use by government agencies which are primarily charged with the responsibility of periodic groundwater assessment.

MATHEMATICAL MODELLING OF GROUNDWATER SYSTEMS: A CASE STUDY OF CONJUNCTIVE WATER USE PLANNING IN THE SHARDA SHAYAK CANAL COMMAND, U.P.

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ABSTRACT

The problems of waterlogging and Usar spread, periodic shrinkage of arable land, groundwater contamination and ecological changes taken place over the years in the Sharda Sahayak Canal Command Area (SSCCA) is a matter of serious concern. The study area of Sai-Gomti doab of the SSCCA has been carefully chosen so that the methodology adopted in devising the conjunctive water use strategy could find its applicability not only in the command but else whereas well. Firstly the water resource potential, water demand and water use pattern (groundwater and surface water components) was deciphered; secondly a groundwater model simulating flow, recharge, canal bed seepage, groundwater draft was devised to test the efficacy of various planning options. Based on the simulation studies it is expected that improved performance and the most desirable changes in the area could only be brought about by resorting to regulated ground draft and rostering of canals in different crop seasons. Another significant finding of the simulation studies is that lining of entire canal network does not improve the performance significantly rather the cropping pattern and the water use pattern holds the key in the command.

INTRODUCTION

With the commissioning of Sharda Sahayak Irrigation system (1978), general rise of groundwater levels has been observed within two years (Singh *et al.*, 1984). Over the years the rising groundwater trends has resulted in the spread of salt infested land (Usar) owing to capillary rise.

Keeping in view the hazards posed by this rising trend the Government of India constituted a task force (December 1983) to identify critically waterlogged/areas prone to waterlogging and suggests remedial measures. It has been observed that excessive availability/use of surface water in upper and middle reaches of the canal command has given rise to significant seepage resulting in general rise of groundwater levels, thus, the agriculture productivity is affected almost in whole of the canal command area for want of well defined strategy for optimal utilisation of water resources.

In late eighties and early nineties, Central Groundwater Board used this tool of modelling (USGS MODFLOW) in various projects to simulate the aquifer response subjecting various stress conditions based on present and future plans of groundwater development, and evolved strategies for conjunctive water use in the following canal commands:

i) Sharda Sahayak Pariyojana, Uttar Pradesh
ii) Indira Gandhi Nahar Pariyojana stage-I Rajasthan
iii) Mahi - Kadana, Gujrat
iv) Hirakund, Orissa
v) Ghat Prabha, Karnataka and Andra Pradesh
vi) Tungabhadra, Andra Pradesh and Karnataka.

These canal command areas were having their own problems of reduction in crop yield owing to over/unplanned use of surface water in the command. The conjunctive water use strategy has been finalized in the Sharda Sahayak Pariyojana U.P. and is now under implementation. The case of Mathematical modelling as a tool for assessing the aquifer response by simulating various planning options in the command is presented here.

PROJECT BACKGROUND

The Sharda Sahayak Command area development Project (with gross command as 40.02 lac ha) was framed in 1967 and the same commissioned in June' 1974. The project is considered an engineering marvel involving inter-basin transfer of water from a major river Ghagra to Sharda basin through a link canal and a feeder channel, 258.8 km in length with discharge capacity of 650 cumec. The project was completed in 1985 involving an expenditure of rupees 733.23 crores. It is envisaged to irrigate an area of 19.23 lac ha by achieving 96 % of irrigation intensity (60 % for Karif and 36 % for Rabi crops). The cost of irrigation works out to Rs. 3812/ha after full development. The revenue return on the capital layout has been computed as 2.32 % with b/c ratio as 8.75, which is considered to be quite economical.

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The Government of India (March, 1990) asked the Central Groundwater Board to take up studies in Sharda Sahayak canal command area (Sai - Gomti Doab; 8270 Km^2) for devising conjunctive water use strategy for optimal use of complementary aspect of the two resources of water. The area has been selected in such a way so as to be representative for the command and the methodology adopted for achieving the objective would find applicability elsewhere in the command area.

LOCATION OF STUDY AREA, AERIAL EXTENT AND PHYSIOGRAPHY

The study area forms central part of the Sharda Sahayak Command which exhibits elongated linear disposition in Northwest - Southeast direction (Fig.1). It is bounded by north latitude 25^0 37' and 26^0 50' and east longitude 81^0 00' and 82^0 48' falling in Survey of India topographic sheet Nos. 63 F,G, J & K. It covers an area of 8270 Km^2 falling in parts of Lucknow (650 km^2), Barabanki (500 km^2), RaeBareli (2400 Km^2), Sultanpur (2600 Km^2), Pratapgarh (1450 Km^2) and Jaunpur (670 Km^2) districts. The area is bounded in the north by Gomti and in the south by Sai river and these two rivers converge to meet about 5 Km due NE of Jalalpur. The Feeder channel, between Sai and Gomti aqueducts, falling in Rae Bareli and Lucknow districts respectively form the western limit of the study area.

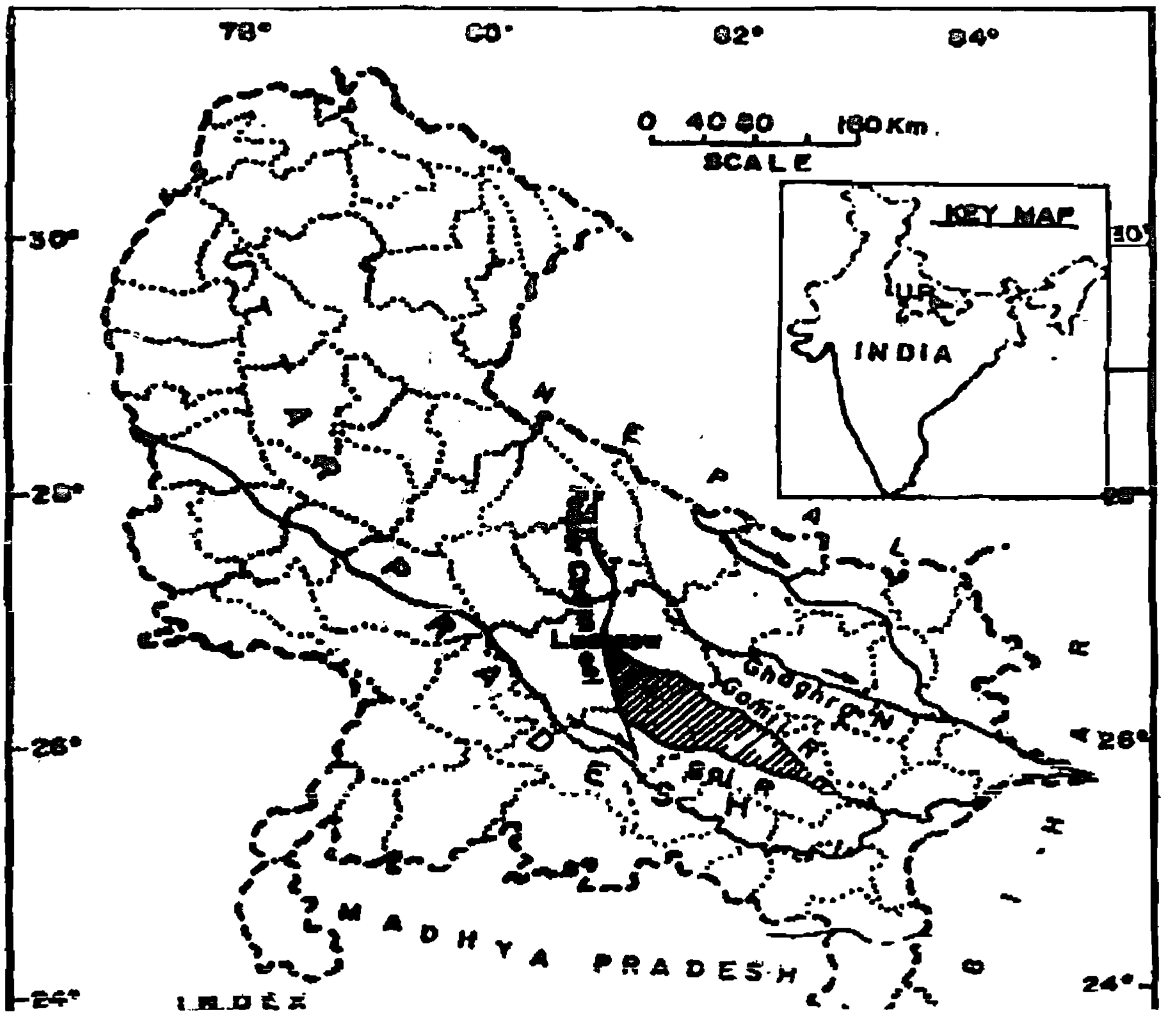


Fig.1 Location Map of the Study Area

GEOLOGY AND HYDROGEOLOGICAL SET UP

Geology

The study area Sai - Gomti interfluvial tract forms a part of the Central Ganga Plain. It is underlain by soft/unconsolidated sediments - the Gangetic alluvium of Quaternary Era (Age: Holocene to Recent).

The sediments were deposited in structural trough - the 'foredeep' on Vindhyan/Granite basement. The soft sediments have assumed an enormous thickness, which varies from place to place. Deep drilling data indicated that, it is 487 m thick at Sultanpur, Janauli in RaeBareli district where Granite basement was encountered; 399 m at Kandhai in Pratapgarh (Vindhyan sandstone as basement) and in Jaunpur district at Leduka site and Jaunpur proper thickness was 745 m and 597 m respectively, these soft sediments having been deposited over Vindhyan shale/sandstone.

Structurally, the Ganga basin has been referred to as 'Great Rift' or 'foredeep' by earlier workers like Suess (1904-21), Burred (1915), and Oldham *et al.* (1917). Recent data on Aeromagnetic survey (ONGC) are suggestive of existence of deep ridges or topographic highs dividing the 'foredeep' into several sub-basins. One such prominent ridge has been referred to as 'Faizabad ridge', which trends NE-SW. This represents probable north-easterly extension of the Bundelkhand massif. The resultant depression served as repository of huge thickness of sediments over geological time.

Stratigraphy

The soft sediments/unconsolidated formations were deposited over granite basement or at pleas over the rock units of Vindhyan System viz. sandstone/shale. In general, the basement is overlain by Neogene sediments with a pronounced unconformity whereas the soft sediments of Quaternary era, rest over the Neogene sediments with an unconformity. The generalised geological succession is given in Table (1).

Hydro-geology

The hydrogeological frame work has been well established for the area which is based on subsurface probing by way of bore hole cutting and electric log data. Overall view of the area indicates existence of three aquifer system, top phreatic aquifer occurs down a depth of 30 m followed at depth by middle aquifer up to depth of 240-250 m and the third aquifer occurs below 250 m depth. Top phreatic aquifer is extensive and occurs far beyond the study area. It is predominantly clayey to silty in composition with a few thin bands of fine to medium sand. It has fresh water. The middle aquifer is characterised by alternations of clay silt-sand with occasional Kankar and gravel. Groundwater occurs under confined conditions. It shows poor quality of groundwater which range from brackish to saline taste. A formation water sample (depth range: 179-185 m b.g.l.) collected during zone test from Hardoi well field (Maharajganj Block, district RaeBareli) show electrical conductivity value as 3571/micro mhos/cm at 25^{0}C.

The exhaustive subsurface data as available from the study area suggest extensive nature of the saline aquifer. It is sandwiched between two fresh aquifer i.e., top phreatic aquifer and below the confined aquifer. The depths of the saline aquifer exhibit much variation. In Sultanpur district, it occurs between 70-90 m, 80-130 m and 125-200 m below ground level at Jagdishpur, Pacheri and Jakha Shivpur respectively. Similarly in Pratapgarh district the saline aquifers were also deciphered between 130-384 m and 90-355 m below ground surface at Utras and

Jagdishgarh, respectively. At Agai and Dehlupur (due south of Sai river- outside the study area), these were struck between 152-170 m and 233-448 m below ground level.

Table 1. Geological Succession in Project Area (ONGC 1983).

Time unit	Rock unit	Time rock	Basin unit	Sedimentation cycle
1	2	3	4	5
Recent to 0.1 M.Y.	Sand silt, clay	Newer alluvium	Either side of Faizabad Ridge-east and central Uttar Pradesh	Ganga alluvium energy cycle
Holocene < 1 M.Y.	Sand,silt clay, gravel and kankar	Older alluvium		
		Disconformity		
Pleistocene Pliocene (1 to 11 M.Y.)	Conglomerate Sandstone sand and subordinate clay	Upper Siwalik		Garchandi Kianagarh energy sequence
		Unconformity		
Pre-Cambrian	Sandstone limestone and shale	Rewa, Kaimoor & Bhandar series upper Vindhyan	Vindhyan Basin on either flanks Faizabad Ridge	Vindhyan sedimentation
		Non- conformity		
Archaean	Granite	Bundelkhand massif	Faizabad Ridge	

OCCURRENCE AND MOVEMENT OF GROUNDWATER

The groundwater in the study area occurs under unconfined and confined conditions. Besides, semi unconfined to semi confined condition/conditions may be developed locally. This is due the fact that there does not exist laterally a well persistent impervious/semi pervious layer. Thus, depth wise situation would exhibit a free surface aquifer at the top followed at depth by semi unconfined/semi confined and confined systems.

The general regional flow of groundwater is towards Southeast. Locally the flow of groundwater in the upper north-western part is north-easterly to easterly in Gomti basin and south to south westerly in Sai basin.

The water surface elevation contours in the north western part near the Sharda Sahayak Feeder Channel lies at 115 m above mean sea level and 71 m near the confluence of Sai and Gomti rivers in the south eastern of the study area. The hydraulic gradients as observed from Northwest to south East of the area, vary between 0.52 m/km in Sai basin. In Gomti basin it varies between 0.44 m/km and 1.08 m/km. The average gradient of the groundwater flow in the study area was 0.22 m/km.

Phreatic aquifer

It is extensive and covers the entire study area but it occurs far beyond the boundary as well. It is restricted to 30-35 m below ground level. General behaviour of groundwater regime under phreatic conditions, has been studied using the periodic water level (month-wise) data as collected from 177 observation network stations. The location of the hydrograph network stations are shown in the Fig. 4.

Depth to water level maps

Month-wise data have been used to prepare depth to water level maps (different seasons i.e., pre-monsoon and post-monsoon period) from the year 1978 to 1992. Pre and post-monsoon depth to water level maps are depicted in Fig. 2 and Fig. 3. The percentage of area under the two categories namely water logged (0-2 m b.g.l.) and area prone to water logging (2-4 m b.g.l.) for the year 1991 and 1992 are summarised in Table 2. Analysis of the depth-to-water-level maps and the long term water level data reveal that gross area under 0-4 m below ground level (i.e. water logged + area prone to water logging) in the pre-monsoon was 15.18 and 14.98 %, respectively and the same in post- monsoon was 57.89 and 58.94 %, respectively.

Table 2. Areal Extent Under Different Depth to Water Level Ranges during Pre-Monsson and Post-Monsoon Period (1991-92).

Depth to Water Level (in m b.g.l.)	Pre-Monsoon	Post-Monsoon	Pre-Monsoon	Post-Monsoon
	1991		1992	
0-2	0.187 %	25.44 %	0.54 %	33.55 %
	(1,616 ha)	(2,24,450 ha)	(4,848 ha)	(2,96,274 ha)
2-4	15.00 %	32.45%	14.44 %	25.39 %
	(1,34,670 ha)	(2,87,296 ha)	(1,25,692 ha)	(2,24,450 ha)

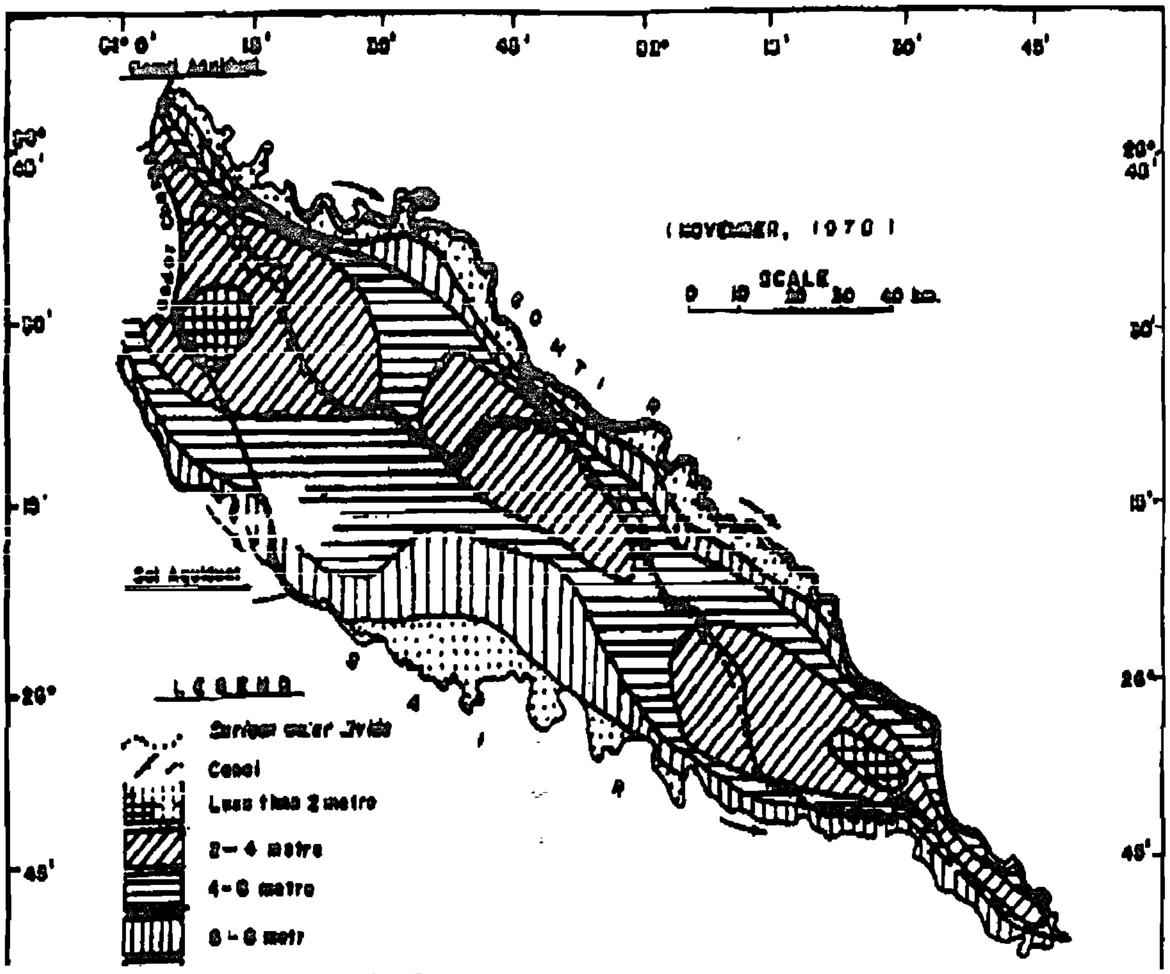


Fig. 2. Pre-monsoon depth to water level map

Long term behaviour of water levels

Historical water levels of different observation network stations over the past decade have been used to prepare hydrographs. The hydrographs suggest rising trend of the water levels in the phreatic zone over the most part of the study area. It is seen that the magnitude of such rise varies considerably. Mohanlalganj block (Lucknow district) maintains 'No change' trend in the water level whereas Gossainganj shows rising trend. In RaeBareli district the magnitude of water level rise was from 0.44 to 2.79 m with average value for the district as 1.89. In Sultanpur, it varies between 0.17 and 4.48 m and for Pratapgrah it ranged between 0.07 and 4.06.

Rising Water Level Trend

The long-term groundwater level trends (1973 - 1993) of national hydrograph stations (NHS) present in the area show by and large rising trend (Table 3). Monitoring of water levels over 177 observation network stations have precisely demarcated the water logged area (0-2 m b.g.l.) during post monsoon period (Fig. 3), which is 26 % of the entire area under study.

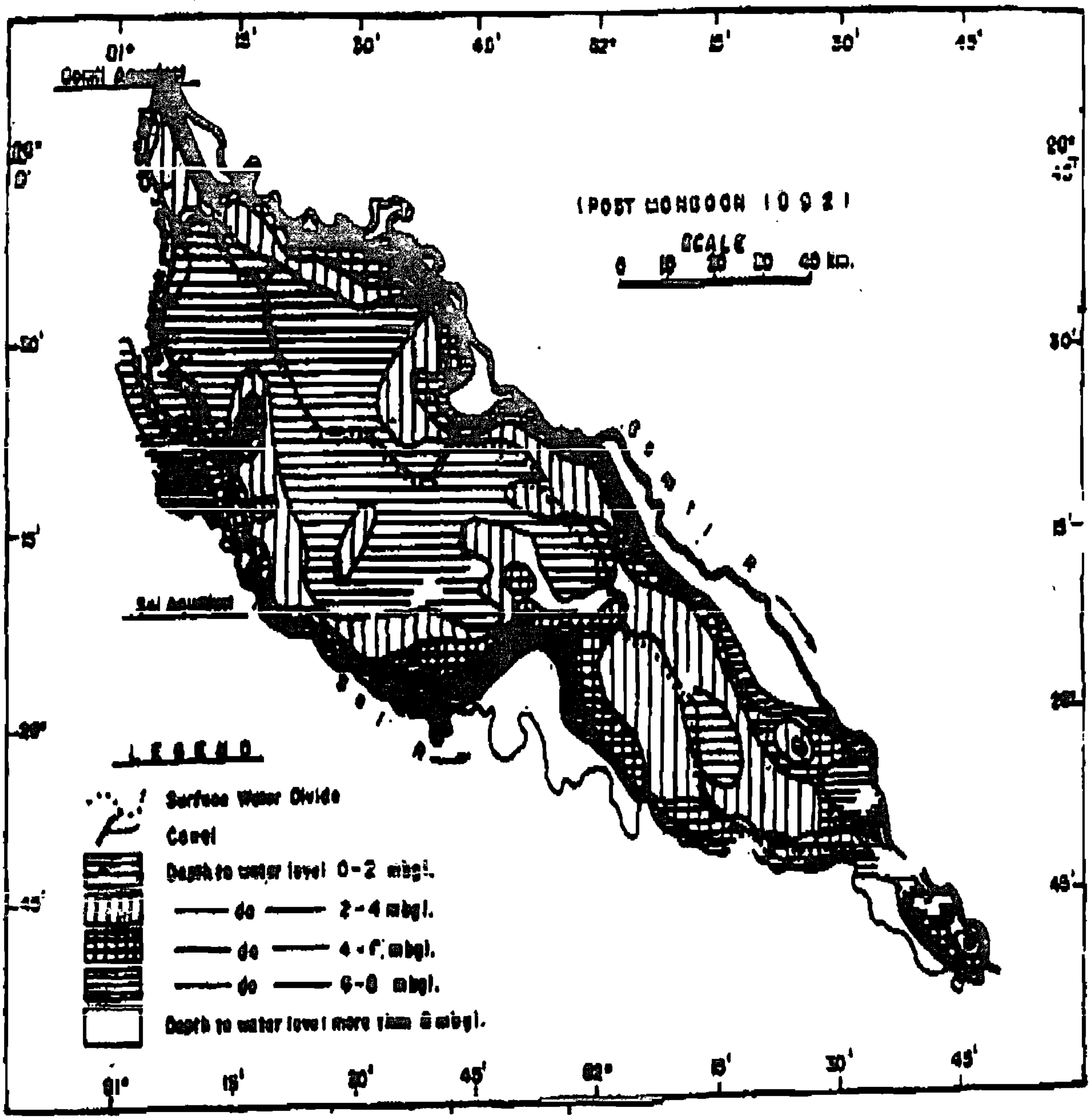


Fig. 3. Post-monsoon depth to water level map

Shrinkage of Arable Land

The periodic shrinkage of arable land is evident from the progressive increase of water logged area during post monsoon period from 1978 - 1992:

a. Waterlogged area November, 1978 -- 100 km^2 (1.2 %)
b. Waterlogged area November, 1992 -- 2206 km^2 (26.7 %).

GROUNDWATER CONTAMINATION AND ECOLOGICAL CHANGES

Comparative study of groundwater quality data from 1979 to 1992 (Table 4) clearly indicates the level of groundwater contamination and ecological changes that have taken place in the area and is a matter of serious concern.

Confined aquifers

Deep exploratory drilling down to 600 m below ground level at different sites in the study area have provided reliable and comprehensive information for ascertaining and establishing occurrence of aquifer system and their geometric configuration. The bore hole cuttings as also the electric logs suggest occurrence of three aquifers that are separated from one another. These are separated from the top phreatic aquifer by impervious to semi-pervious regionally extensive layers. These layers exhibit typical fluviatile features of facies variation. Thus inter-connection through such layers modify the hydrogeological situation locally.

The Central Groundwater Board and the State Groundwater Department have carried out exploratory drilling program in the study area and have constructed a number of test wells. Besides, semi-government/private agencies have constructed a number of production wells. These wells are generally constructed within 400 m depth. The pumping test data indicate much variations of aquifer parameters. Generally, the transmissivity varies between 1400-5300 m^2/day in RaeBareli district, 90 - 520 m^2/day in Lucknow district, 1015 - 4340 m^2/day in Sultanpur district, 4310 - 7520 m^2/day in Jaunpur district and 170 - 7520 m^2/day in Pratapgarh district whereas the range of storativity for the area is $0.7 \times 10^{-4} - 3.7 \times 10^{-6}$.

Table 3. Range of Water Level Rising Trend (m) between 1973 and 1993.

District	Minimum	Maximum
Barabanki	0.73	3.03
Jaunpur	0.26	2.29
Lucknow	0.23	2.88
Pratapgarh	0.08	7.79
RaeBareli	0.22	4.48
Sultanpur	0.19	3.68

Table 4. Selected Chemical Constituents of Groundwater Quality.

S. No.	District	Year	EC (micro S/cm at 25 °C)	Cl (epm)	Na (epm)
1.	Lucknow	1979	349 - 576	.20 - 5.0	1.1 - 6.3
		1992	441 - 1325	.31 - 7.3	0.5 - 5.9
2.	Barabanki	1979	402 - 1004	.20 - 6.1	1.1 - 6.1
		1992	328 - 1278	.25 - 3.7	0.6 - 15.2
3.	Sultanpur	1979	720 - 2583	.40 - 8.2	1.6 - 7.5
		1992	337 - 3372	.31 -20.4	0.8 - 65.2
4.	RaeBareli	1979	480 - 2226	20 - 7.5	1.1 - 5.8
		1992	454 - 3472	.31 - 8.3	0.8 - 29.1
5.	Pratapgarh	1979	643 - 1587	.20 - 7.8	1.7 - 3.1
		1992	366 - 2141	.19 - 6.3	1.5 - 8.3
6.	Jaunpur	1979	608 - 1859	.20 - 5.6	0.8 - 9.4
		1992	424 - 3478	.39 -13.7	1.2 - 4.4

SURFACE WATER RESOURCES

The project area lying East of Sharda Sahayak Feeder channel (S.S.F.C.) receives surface water through the channel which take off between Gomti Aqueduct (at 153.400 Km on S.S.F.C.) and Sai Aqueduct (at 232.780 km on S.S.F.C.) Sharda Sahayak Canal net work system was commissioned during the year 1978. Out of 43 blocks of the study area, 36 blocks are covered by net work of Sharda Sahayak Canal system. The Blocks devoid of Canal Network irrigation are Sadar, sandwa Chandrika and Shivgarh of Pratapgarh district and Dharmapur, Jalalpur and Sikrara of Jaunpur district.

MATHEMATICAL MODELLING STUDIES

Single layer Groundwater flow model has been devised for simulation studies to test the conjunctive water use planning options. The simulation is based on the available information relating to aquifer characteristics, rainfall, evapotranspiration and canal and river discharges data. The process simulated are the groundwater flow, transient seepage from the canal bed, total recharge to the groundwater system (i.e. through rainfall, return flow from the irrigation and tanks, ponds, lakes etc. and the groundwater draft).

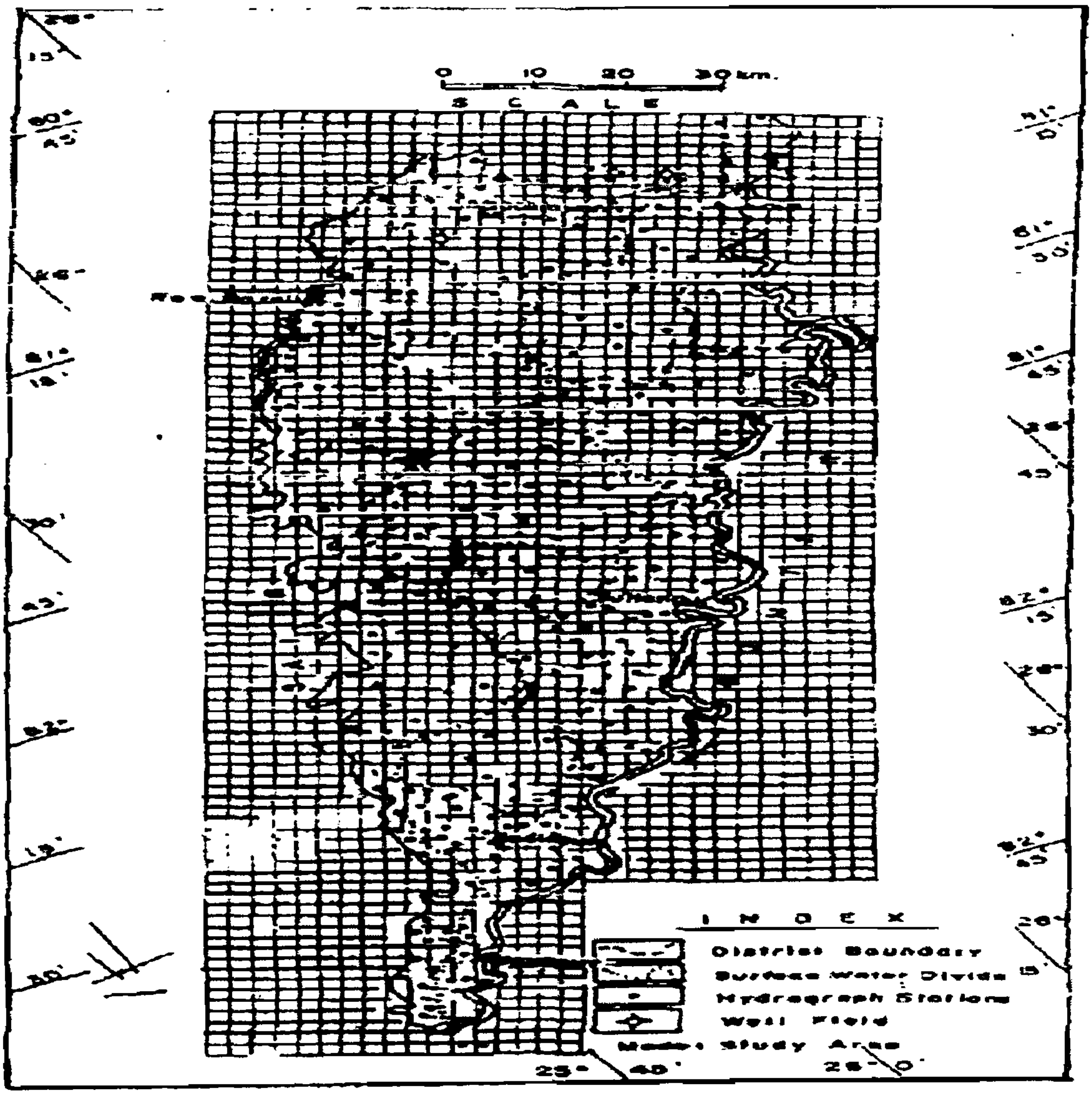


Fig. 4. Discretised Map of Sai-Gomti Interfluve Parts of Sharda Sahayak Canal Command, U.P.

DEVELOPMENT OF SIMULATION MODEL

Discretisation of Modelled area

Entire Sai - Gomti Doab falling in the Sharda Sahayak canal command spread over an area of 8287 km^2 has been selected for simulation studies. The area is representative of the whole of the command. It is expected that the methodology adopted and the conclusions arrived at would find their applicability elsewhere in the canal command.

The area has well defined physical features, such as intense network of canals-(Branches/ Distributaries/Minors) and vast tracts of water logged and salt infested areas. The model area is bounded in the north by the river Gomti and in the south by Sai River. The confluence of the two rivers in Jaunpur district forms the eastern extremity of the area and the feeder channel section between Gomti and Sai aqueducts lying between 153.4 and 184.16 km forms the western boundary (Fig. 4).

The area has been discretised into equi-dimensional 2580 cells (30 columns and 86 rows). Each cell measures 2500 meters in length and with identical breadth. Thus each cell represents 6.25 km^2. The model grid is so laid that one axis of the grid coincides with that of the regional direction of groundwater flow (Fig. 4).

Aquifer Geometry and characteristics, electric and lithological logs of over 70 bore holes of the area indicate presence of phreatic aquifer together with semi-confined aquifer, the thickness of which ranges between 25-70 meters. This zone as a whole has been simulated in the model. Because of Inadequacy of the data on aquifer parameters, the figures for hydraulic conductivity and specific yield were adopted from the contiguous areas and reports.

Boundary Conditions

The feeder channel section between Gomti and Sai aqueducts, Gomti and Sai rivers have been simulated as constant head boundaries.

Canal network

Sharda Sahayak Canal network that occupies 616 cells of the model grid and the transient seepage through the canal bed has been simulated in the model by taking physical dimensions of the canal and the conductance of the canal bed.

Groundwater Draft

Block-wise groundwater draft figure for the year 1991-92 have been used for cell-wise distribution of draft. Total annual draft was of the order of 958 MCM, which includes 52 MCM draft for domestic consumption.

Groundwater Recharge

The simulated recharge includes rainfall (25 %), return flow from irrigation and shallow surface water bodies. For prognostic runs 70 years normal rainfall (IMD) has been taken into consideration for computing recharge from rainfall.

Stress Period and Time Steps

During steady-state calibration stress period and time steps of one day was taken. During unsteady-state calibration stress period of 12 months (June 1991-May 1992) and time step of 30 days were selected keeping in view the availability of canal discharge data for the corresponding period.

Modifications and additions in the USGS MODFLOW Source Code

Following modification in the source code of USGS 3D MODFLOW program were carried out:

i) Memory management: The main program was originally written to accommodate only 1600 cells hence in order to simulate 2580 cells (30 x 86) LYNX array was broken down to six sub arrays suiting the MS Fortran 3.30 compiler requirements and 640 KB RAM.
ii) Well-module of MODFLOW has been modified and made to accept four (4) multiplication factors and four flags tagged with well location so that draft of any block can be varied as per the requirement during prognostic run.
iii) Recharge module of MODFLOW has also been made to accept the multiplication factor for the prognostic runs.
iv) Several programs in Fortran-77 were written and compiled, to process, analyse and prepare the data files. Application software like SURFER, LOTUS worksheet and Word Star package were also used to prepare data files. Harvard Graphic package was used for graphical presentation.

Steady State Calibration

The modelling started with the steady state calibration. As a first step attempts were made to confirm the water levels of pre-monsoon period (June 1991) from the 174 observation network stations. During calibration (1000 odd runs) parameters like hydraulic conductivity, recharge (seepage) distribution from canal bed, and groundwater deaft were subjected to change/ modification with a view to obtain history match. However, an acceptable match was obtained (Table 5). It is seen that the average difference in field and model levels is 0.44 m, which is within acceptable limit to start with.

Table 5. Steady State Calibration - Field and Model Head Comparison (June, 1991).

LAYER	COLUMN	ROW	FIELD	MODEL	DIFF * LAYER	COLUMN	ROW	FIELD	MODEL	DIFF * LAYER	COLUMN	ROW	FIELD	MODEL	DIFF
1	23	1	120.7	120.7	.0 * 1	26	23	101.8	101.8	.0 * 1	15	46	93.9	93.9	.0
1	25	1	121.2	121.2	.0 * 1	4	24	102.6	102.6	.1 * 1	8	47	90.4	90.4	.0
1	24	2	113.1	113.1	.0 * 1	9	24	106.2	106.2	.0 * 1	16	48	92.3	92.3	.0
1	24	5	108.6	108.5	.1 * 1	10	24	106.0	106.0	.0 * 1	20	48	89.3	89.3	.0
1	10	6	109.9	109.9	.0 * 1	15	24	106.0	106.0	-.1 * 1	21	48	88.3	88.4	.0
1	18	6	116.8	116.8	.0 * 1	4	25	100.4	100.4	.0 * 1	8	49	83.2	83.2	.0
1	10	7	107.9	107.9	-.1 * 1	15	25	106.1	106.1	.0 * 1	14	49	90.2	90.2	.0
1	11	7	110.6	110.6	.0 * 1	21	25	103.5	103.5	.0 * 1	17	49	91.9	91.9	.0
1	13	7	111.0	111.0	.0 * 1	5	26	99.3	99.3	.0 * 1	18	49	91.8	91.8	.0
1	19	7	112.0	112.0	.0 * 1	18	26	100.9	100.9	.0 * 1	10	52	87.6	87.6	.0
1	20	7	111.3	111.3	.0 * 1	21	26	102.0	102.0	.0 * 1	9	56	83.7	83.7	-.1
1	21	7	112.7	112.7	.0 * 1	4	27	96.9	96.9	.0 * 1	7	58	79.6	79.6	.0
1	24	7	101.3	101.3	.0 * 1	8	27	104.3	104.3	.0 * 1	9	58	85.0	85.0	.1
1	13	8	112.6	112.6	.0 * 1	13	27	102.8	102.8	.1 * 1	19	58	84.3	84.3	.0
1	21	8	113.6	113.6	.0 * 1	21	27	99.9	99.9	-.1 * 1	10	59	86.2	86.2	.0
1	8	9	105.3	105.4	.0 * 1	15	28	103.6	103.6	.1 * 1	13	59	86.4	86.4	.1
1	12	9	110.8	110.8	.0 * 1	17	28	100.9	100.9	-.1 * 1	18	60	79.6	79.6	.0
1	22	9	109.6	109.5	.0 * 1	25	28	88.6	88.6	.0 * 1	21	60	75.8	75.8	.0
1	23	9	107.4	107.4	.0 * 1	12	29	100.7	100.7	.0 * 1	18	62	75.4	75.4	.0
1	11	10	110.5	110.5	.1 * 1	20	29	98.5	98.5	.0 * 1	12	64	79.5	79.5	.0
1	12	10	110.9	110.9	.0 * 1	23	29	100.0	100.0	.0 * 1	15	64	79.6	79.5	.0
1	15	10	110.7	110.7	.0 * 1	8	30	98.9	98.9	.0 * 1	15	63	79.8	79.8	.0
1	21	10	113.3	113.3	.0 * 1	15	30	103.5	103.5	.0 * 1	16	65	82.9	82.9	.0
1	9	11	109.6	109.6	.0 * 1	22	30	97.1	97.1	.0 * 1	17	66	81.7	81.7	.0
1	10	11	107.5	107.5	.0 * 1	5	31	102.1	102.1	.0 * 1	11	67	81.6	81.6	.1
1	19	12	110.0	110.0	-.1 * 1	18	31	102.1	102.1	.0 * 1	15	67	77.7	77.7	.0
1	20	12	113.0	113.0	.0 * 1	24	31	96.4	96.4	.0 * 1	11	68	80.8	80.8	.1
1	11	13	109.8	109.8	.0 * 1	12	32	102.4	102.4	.0 * 1	13	68	83.2	83.2	.0
1	21	13	110.3	110.3	.0 * 1	21	32	92.9	92.9	.0 * 1	14	68	81.2	81.2	.1

LAYER	COLUMN	ROW	FIELD	MODEL	DIFF * LAYER	COLUMN	ROW	FIELD	MODEL	DIFF * LAYER	COLUMN	ROW	FIELD	MODEL	DIFF
1	8	14	103.6	103.6	.0 * 1	12	33	98.6	98.6	.0 * 1	16	68	79.0	79.0	.2
1	22	14	107.6	107.6	.0 * 1	7	35	97.4	97.4	.0 * 1	16	69	75.9	75.9	-.1
1	8	15	105.3	105.3	.0 * 1	9	35	98.3	98.3	.0 * 1	17	70	75.1	75.1	1
1	11	15	109.4	109.4	.1 * 1	11	35	99.3	99.2	.1 * 1	12	71	77.2	77.2	.1
1	7	16	102.0	102.0	-.1 * 1	13	35	99.7	99.6	.0 * 1	16	71	79.2	79.2	.0
1	15	16	108.5	108.5	.0 * 1	14	35	98.7	98.7	-.1 * 1	14	72	79.3	79.2	.1
1	9	17	108.0	108.0	.0 * 1	17	35	101.5	101.5	.0 * 1	15	73	74.2	74.2	.0
1	10	17	106.0	107.2	-1.2 * 1	21	35	96.9	96.9	.0 * 1	12	74	76.5	76.5	.0
1	12	17	104.4	104.4	.1 * 1	6	38	92.6	92.6	.0 * 1	13	74	77.5	77.5	.0
1	5	18	97.4	97.4	.0 * 1	9	38	92.5	92.5	.0 * 1	12	75	75.2	75.2	.0
1	7	18	105.8	105.8	.1 * 1	12	38	97.4	97.4	.0 * 1	11	76	74.4	74.4	.0
1	13	18	107.0	107.0	.0 * 1	18	38	98.1	98.0	.1 * 1	10	77	68.1	68.1	.0
1	22	18	107.6	107.6	.0 * 1	22	38	94.7	94.7	.0 * 1	11	77	75.7	75.7	.0
1	6	19	103.9	103.9	.0 * 1	11	39	94.9	94.9	.0 * 1	12	77	74.6	74.6	.0
1	8	19	105.1	105.1	.0 * 1	15	39	95.7	95.7	.0 * 1	10	79	66.0	66.0	.0
1	12	19	105.4	105.4	.0 * 1	21	39	96.6	96.6	.0 * 1	11	79	73.7	73.6	.1
1	15	19	106.7	106.7	.0 * 1	13	40	95.5	95.5	.0 * 1	12	79	73.0	73.0	.0
1	5	20	101.6	101.6	.0 * 1	16	40	96.5	96.4	.0 * 1	9	81	65.0	65.3	-.3
1	17	20	104.6	104.6	-.1 * 1	18	40	93.7	93.7	-.1 * 1	11	81	73.8	73.8	.0
1	7	21	103.1	103.1	.0 * 1	22	40	95.7	95.6	.1 * 1	12	81	72.1	72.1	.0
1	19	21	106.8	106.8	.0 * 1	10	41	92.3	92.3	.0 * 1	11	82	73.7	73.7	.0
1	21	21	107.2	107.2	.0 * 1	15	41	94.7	94.7	-.1 * 1	12	82	70.8	70.8	.0
1	5	22	102.7	102.7	.0 * 1	19	41	95.0	95.0	.0 * 1	13	82	66.0	66.0	.0
1	8	22	100.1	100.1	.0 * 1	13	42	92.4	92.4	.0 * 1	11	83	71.9	71.9	.0
1	9	22	102.0	102.0	.0 * 1	14	43	95.2	95.2	.0 * 1	12	84	76.5	76.5	.0
1	11	22	106.4	106.4	.1 * 1	12	43	91.1	91.0	.0 * 1	10	85	67.5	67.2	.3
1	16	22	107.3	107.3	.1 * 1	13	44	92.1	92.1	.0 * 1	12	85	65.3	65.3	.0
1	4	23	102.6	102.6	.0 * 1	15	44	94.9	94.9	.0					
1	19	23	105.7	105.7	.0 * 1	20	44	95.8	95.8	.0					
1	24	23	106.3	106.3	.0 * 1	14	46	87.9	87.9	.0					

AVERAGE DIFFERENCE FOR UPPER LAYER:04 m Water Balance

By definition of the steady - state the total input must balance with the total output; By studying the steady - state balance - total input is 16,24,500 m^3/day which includes recharge to system of 15,93,500 m^3/day and 12,553 m^3/day of feeder canal seepage. Total canal bed seepage is 18,508 m^3/day. The output component is 16,24,400 m^3/day, which includes groundwater draft of 14,13,200 m^3/day and base flow to Sai and Gomti rivers of 2,11,250 m^3/day. Net balance of steady - state is 90.125 m^3/day with percent discrepancy of 0.01, which is quite acceptable considering the size of the model.

Unsteady State Calibration and Verification

A period of twelve month from June 91-May 92 was chosen for unsteady state calibration, where in 250 odd runs parameters like specific yield and monthly groundwater draft (distribution) was modified/changed to achieve an acceptable history match of monthly water levels of 177 hydrograph stations. The period for verification was taken from June 92-November'92, where the history match was obtained without playing around with any of the input parameters for the period of verification.

Prognostic Runs

Several scenarios were simulated to select the right option for the conjunctive water use planning. Stress Period of 20 years simulated keeping the parameters of verified models to generate the future scenarios. Time Step of 365 days were kept in the scenario I and II and 182 days for the Scenario III.

Scenario I

Stipulation: Present recharge from rainfall, return seepage from irrigation and other surface water bodies and draft remains unchanged.

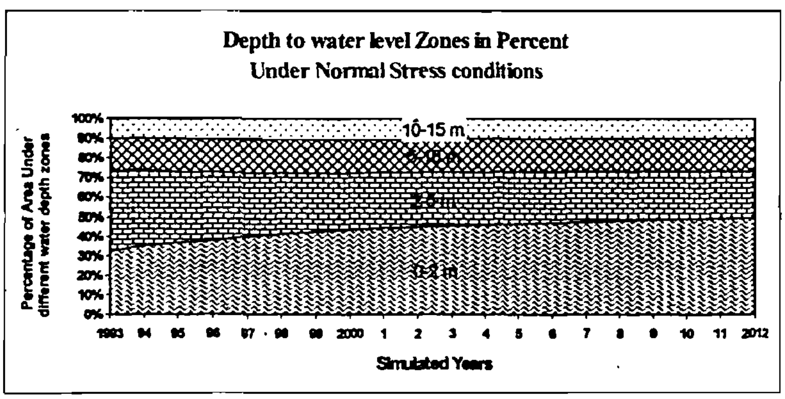


Fig. 5 Scenario I

Result: The prognostic run (Table 6 and Fig 5) indicate that the area falling in 0 - 2 m below ground level depth range increase from 33.18 % to 54.98 % in next 20 years. Besides, there is marginal increase of the area falling in 0-4 m b.g.l. depth range from 61.99 % to 69.16 % during the same period.

Scenario II

Stipulation: If the canals are fully lined keeping other variables as under Scenario I.

Results: The prognostic run indicates marginal improvement in the area falling under 0-2 m below ground level depth range from 31.22% to 48.11% as compared to Scenario I. Table 7 and Fig. 6 clearly demonstrate that under this situation the pace of spread of water logged area is comparatively slow yet it maintains the same trend as under Scenario I. Therefore it can be

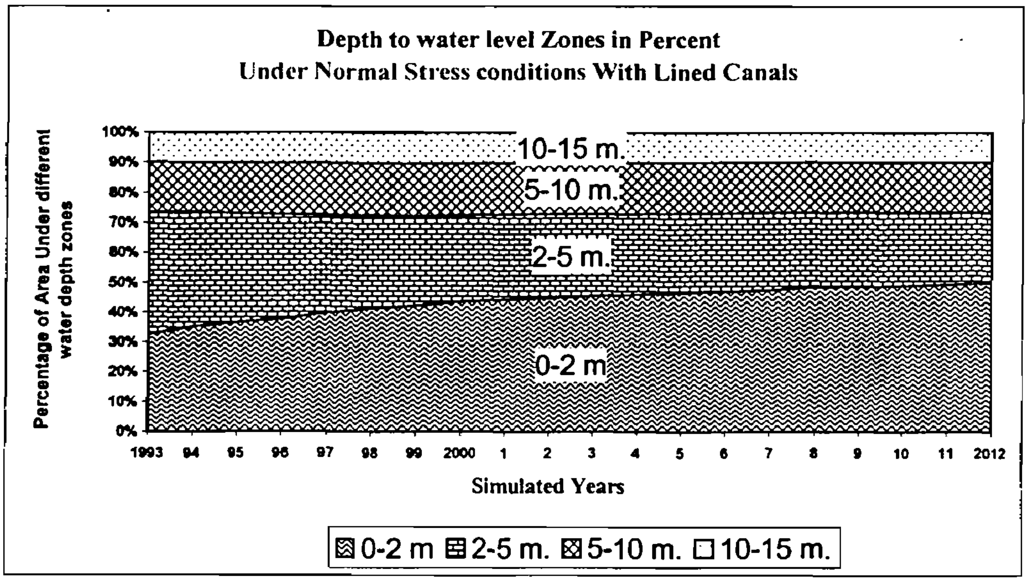


Fig 6. Scenario II

concluded that even lining the entire canal network could not arrest pace of rise in water table in the command.

Scenario III

Stipulation: Regulated pumping - 1248.8 MCM during Karif and 226.7 MCM during Rabi season and 'rostering' of canal water supplies under the present average cropping intensity of 153%.

Results: The prognostic run indicate that the water levels in the larger part of the area remain within desirable /manageable limits.

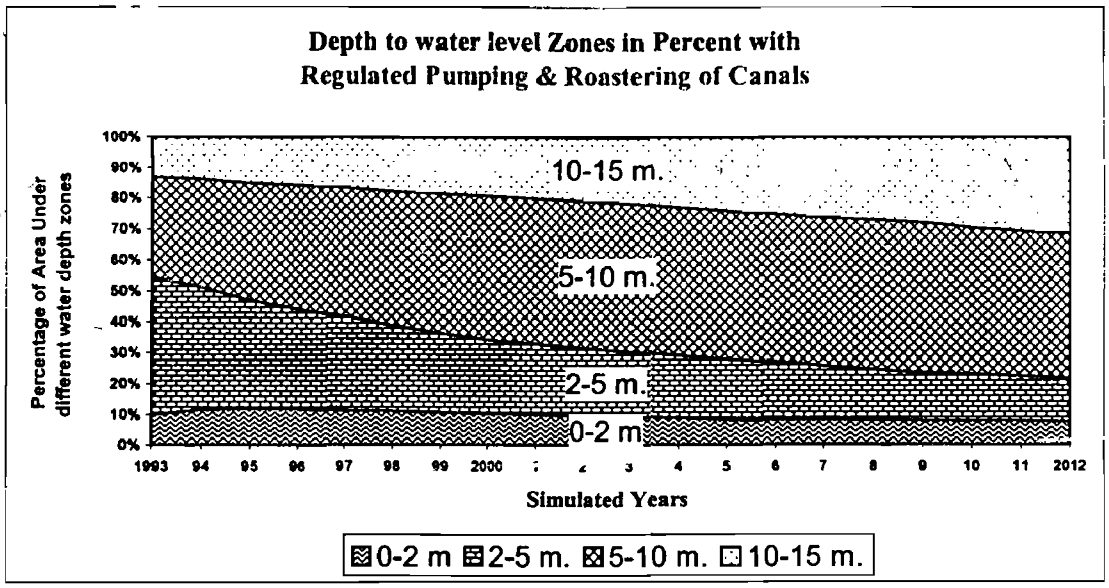


Fig. 7. Scenario III

Perusal of Table 8 and Fig 7 clearly indicate that the percent area with water levels down to 2.0 m depth constitute less than 7 % of the total area under different water depth zones. It also shows gradual and steady decline of water levels in 10 years and thereafter nearly gets stabilised. It is significant to mention that by the end of the decade of the implementation of the suggested strategy, the percent area under 0-5 m water level below ground level, get restricted to less than 20 % of the area. This also shows that the percent area with water levels 0 - 5 m bgl constitute nearly 55 % of the area. Whereas the percent area with water levels between 10-15 m and over 15 m bgl together constitute less than 20 % of the area.

The Table 8 and Fig. 7 also demonstrate that beyond the first decade of the adoption of the suggested conjunctive water use strategy, there is gradual increase in the percent area with water levels between 10-15 m b.g.l. and more than 15 m b.g.l.

Conjunctive Water Use Mechanism

The conjunctive water use mechanism has been evolved for the study area not only for scheduling of optimum use of water resources *vis-à-vis* demand but also to tackle the problem of rising water levels and spread of salt infested land - the Usar.

Table 6. Depth to Water Level Zones in km^2 (Scenario I) Under Normal Stress-Conditions (area in %).

Year	0-2 m	2-5 m	5-10 m	10-15 m	(0-2) m	(0-4) m	(2-5) m
1993	2750.00	3156.25	1281.25	787.50	33.18	61.99	38.08
1994	3087.50	2831.25	1256.25	800.00	37.25	63.50	34.16
1995	3337.50	2587.50	1243.75	806.25	40.27	63.73	31.22
1996	3531.25	2418.75	1212.50	812.50	42.61	64.18	29.19
1997	3625.00	2356.25	1181.25	812.50	43.74	64.86	28.43
1998	3737.50	2262.50	1156.25	818.75	45.10	65.31	27.30
1999	3850.00	2150.00	1162.50	812.50	46.46	65.76	25.94
2000	3975.00	2043.75	1156.25	800.00	47.96	66.21	24.66
2001	4031.25	2012.50	1137.50	793.75	48.64	66.67	24.28
2002	4125.00	1931.25	1137.50	781.25	49.77	66.97	23.30
2003	4175.00	1900.00	1118.75	781.25	50.38	67.35	22.93
2004	4225.00	1862.50	1112.50	775.00	50.98	67.65	22.47
2005	4256.25	1862.50	1081.25	775.00	51.36	68.02	22.47
2006	4293.75	1837.50	1068.75	775.00	51.81	68.33	22.17
2007	4325.00	1818.75	1056.25	775.00	52.19	68.40	21.95
2008	4368.75	1787.50	1043.75	775.00	52.71	68.55	21.57
2009	4437.50	1731.25	1031.25	775.00	53.54	68.70	20.89
2011	4512.50	1668.75	1018.75	775.00	54.45	69.00	20.14
2012	4556.25	1631.25	1018.75	768.75	54.98	69.16	19.68

Table 7. Depth to Water Level Zones in km^2 (Scenario II) Under Normal Stress Conditions with lined Canals (area in %).

Year	0-2 m	2-5 m	5-10 m	10-15 m	(0-2) m	(0-4) m	(2-5) m
1993	2587.50	3268.75	1331.25	787.50	31.22	61.54	39.44
1994	2806.25	3062.50	1306.25	800.00	33.86	61.84	36.95
1995	2931.25	2887.50	1350.00	806.25	35.37	62.07	34.84
1996	3018.75	2781.25	1350.00	825.00	36.43	61.92	33.56
1997	3187.50	2587.50	1381.25	818.75	38.46	62.14	31.22
1998	3300.00	2468.75	1381.25	825.00	39.82	61.92	29.79
1999	3381.25	2368.75	1393.75	831.25	40.80	61.92	28.58
2000	3468.75	2300.00	1375.00	831.25	41.86	62.67	27.75
2001	3531.25	2262.50	1362.50	818.75	42.61	62.52	27.30
2002	3575.00	2231.25	1350.00	818.75	43.14	62.82	26.92
2003	3625.00	2187.50	1356.25	806.25	43.74	62.75	26.40
2004	3668.75	2143.75	1356.25	806.25	44.27	63.05	25.87
2005	3706.25	2131.25	1337.50	800.00	44.72	63.42	25.72
2006	3756.25	2081.25	1337.50	800.00	45.32	63.80	25.11
2007	3793.75	2056.25	1325.00	800.00	45.78	64.03	24.81
2008	3856.25	1993.75	1325.00	800.00	46.53	64.03	24.06
2009	3875.00	1981.25	1318.75	800.00	46.76	64.18	23.91
2010	3906.25	1950.00	1318.75	800.00	47.13	64.48	23.53
2011	3937.50	1918.75	1318.75	800.00	47.51	64.63	23.15
2012	3987.50	1875.00	1312.50	800.00	48.11	64.78	22.62

Table 8. Depth to Water Level Zones in km^2 (Scenario III); Regulated Pumping and Rostering of Canals (area in %).

Year	0-2 m	2-5 m	5-10 m	10-15 m	>15m	(0-2) m	(2-5) m
1993	793.75	3525.00	2568.75	1037.50	362.50	9.58	42.53
1994	918.75	3118.75	2762.50	1087.50	400.00	11.09	37.63
1995	937.50	2750.00	2993.75	1193.75	412.50	11.31	33.18
1996	925.00	2518.75	3150.00	1231.25	462.50	11.16	30.39
1997	881.25	2368.75	3256.25	1306.25	475.00	10.63	28.58
1998	868.75	2150.00	3381.25	1387.50	500.00	10.48	25.94
1999	831.25	1987.50	3512.50	1443.75	512.50	10.03	23.98
2000	800.00	1862.50	3612.50	1493.75	518.75	9.65	22.47
2001	781.25	1768.75	3643.75	1550.00	543.75	9.43	21.34
2002	725.00	1706.25	3668.75	1606.25	581.25	8.75	20.59
2003	712.50	1625.00	3675.00	1668.75	606.25	8.60	19.61
2004	681.25	1556.25	3662.50	1756.25	631.25	8.22	18.78
2005	631.25	1493.75	3675.00	1843.75	643.75	7.62	18.02
2006	625.00	1443.75	3631.25	1931.25	656.25	7.54	17.42
2007	631.25	1331.25	3643.75	2000.00	681.25	7.62	16.06
2008	612.50	1231.25	3675.00	2050.00	718.75	7.39	14.86
2009	593.75	1175.00	3650.00	2112.50	756.25	7.16	14.18
2010	587.50	1137.50	3556.25	2225.00	781.25	7.09	13.73
2011	575.00	1087.50	3487.50	2300.00	837.50	6.94	13.12
2012	556.25	1050.00	3468.75	2356.25	856.25	6.71	12.67

It is significant to note that during the post monsoon period 59 % of the area falls under 0-4 m below ground level (i.e. waterlogged and the area prone to waterlogging) and during pre-monsoon period, the same area gets reduced to just 15 %. Thus suitable conjunctive water use mechanism has to be devised so as to scale down the percentage of area under 0-4 m b.g.l. subsequently.

Several factors have been taken into consideration for evolving the conjunctive water use mechanism given as under:

- Month-wise quantitative evaluation of available groundwater resource.
- Month-wise quantitative evaluation of available surface water resource.

i) Month-wise match of water availability and demand to ascertain water surplus/deficit areas.

ii) Ensuring regional decline of water surface in water logged and areas prone to logging to safe levels during the Karif crop season i.e. beyond 5.0 m below ground surface.

iii) Regional lowering of water levels to be achieved in such a way so as to ensure that the hydraulic head of the underlying semiconfined/confined poor quality (Brackish to saline) aquifer remains well below the phreatic level in order to stop the possible upward leakage.

iv) Ensuring 'stabilised condition' of water levels within safe and economic limits in the larger part of the area during the Rabi crop season (i.e. ensuring that water levels remain within 10 m below ground level).

It has been observed that excessive use and availability of water during Karif has given rise to certain deleterious effects like shallow water conditions and associated problem of Usar lands. Thus, the conjunctive water use mechanism has been evolved to restrict the use and availability of water to the extent it is necessary to meet the crop water requirement and other uses of water.

The cardinal principle in working out the conjunctive water use mechanism for the area has been "regulated pumping and rostering of canal supplies during specific period of time".

Regulated groundwater draft to the tune of 1248.8 MCM during Karif and 226.7 during Rabi has been proposed whereas the irrigation by surface water component is required to be scaled down to 205.5 MCM during Karif and 691.00 MCM during Rabi crop season (Fig. 8).

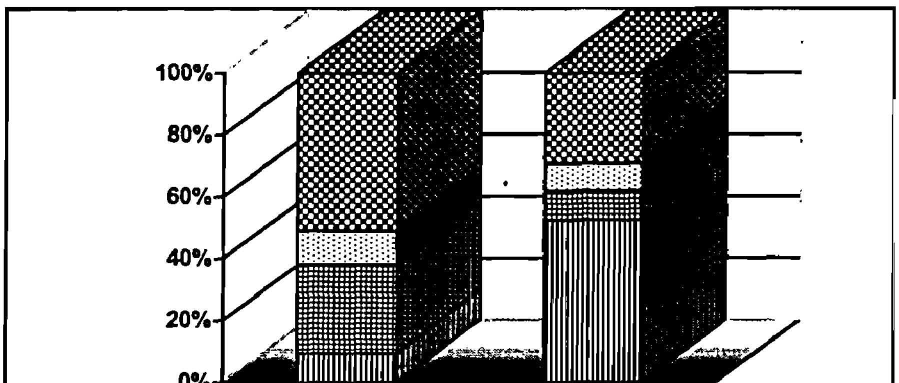
For the proposed quantum of groundwater draft, additional 21375 shallow tubewell will be required to be installed to existing battery of 56625 shallow tubewells to take the existing density per 6.84 tubewells/100 ha. (a shallow tubewell in 14.6 ha) to 9.43 tubewells/100 ha (one tubewell in 10.6 ha). The simulation studies have clearly indicated that the water levels in the larger part of the area would remain within desirable limits, once the conjunctive water use as suggested is implemented. Besides, immediate impact of the conjunctive water use mechanism would be the reduction of water logged area and the one prone to water logging percent area from 59 % to 28 % within the initial decade of the adoption of the scheme.

RECOMMENDATIONS

Different parameters/variables for the evaluation of groundwater resource need refinement. The parameters such as specific yield, field data on infiltration characteristics in different soil/lithological situations, seepage from canals and other surface water bodies, return seepage from applied irrigation, groundwater levels and their fluctuations etc. need to be studied, collected and compiled with fair degree of accuracy.

The quantification of surface water as available through canals needs refinement. Proper records relating to the variation in discharge which may occur from time to time in different channels and the volume of water diverted through 'escape' should be precisely known.

Programme of construction of piezometers should be undertaken for proper understanding of hydrogeological and hydrochemical regimes.



	Present	CWU
SW (Rb)	1207	691
SW (kh)	259	205.5
GW (Rb)	679	226.7
GW (kh)	227	1248.7

Fig. 8. Present and Proposed Water Utilisation.

A limited number of piezometers may be installed in the phreatic layer in selected areas to supplement information relating to groundwater levels, chemical quality of water etc..

Whereas a sizeable number of piezometers should be installed in the under lying semiconfined/

confined layer having poor quality of water. The subsurface data thus obtained would help in precise delineation of the aquifers. Close monitoring of groundwater levels and regular groundwater sampling and their analysis would provide vital information on variation in chemical quality in space and time.

With such data-base it may open up avenue for possible blending of fresh water (available from phreatic aquifer) with brackish/saline water (from underlying semi confined/confined aquifer) to supplement enhanced demand of water in future. Besides, it will provide necessary data base for solute transport model for posterity should it become necessary to reclaim the saline aquifer through artificial recharge.

The mathematical model set-up for devising planning options for better performance of conjunctive water use strategy needs to be updated from time to time for realistic projections. After the implementation of the conjunctive water use strategy, periodic and close monitoring of groundwater regime needs to be taken up so as to update and apply corrections in the model.

Single layer model set up under the present studies should be replaced by two layer model so as to take cognisance of 'leakage' and establish inter-relationship of the two aquifer.

Under the conjunctive water use strategy, fixed quantity of water has been recommended to be pumped out. This aspect should be strictly adhered to in order to understand the variation, if any, in the outcome of the anticipated results. Blockwise/crop season wise groundwater withdrawal figures have been computed should be strictly followed irrespective of the number of groundwater structures.

It is expected, once the scheme is followed in its strict term of reference, the results as expected would follow viz. elimination of adverse effects like water logging and soil salinity/alkalinity and better management of water resources. In the area (< 7 %) where it is not possible to overcome waterlogging by conjunctive water use strategy, horizontal pipe drainage programme or even inter aquifer transfer of water using connector wells/siphon may be attempted.

CURRENT TRENDS IN ISOTOPE HYDROLOGY TECHNIQUES FOR DEVELOPMENT OF WATER RESOURCES IN WESTERN RAJASTHAN

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INTRODUCTION

Water is an essential requirement for the existence of life on the earth and development of society. The total amount of water on our planet is constant but its distribution varies to a great extent with space and time. The largest portion of global water balance i.e. more than 97.2% is present in the form of oceans. Because of high salinity this water is not of direct use for human population. By natural processes, i.e. evaporation and condensation this water undergoes phase changes and through precipitation it provides life to all living beings including flora and fauna. The second largest portion of global water (~ 2%) is frozen in the form of glaciers on high mountains which again is not suitable for human consumption. The most utilisable form of water (0.6%) on earth, is the groundwater. Rest of the water balance (< 0.2%) is distributed in the form of surface water resources like lakes, reservoirs, small seas, rivers, dams etc. The geographical boundaries of surface waters can be defined but groundwater cannot be controlled by geographical boundaries. Since the demand for water will continue to increase due to increase in population, industrial development and agriculture requirements there is need to have optimum utilisation, conservation and proper management of water resources.

Hydrology is a geoscience that deals with the study of origin, distribution and behaviour of water in nature. This is how one can define Hydrology in simplest manner. A more comprehensive definition of this branch of science given by the U.S. Federal Council for Science and Technology is as follows:

" Hydrology is the science that treats the waters of the Earth, their occurrence, circulation and distribution, their chemical and physical properties and their relation to living things".

Isotopic composition of water molecule refers to the physical properties mentioned in this definition. The domain of hydrology embraces the full life history of water on Earth. Thus, hydrology covers all forms of water, their physical and chemical changes during their circulation in nature.

Isotope techniques provide valuable information for greater understanding of our water resources. Now a days use of isotope techniques in hydrological investigations is considered as a modern tool which provides additional information to the existing knowledge about water resources and some times it provides unique solution to a particular hydrological problem. However it is suggested that isotope techniques should be used in conjunction with conventional hydrological data available on regional basis.

SCOPE OF ISOTOPE HYDROLOGY

Isotope hydrology includes the application of nuclear techniques for various studies of atmospheric waters, surface waters and groundwater and their interrelationship. In atmospheric waters the isotope techniques have been used to investigate the origin and movement of atmospheric moisture. In surface water studies the nuclear techniques have been used to determine water equivalent of snow cover, study of glaciers, stream flow measurements, run off analysis, rate of sedi-mentation, dynamics and water balance of lakes and reservoirs and leakages from lakes and reservoirs. In groundwater studies the isotope techniques have been suitably used to investigate the groundwater recharge, aquifer characteristics, origin and dating of groundwater, surface water- groundwater relationship, interconnection between groundwater bodies, origin of geothermal waters, identification of palaeo waters and source of salinity of groundwater in coastal regions. More recently, isotope techniques have been used in the study of extent of pollution to subsurface water.

ISOTOPE HYDROLOGY IN ARID REGIONS

Conservation of water resources is more important in arid and semi- arid regions. These regions experience very low and erratic rainfall. Surface water resources are very less and therefore exploitation of groundwater resources becomes necessary to meet the drinking water requirements of the society. Over exploitation of groundwater may have deleterious effect on aquifer systems if there is no recharge by natural or artificial processes, thus affecting the quality and quantity of water. Ground water recharge studies are therefore more important in such regions. The most important information required for a regional hydrological system is, whether the aquifer is getting modern recharge or not. If so what is the annual rate of recharge? If not, how old the ground water is? Isotope hydrology can be conveniently used to distinguish old and recent waters. Isotope techniques are very effective in identification of source of recharge, evaluation of rate of recharge due to rainfall or irrigation, contribution of surface water to groundwater, interconnection between groundwater bodies, estimation of age of groundwater, underground flow rate and direction and contamination of groundwater by any other source of water.

Isotopes being used for hydrological investigations include both environmental as well as artificially produced radioisotopes. Environmental isotopes are those isotopes which, are naturally produced in the atmosphere and the investigator has no direct control over them. However, the variation of these isotopes with time and space provides important clues to various hydrological problems. The environmental isotopes of interest include both stable (D and ^{18}O) as well as radioactive isotopes (^{3}H, ^{14}C, ^{32}Si, ^{36}Cl etc.) as natural tracers. These isotopes are normally produced by cosmic reactions occurring in Earth's atmosphere. However, the nuclear bomb produced tritium, also become the part of environmental tracers and it provides useful information for identification of modern recharge to groundwater bodies. Reactor produced ^{3}H and ^{60}Co are used as artificial isotopes for the study of rate of annual recharge by injected tracer method. ^{82}Br radioisotope has been used for the discharge measurement of rivers and streams. Some other radioisotopes are used as per the requirement and type of experiment. The selection of tracer depends mainly on the type of problem and characteristics of isotope like its half-life and type and energy of radiation it emits.

The use of isotopes in hydrology at international level were started in 1959 by the International Atomic Energy Agency (IAEA) with the establishment of Isotope Hydrology section at its headquarters in Vienna. The agency encouraged projects on applied isotope hydrology mainly in the developing countries. Moreover, IAEA have been publishing data on tritium, deuterium and oxygen-18 in precipitation samples from a global network of stations. It also distributes water standards for calibration purposes. Gradually, there has been increase in application of stable and radioisotopes for understanding natural hydrological processes in developing countries.

In India, the application of environmental isotopes was initiated by Tata Institute of Fundamental Research, Bombay to investigate the groundwater recharge and estimate the groundwaters in arid and semiarid regions of Gujarat and Rajasthan during the early sixties. Similarly, the Physical Research Laboratory, Ahmedabad and National Geophysical Research Institute, Hyderabad also started application of isotope techniques for hydrological investigations. Thereafter, being an Atomic Installation, the Bhabha Atomic Research Centre, Mumbai took lead in the propagation of Isotope hydrology research in addition to other peaceful uses of atomic energy. The other major institutions which have been involved in the use of isotope techniques in hydrology in one way or the other are Central Arid Zone Research Institute, Jodhpur and Nuclear Research Laboratory, Delhi (ICAR), Defence Laboratory, Jodhpur (DRDO), UP Irrigation Research Institute, Roorkee, National Institute of Hydrology, Roorkee and Centre for Water Resources Development & Management (CWRDM), Kozhikode (Kerela) and a few more central and state government organisations. However, still there is lack of awareness regarding the use of isotope techniques among the water resources management agencies like groundwater departments and public health engineering departments. This is probably due to lack of training and lack of effort in the co-ordination of research and development programmes in this direction. Secondly these techniques have not so far been introduced in the universities probably due to lack of infrastructure. Therefore there is a need and lot of scope to popularise the use of isotope techniques for better understanding and management of our precious water resources.

ISOTOPE HYDROLOGY ACTIVITIES AT DLJ

Water has been one of the most important thrust areas of research at Defence Laboratory, Jodhpur right from its inception. This laboratory has done pioneering work in the field of water quality monitoring and surveillance, desalination of brackish water by electro-dialysis and management of water both in defence as well as civil sector. Moreover, the laboratory had done commendable work in disaster management by purification and supply of safe drinking water to the earth quake victims in Latoor and Usmanabad. Thus, Research and development on different aspects of water have been the main charter of this Laboratory. Western Rajasthan has been facing the problem of availability of water due to its hot and dry climatic conditions. Therefore, it has always attracted the attention of scientists to use modern science and technology to have better understanding of water resources particularly the groundwater recharge patterns, interconnections, relation with other water bodies and estimation of age of waters in arid regions.

ISOTOPE HYDROLOGY INSTRUMENTATION

The facilities of isotope techniques were created at Defence Laboratory Jodhpur during the early 1980's for various Research and Development applications. Since water has been among the important thrust areas of DLJ, it was considered necessary to create some basic facilities for isotope hydrology work in consultation with experts from Bhabha Atomic Research Centre, Bombay. Initially, a liquid scintillation counter for low level beta activity measurement and an auto gamma counter for gamma activity measurement were procured from Packard (U.S.A.). These counting systems were used mainly for tracer injection experiments using tritium and cobalt- 60 tracers in estimation of recharge at certain selected sites. During this process other facilities for tracer injection and soil sample extraction in the field were also generated. A field rate meter for in situ measurement of gamma activity was also procured. Subsequently, facility of mass spectrometers for stable isotope ratio measurements of D/H and $^{18}O/^{16}O$ in water was established. This is a sophisticated equipment supplied by V.G. Isogas Co. U.K. For oxygen -18 measurements the water sample is equilibrated with carbon dioxide gas and the isotope ratio of sample gas is measured with respect to the reference gas by the mass spectrometer. The system has an attachment of sample preparation unit Isoprep-18 in which 24 samples can be simultaneously equilibrated. The sample preparation for hydrogen isotopic ratio measurement is based on the reaction of water with uranium metal to produce hydrogen at 600^0C. The facilities have also been created for using zinc reduction method for hydrogen sample preparation where sample and reference gas can be prepared separately in special type of reaction tubes. The results are expressed in delta form defined as:

$$\delta = \frac{Rs - Rr}{Rr} x1000 \quad \text{per mil (parts per thousand)}$$

where Rs and Rr refer to isotopic ratios D/H or $^{18}O/\,^{16}O$ in sample and reference , respectively. The instrument is calibrated with the help of IAEA reference standards V- SMOW and SLAP abbreviated for Vienna Standard Mean Ocean Water and Standard Light Antarctic Precipitation.

Thus, the equipment systems available at Defence Laboratory, Jodhpur for hydrological investigations can be briefly summarised as follows:

1. Mass Spectrometer MM 602E for D/H Measurements.
2. Mass Spectrometer MM 903E for along with Sample preparation unit Isoprep-18 for $^{18}O/^{16}O$ Measurements.
3. Liquid Scintillation Counting System (ECIL) for tritium activity measurements.
4. Field rate meter for in situ measurement of gamma activity in tracer injection experiments.

5. Field analysis kit for pH, Electrical Conductivity, Dissolved oxygen and temperature measurement of groundwater samples.
6. Soil Moisture Extraction apparatus.
7. Tracer injection and extraction facilities and
8. Other. Tracer handling and counting facilities.

STATUS OF WORK DONE ON ISOTOPE HYDROLOGY IN ARID AND SEMI-ARID REGIONS

Isotope techniques provide valuable information regarding the groundwater resources in arid regions, which is otherwise not possible by conventional hydrological data. The most important information required for a regional hydrological system is, whether the aquifers are receiving modern recharge or not. If not, what is the average age of a groundwater body? Is there any contribution of any other source of water? Identification of paleo waters, etc. in groundwater flow rate and direction. Isotopes can be suitably used to get all these information.

The application of stable isotope signatures in arid zone problems is more significant because the effect of evaporation and hence the isotopic enrichment is more pronounced in such regions.

Practical applications of isotope hydrology were started at Defence Laboratory Jodhpur in 1984 for rainfall recharge studies at Jalore, Siwana, Bhadrajun and Jodhpur by tracer injection method using tritium and cobalt-60 tracers. These studies were conducted in collaboration with Bhabha Atomic Research Centre, Mumbai and Central Arid Zone Research Institute, Jodhpur. Gradually with the creation of Mass Spectrometry facility the use of stable isotope measurement for understanding recharge processes in arid parts of Rajasthan were started. Some of the important case studies undertaken by us are discussed below:

GROUNDWATER RECHARGE STUDIES IN LIMESTONE AQUIFERS OF WESTERN RAJASTHAN

This study was undertaken with the aim of identifying recharge areas in the limestone belt of aquifers in Jodhpur and Nagaur districts of western Rajasthan. The study was important in the context of emergency plan for supply of drinking water to Jodhpur from tube wells of Ransi village in Bilara block. The study was based on stable isotope D and ^{18}O measurement in about

50 well water samples as well as rainwater for three successive years. Tritium and carbon-14 measurement of some representative wells were got done at BARC, Mumbai. In general there is depletion in heavy isotope content as well as tritium values as we move from South East to Northeast direction in the lime stone belt. With this study it could be possible to identify active recharge areas, surface water - groundwater relationship, groundwater dynamics and estimation of age of groundwater.

ISOTOPE STUDY OF WATER RESOURCES IN BORDER AREAS OF JAISALMER

The aim of this study was to investigate whether shallow groundwater in Shahgarh bulge area of Jaisalmer is receiving modern recharge or not. The area is strategically important because it is surrounded by international boundary from there directions. In this study again environmental isotopes (D, ^{18}O and ^{3}H) were measured in water samples collected from shallow wells/ hand pumps from Shahgarh to Jhalaria. A few deep well waters were also analysed for stable isotopes. Tracer injection experiment was also conducted at Mehrana. The results of stable isotope data as well as tracer injection experiment indicate that practically there is no modern recharge to these shallow waters and they are quite old waters. However, the water is available at shallow depth. The development of I.G. canal may have some impact on the hydrogeology of this area in future and isotope data will be useful for understanding these changes.

IMPACT OF INDUSTRIAL EFFLUENT ON GROUNDWATER

The industrial effluent from textile dying industries is discharged onto the rivers, which are generally dry in non- monsoon period. There are several shallow wells along the banks of Jojari River, which are used for irrigation. A preliminary study based on $^{18}O/^{16}O$ isotope ratio measurements was done to investigate the extent of groundwater pollution in Salawas area. The study indicate that there is scope of use of stable isotope measurements along with general chemical analysis to identify the wells affected by industrial effluent and the extent of pollution.

SCOPE OF WORK ON ARID ZONE PROBLEMS

1. Studies on Groundwater Recharge Patterns in Water Potential Zones.
   A. Generation of stable isotope data i.e. D/H and $^{18}O/^{16}O$ in well waters as well as local precipitation
   B. Evaluation of recharge due to rainfall/irrigation at representative locations.
2. Studies on impact of canal seepage on shallow and deep groundwater using isotopic and

chemical data.

3. Groundwater Pollution Studies using Isotopic and Chemical Data.
   A. Stable isotope measurement of industrial effluent and well waters in the discharge zone.
   B. Chemical analysis of water samples.
   C. Studies on effectiveness of gamma radiation for treatment of industrial wastewater.
4. Development of Suitable Methodology for Rainwater Harvesting in Arid Regions.

GROUNDWATER MODELS FOR DISCUSSION

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THEORETICAL MODELS

A. Well Hydraulics

The models planned to be discussed, consist of the work done on well flow relating to obtaining analytical solutions of flow problems using continuity equation in spherical coordinates for following situations:

1. Steady state flow to a non-penetrating well without recharge.
2. Steady state flow to a cavity well in a leaky aquifer.
3. Unsteady state flow to a cavity well with constant pumping.
4. Unsteady state flow to a cavity well in a leaky artesian aquifer.

The objective has been to find analytical solutions to determine hydraulic conductivity and storage coefficients for assessment of groundwater potential and other modelling purposes.

B. Subsurface Drainage

For lowering water tables in waterlogged and salt affected lands, pipe drainage consisting of two perforated pipes placed at 1 to 2 m depth below the ground are used. Analytical solutions have been obtained using Boussinesq's equation for the following conditions:

1. Unsteady state water table decline in a sloping land.
2. Unsteady state water table fluctuation with a constant and exponential recharge in a sloping aquifer.
3. Unsteady state water table fluctuation in stream aquifer system in a semi-infinite aquifer.
4. Unsteady state water table fluctuation in a vertically heterogeneous system using Girinsky's potential for (i) two layered soil, (ii) linearly varying heterogeneity and (iii) exponentially decreasing heterogeneity.
5. Water table decline/fluctuation in a bi-level drainage system.

C. Physical Models

These were made to simulate flow system for validating analytical solutions or finding experimental solutions.

(a) Vertical Hele-Shaw model was used for simulating subsurface drainage for following conditions:

1. Water table decline in sloping land.
2. Water table fluctuation with constant and exponentially decreasing recharge.
3. Water table decline in a heterogeneous soil/layered soil.

(b) Horizontal Hele-Shaw model to simulate unsteady state well flow in a confined aquifer of non transmissibility and storage coefficient to be used for validation of a particular flow system.

(c) Electrolytic tank model

1. To find dimensionless experimental solution for unconfined well flow.
2. To find dimensionless experimental solution for confined well flow to a cavity well.

(d) Heat flow analog to simulate unsteady state well flow to a cavity well.

GROUNDWATER MODELS FOR DECISION SUPPORT IN IRRIGATION WATER MANAGEMENT

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Optimum management of the available surface and subsurface water resources with respect to quantity and quality will be urgently needed in view of increasing demand, limited resources, falling/rising water tables and soil salinization problems. Efficient water management is one of the key elements in successful operation of irrigation schemes in arid and semi-arid regions. New technologies and improvement of on-farm water management are essential to solve the problems of rising/falling water tables and soil salinity. At the same time, it is equally important to develop regional water management policies, which may enable irrigation managers/planners to optimally manage the scarce available water resources.

Before proceeding to find alternative solutions for the emerging water management problems, an in-depth analysis of the present situation is imperative. Only with a comprehensive, complete and quantitatively defined problem analysis, alternative strategies for solving the problems can be defined and evaluated. Definite solutions to all these problems is impossible to realize solely at the farm level. Regional solutions, based on integrated approach for ground and surface water management along with improved on-farm water management, have to be found. The groundwater model can be used as a regional model to study the effect of net recharge on water table behaviour in the area. The net recharge to the aquifer is the linking factor between the water balance of the unsaturated zone and the groundwater balance. This net recharge constitutes various recharge and discharge components, viz: rainfall, seepage from irrigation conveyance system, field irrigation losses, capillary rise from water tables and pumping from tube wells. In this case, the net recharge from different sources is assigned in the centre of each nodal area as a lumped parameter calculated or estimated by using norms. It suffers from two lacuna, firstly, the net recharge thus, calculated may not represent the actual recharge simulating real field conditions due to the use of general norms and secondly, it does not help in studying the effect of different interventions from unsaturated part of the hydrologic cycle on the water table behaviour in the area so that the remedial measures can be taken.

Thus, it is very important that an integrated water management model is developed combining an unsaturated flow model and a groundwater simulation model in order to simulate the extremely complex groundwater-surface water system involving multiple interactions of the various components of the hydrologic cycle. Some efforts have been made in this direction. The integrated model basically consists of a number of closely related sub-models required for pre-processing of data and computation of water distribution, canal seepage and leakage and spatial distribution of crop water requirements. The following are some of the practical/feasible water management interventions, which could be studied and their impact on water table behaviour assessed:

i) Change in cropping pattern
ii) Variation of available canal water in time and space
iii) Change in assessment of water rate from warabandi to warimetric system
iv) Water supply according to demand as against based on cultivable area
v) Impact of method of irrigation water application/irrigation efficiencies
vi) Conjunctive use of canal and saline ground water

Before the model is to be used for studying the impact of various water management scenarios on the water table in the area, it needs to be calibrated and validated for a number of years. The calibration of a model includes the determination of the spatially distributed value of certain input parameters of which no exact information is available. Therefore, the value of different parameters is varied within a preset range. Model results obtained with the input parameters are compared with observed results and the parameters giving the best match of calculations with observations are fixed for further model applications. The adjustments of the value of parameters is a matter of professional guessing based on the logic of the water and salt balance. The calibration aims at achieving a close match between the calculated groundwater table depth. The validation of the model includes the determination of the reliability of predictions made through the model for circumstances, which differs from those for which the model was calibrated.

The quality component of the soil profile and aquifer also needs to be incorporated in the regional model so that impact of various water management strategies is also studied with respect to increase/decrease of salt load in the root zone as a result of long term use of poor quality irrigation water.

The quality of various hydrological and other data is also one of the very serious limiting constraints for development and application of such a model on regional scale. Sincere and concerted efforts are therefore, required to ensure quality of collected/measured data for achieving desired objectives.

LOCALIZED GROUNDWATER RECHAGE SYSTEM

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Groundwater is one of the most important resources in the arid region. However, groundwater become usable only when the zone of saturation is perennial and the dissolved minerals in the water area fit for desired use. In arid areas, where groundwater is practically absent or saline in nature, village nadis are the only source of rainwater storage and subsequently for domestic uses. This method of surface ponding of rainwater is quite vulnerable to pollution, besides containing high concentration of suspended solids. The losses due to evaporation are also high from such water bodies. However, if this water can be stored as groundwater, not only water will be free from suspended solids and polluting agents but also the losses can be minimized. Such a system of groundwater storage can provide clean, year round potable water for domestic use in the arid areas.

In the Kalyanpur village of Barmer district the groundwater exists in confined aquifer and is highly saline. Therefore, for the drinking purpose the village nadis are the only source of water. The topsoil (0-30 cm) is sandy-gravelly with high hydraulic conductivity (K_s = 2.6 m/day). However, below the surface, the soil is very compact and clayey-gravelly. While, the surface soil is very conductive to surface runoff generation the subsurface restricting layer causes the water to remain stagnant for 6-7 months. The first aquiclude in the study area is 29.13 m deep from the surface. Hence, the subsurface strata, because of high porosity permits formation of an unconfined groundwater table, with sufficient storage to supply the year round water. An open well is dug up to the aquiclude at one corner of the infiltration basin). The water table remains constant at about 9.2 m, attains the peak in the monsoon season and subsequently levels off. In order to assess the recharging potentials of such sites the variation of groundwater mound needs to be investigated.

The system was investigated for studying the recharging characteristics of the site. The water level in the well was measured at monthly interval during the dry season and at 15 days interval during the rainy season. The saturated hydraulic conductivity of the soil layers upto 45cm depth was measured by Guelph permeameter. It is assumed that the soil profile from

30 cm to the depth of recharge aquiclude is isotropic. The geometry of the recharge basin was also measured at regular intervals.

The rise of mound in unconfined aquifer below a square or rectangular recharge basin is given as:

$$h_{x,y,t} - H = \frac{V_a t}{4f}\left\{\begin{array}{l} F[(W/2+x)n,(L/2+y)n] + F[(W/2+x)n,(L/2-y)n] + F[(W/2-x)n,(L/2+y)n] \\ +F[(W/2-x)n,(L/2-y)n] \end{array}\right\} \quad (1)$$

where $h_{x,y,t}$ is height of water table above impermeable layer at x,y and time t (Fig. 1.) m; H is original height of water table (m); V_a is arrival rate of water from infiltration basin, (m/day); t is time since start of recharge (day); f is porosity; L is length of recharge basin (m); w is width of recharging basin (m); $n = (4tT/f)^{-0.5}$; T is aquifer transmissivity (m^2/day) and the aquifer function F is given by the definite integral:

$$F(\alpha,\beta) = \int_0^1 \operatorname{erf}\left(\alpha\tau^{-0.5}\right)\operatorname{erf}\left(\beta\tau^{-0.5}\right)d\tau \quad (2)$$

The equation for decay of groundwater mound after cessation of infiltration is given as:

$$h_{x,y,t} - H = Z(x,y,t) - Z(x,y,t-ts) \quad (3)$$

where t is time since water began to arrive at the water table, ts is the time since water ceased to arrive at the water table, and (x,y, t) and (x,y, t-ts) represent the right hand part of equation (1) with t and t-ts as time factors.

Infiltration rate V_a was estimated using Green and Ampt (1911) equation, which can be given as:

$$v_a = k(Hw + Lf + her)/Lf \quad (4)$$

where, V_a is infiltration rate (m/day); k is hydraulic conductivity of wetted zone (m/day); Hw is depth of water above soil (m); her is critical pressure head of soil for wetting and Lf is depth of wetting front. The k value may be taken about one half of k at saturation. Equation (4) shows that as the wet front Lf increases. V_a decreases and approaches to k when Lf become large compared to Hw-her. Thus, the final infiltration rate of a deep, unconfined soil is equal to k.

When the wetting front reaches a layer of reduced hydraulic conductivity or an impervious layer, a perching mound will rise. The recharge water then begins to flow vertically and laterally in the aquifer. The rate of rise of groundwater mound decreases with the time and eventually mound may reach a pseudo-equilibrium position. When infiltration is stopped the groundwater mound will recede and spread until a horizontal water table is established.

In the study area, however, the nature of groundwater mound reveals that it reaches its peak and then starts receding even though the infiltration continued. This may be because of the fact that the rise in groundwater mound was almost up to the surface. A high rise of mound in the vadose zone restricts the infiltration rate and causes greater lateral flow then the vertical flow. It may be due to this reason that the groundwater mound was falling even during the infiltration.

Under this situation equations (1) and (3) cannot be applied in a straight forward manner. Therefore, we first estimated the peak height of ground water mound. Subsequently it was assumed that after attaining the peak the infiltration has become zero. With this assumption, the decay of groundwater mound was estimated for next time interval. However, since the infiltration has not actually stopped, the rise in mound for this time interval was calculated taking the risen water table into consideration. The result obtained with this procedure are given in table 1. The table 1 shows that the observed and estimated variation of ground water mound was satisfactory. The last line in the table is for the period when infiltration was actually stopped. This procedure appears to be over simplification of the actual problem, even though the prediction of groundwater table was quite close to the observed values except for the intervals when infiltration was not zero (Fig. 1). This may be because of the fact that the aquifer in the study area is very small in extent and therefore, variation due to an isotropy may be minimum. The ratio T/f is the aquifer parameter that determines the rise and fall of groundwater mounds. Conversely, T/f can be calculated, if fluctuation of mound is known.

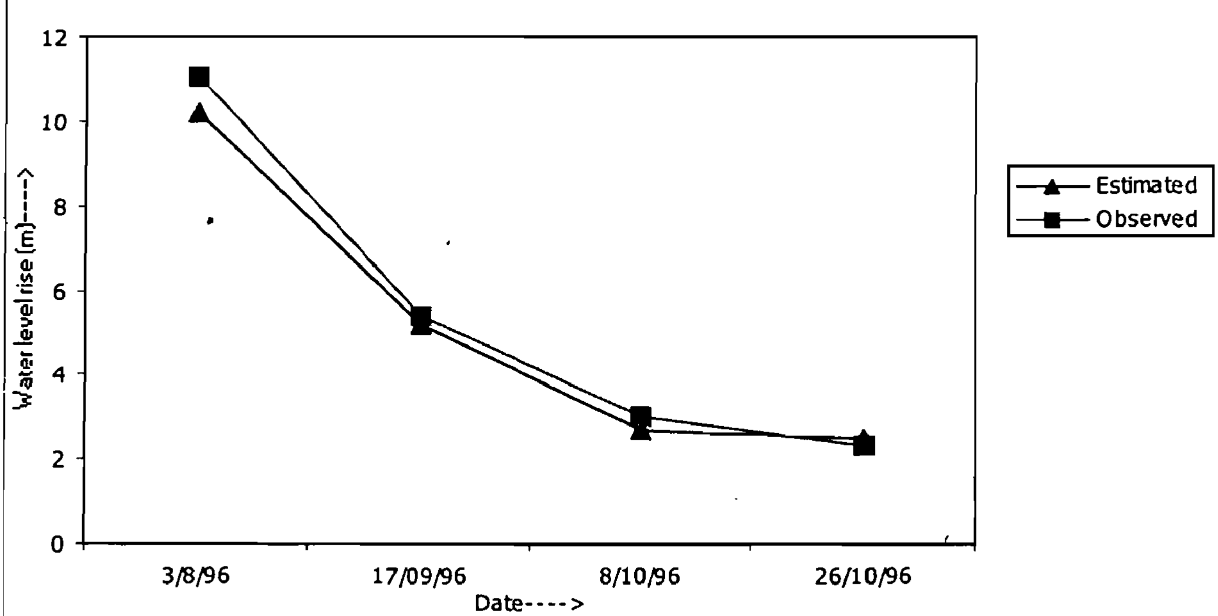
A system of localized ground water recharging was studied. This procedure could be applied to evaluate the suitability of certain aquifers for recharge and to determine the best layout of infiltration basin. The ratio T/f, calculated from the observed rise of mound below an experimental recharge basin can be used to predict the rise and fall of the mound below saturated recharge basin geometries for most efficient utilization of the ponded water.

Table 1. The parameters and calculation of groundwater mound below the recharge basin.

Date	Time (t) (days)	(t-ts) (days)	H (m)	T2 (m/days)	W (m)	L (m)	Estimated (hp, t-H) (m)	Observed (hp, t-H) (m)
20/07/96	-	-	9.18	-	-	-	-	-
03/08/96	42	-	9.18	4.56	45.0	45.0	10.21	11.05
17/09/96	87	45	9.18	4.56	45.0	45.0	1.26	-
17/09/96	45	-	10.44	5.19	25.0	25.0	5.19	5.40
08/10/96	108	66	9.18	4.56	45.0	45.0	4.56	-
08/10/96	66	-	10.84	5.37	20.0	20.0	2.70	3.00
26/10/96	126	84	9.18	4.56	45.0	45.0	2.48	2.32

H = 9.18m, K = 0.497 m/day, Va = 0.2 m/day, f = 0.30, W = 22.5 m, L = 22.7 m, x = 1.8 m, y = 0.0 m, T = KH = 4.561 m/day

Fig. 1. Observed and Estimated ground water mound in the recharging basin



CERTAIN NEW VISTAS AND CHALLENGES IN GROUNDWATER MODELLING

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Groundwater targeting has ever remained a matter of enigma to the geo-scientists of all over the world. The precise groundwater targeting in hard rock areas has always been posing a problem for the geo-scientists. Owing to the poly-phase metamorphism and the related variations in rock types multiple deformation and the resultant heterogeneity in the ground-water conduits set in. Though the man has started traditional dowsing techniques in the past, now he has reached an era of exploring the groundwater possibilities using modern tools such as remote sensing and geophysical techniques. The geo-scientists have also started exploring multivariate types of modelling techniques.

The studies carried out by the author and his team of researchers in different hard rock systems of Tamil Nadu using remote sensing and GIS provide a complex scenario in the aspects of groundwater.

The analysis of groundwater flow data in gneiss, granite and charnockitic track of Western Ghats show appreciable variations and thus, calling for detailed look on the role of lithology in groundwater movement. At the same time, the correlation of groundwater flow data with fold pattern in the central and the southwestern parts of Tamil Nadu shows that the flow is centripetal in synclinal and basinal structures, if these are less fractured. Similarly, the correlative study between the extensional shear and release fractures and the transmissivity, permeability and storage coefficient values in parts of North Arcot and Western Ghats indicate that the groundwater flow is predominantly controlled by the extensional fractures which are orthogonal to the fold axis. At the same time, the regional study of Tamil Nadu suggests that in the area south of Cauvery river, the groundwater flow is controlled by the folded structures, whereas, in the north of Cauvery the flow is tutored by the fracture systems. The study of active tectonics and the groundwater movements in Tamil Nadu shows that the groundwater flow is centrifugal in tectonically rising areas and centripetal in the zones of subsidence. Similarly, the exclusive Quaternary fractures act as master conduits followed by the Precambrian fractures, reactivated in Quaternary times and the exclusively Precambrian fractures.

The geomorphic panorama of Tamil Nadu is very divergent along with divergent groundwater regimes, The pattern of sea water intrusion in coastal aquifers provides complex and contrast scenario in tectonically emerging and subsiding coasts. Hence, the concept of modelling warrants detailed reorientation in the context of lithologically, structurally, active tectonically and geomorphologically controlled aquifer systems in the context of fixing boundary conditions and yield prediction, water level prediction and flow prediction models as these geological parameters control the groundwater.

GROUNDWATER MODELLING IN FRACTURED MEDIA

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Groundwater modelling may be used for a variety of purposes, some of which are: estimation of aquifer parameters, regional simulation of groundwater levels, conjunctive use of surface and groundwater, irrigation planing and/or aquifer management. Use of classical porous media models in hard rock terrain may not always be desirable as flow phenomenon in fractured media is different to that of granular porous media. Secondary porosity plays predominant role as compared to primary grain size porosity in such type of medium, which in fact, depend upon the fracture dimensions and configurations. Likewise hydraulic conductivity and storativity values would also differ by several thousand of units for the fractures and the solid matrix..

There are two types of deterministic non-classical aquifer models. First class is Continuum models which represent the classical engineering approach to describe materials of complex and irregular geometry, characterized by several length scales. Physical laws that govern fluid transport at the microscopic level are well understood, with the exception of ultra microporous structures. Leaving aside that case, one could in principle write down the differential equations for momentum, energy and mass and the associated initial and boundary conditions at the fluid-soil interface. These models are widely used because of their convenience and familiarity to the engineers, but they do have some limitations, one of which is concerning scale and averaging. They are also not well suited for describing those phenomena in rock in which the connectivity of pore space or a fluid phase plays a major role. Such models also break down if there are long range correlation in the system. Sandia Waste-Isolation Flow And Transport Model(SWIFT III) is widely used model under this category.

Second class of models, the discrete fracture models, are free from these limitations, but their main shortcoming, from a practical point of view, is the large computational effort required for a realistic discrete treatment of the system. They are particularly useful when the effect of the pore-space interconnectivity or long-range correlation is strong. The discrete models are mostly based on a network representation of the rock mass. The original idea of network representation of a pore space is rather old but it was only in the early eighties that systematic and rigorous procedures were developed to map, in principle, any disordered rock onto an equivalent random network of bonds and sites. In recent years, quite a number of discrete fracture network models have been developed to represent fracture flow; NETFLOW is one of them.

In the present case study, a two-layered finite difference model has been generated for groundwater flow analysis of Ghataprabha sub basin of Krishna river basin. The conceptual model has been calibrated for steady state condition and validated for both the steady state and transient condition through USGS, 3D-Finite Difference Code, MODFLOW. Various applications were tried out on the calibrated model, like river drain Influencing the aquifer, reasons for waterlogging, drying out of wells and well design strategies. This Model is useful for groundwater development activity in Ghataprabha sub-basin in Krishna river basin.

PAST ACHIEVEMENTS AND FUTURE CHALLENGES IN THE AREA OF GROUNDWATER MODELLING

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Increasing demand of water in agricultural, municipal, industrial, navigational and recreational sectors are met almost worldwide today with some component of ground water, along with surface water. In fact ground-water supply is much more reliable and free from enormous evaporation losses as compared to the surface water sources which depend primarily on the erratic rainfall and suffer from huge evaporation losses.

Unfortunately, potential groundwater source is not available every where and hence exploration of groundwater was the first land mark in the utilization of ground water which has been completed to a large extent by many countries of the world today. Apart from geological and hydrogeological techniques, which are based upon field observations, geophysical methods involving resistivity and seismic refraction techniques and well logging have been quite successfully used worldwide. More recently, ground-water exploration by remote sensing using satellite images has also matured to give adequate reliable subsurface water potential in an area. Followed by ground-water exploration, drilling technologies for construction of tube wells, namely, rotary, reverse rotary and percussion tool drilling techniques to construct well in soft and hard terrain, have also come up to an accepted standard.

Estimation of aquifer parameters by well draw down methods has matured enough to compute these values for various ground-water flow domains. These parameters have been successfully applied in the modelling of ground-water systems, which is an essential tool for the ground-water systems planning and management. Finite difference, finite element and boundary element techniques have been successfully used to model large systems involving confined, unconfined and sloping base aquifer conditions. Technique of recharge distribution coefficients are successfully used to account for canal seepage losses, agricultural return flow, rainfall recharge, artificial recharge, well pumping and evapotranspiration losses from the aquifer systems. Linear and nonlinear optimization techniques have been used to minimize draw down and maximize aquifer yield from large aquifer regions. Problems of land subsidence and waterlogging have also been addressed effectively by numerical modelling of the aquifer systems.

Past few decades have seen increasing attention towards the ground-water quality deterioration due to industrial and domestic sewage disposal and various agricultural practices. Hydrodynamic dispersion equations have been used to predict the movement of pollutants in the aquifer systems. Spread of heavy elements moving with retarded velocity in the aquifers due to adsorption has also been examined to some degree of reliability. Increasing efforts have been put recently towards aquifer remediation and to check the spread of contaminants in the sub surface region, and monitoring their spread. Seawater intrusion in coastal aquifers has been examined by many researchers as a special aspect of quality modeling.

More recently inverse modelling of aquifer systems have given the confidence to evaluate systems parameters more effectively. Both, ground-water flow and transport models have been used by inverse modelers, followed by various optimization methods to find out the various aquifer parameters to some degree of reliability. Global optimization technique of genetic algorithm has added a required punch to obtain global optimal estimates of the aquifer dispersivity, transmissivity, hydraulic conductivity, and storage coefficient and aquifer recharge. Stochastic groundwater modelling is preferred to deterministic models by some researchers due to stochastic nature of the many variables involved in the governing flow and transport equations.

The achievements of the past are quite significant, which have made ground-water study as a separate subject in many technical institutions and have also caused establishment of ground-water research centers, ground-water modelling centers, and state and central ground-water boards in many countries across the globe. It should be made imperative for all ground-water boards, agencies and research centers and national institutes across a country to have ground-water flow and quality models developed for their regions for a systematic planning and management of ground-water resources. It is a major challenge of the coming millenium to educate the administrative officials in many developing countries where models are not appreciated by these officials due to their complexity and rigorous data base requirement.

Artificial recharge schemes have to be properly executed which have the answer to solve for groundwater flow depletion and quality deterioration. To scientifically analyze the economic viability and technical feasibility of various artificial recharge schemes, catering to a wide variety of hydrogeological flow domains, will be a major challenge of the coming century. It is also very important to check the ground-water quality from further deterioration and to answer how to discontinue the existing practices, which contaminate aquifers? The mechanism of ground-water pollution has to be known more fully and more number of model testing with field data is required world wide, which is confined to a very few selective studies at present. Dispersivity is one questionable parameter, measurements of, which are limited to some laboratory experiments and field tests. This value changes for various models, even, of the same area. It has to be standardized. Inverse models are essential tools for systems modeling. Correct selection of aquifer parameter structure using inverse modelling is worth while challenge for all large heterogeneous anisotropic aquifer system simulation. One of the major challenge is the application of the available modelling knowledge to the benefit of the mankind so that ground-water, which is available in far greater quantities world wide compared to surface water sources may be used to meet the long term demands of all user sector without causing any harmful effects to human health and environment.

REMOTE SENSING IN GROUND WATER PROSPECTING OF ARID AND SEMI ARID PARTS OF RAJASTHAN

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Water is the most precious gift of nature to humanity. The need for proper planning in development, management and optimal utilization of this vital resource is of paramount importance for economic development as well as to sustain it. Rise in population, optimum utilization of land resources for agricultural activity, low rain fall, limited perennial rivers and surface water bodies, alarming rate of reservoir sedimentation due to deforestation and denudation have put up tremendous pressure on groundwater resources of Rajasthan. All these have compelled search for new aquifers to meet out the increasing demand of groundwater for human activities and animal livelihood. This requires tackling carefully through systematic approaches involving judicious mix of conventional methods and new efforts like remote sensing for optimum productivity and use.

Remote sensing, by virtue of synoptic view, repetitive coverage and data availability in multi spectral bands has proved to be reliable tool in mapping groundwater probable zones. Satellite data interpretation based on size, shape, tone, texture and association provides occurrence of various geomorphic units. When integrated with secondary data like lithology resistivity surveys, yields, etc. it not only narrows the probability of finding groundwater but also helps in pinpointing potential aquifers.

Remote sensing data, which reflects true picture of landscape, provide different geomorphic units - hills, pediments, buried pediments, plains - alluvial or sandy, valley fills, sandy area, dune complex, rivers and drainage in a topo sequence. These different geomorphic units in conjunction with lithologic formations like alluvium, sandstone, limestone, gneiss, granite, etc. provide accurate spatial distribution of various groundwater probable zones.

It also helps in delineating lineaments, faults, fractures, drainage pattern and vegetation cover. All these assist in further narrow downing of groundwater potential zones.

Probability of groundwater occurrence in Rajasthan can be generalized as follows:

Hills, residual hills and pediments are generally donar zones and are poor probability zones. Pediments and buried pediments, when formed on limestone, sandstone in gently sloping topo situation are moderate zones whereas shale, phyllite, schist and gneiss formations are poor zones.

Alluvial plains in flat terrain with sand, clay and silt constituents are the excellent zones of groundwater occurrence whereas with sand cover, the probability declines towards moderate.

Valley fills comprising of sand, silt and clay are good prospect zones where as intermontane valley, composed of colluvial material, have moderate to good prospects.

Ravinous areas of eastern Rajasthan act as runoff zones and are poor probable zones.

Flood plains with unconsolidated material of sand, silt and gravel on gentle sloping topo situations have good prospects, depending upon thickness of saturated zone.

In sandy areas, sand dunes are poor zones whereas dunes complex, underlain by definite formations, is moderate to poor zones. Salt playas composed of mud, clay and sand are poor zones with saline quality.

Occurrence of drainage in the above geomorphic units increases the probability of groundwater. In case of intersection of lineaments with drainage the probability significantly increase. In addition to it, if resistivity survey inputs are added to these inputs, they provide accurate identification of aquifer.

CASE STUDY

Keeping the above guide lines in view, an attempt has been made to delineate groundwater probable zones of Bagidora tahsil of Banswara district. The area witnesses undulating topography with annual average rainfall of 949 mm.

Indian Remote Sensing Satellite IRS-1B FCC imagery of path-row (30-52 and 30-51) dated (3-10-92, 24-5-92 and 21-1-93) were interpreted for mapping different geomorphic units, secondary data on yield and quality was collected from State Ground Water Department and through ground truth verification. Integrating all these a groundwater probable zone map was prepared. The different units, formations, yield and prospect zones are shown in Table 1.

Based on this it is inferred that structural hills formed of phyllite and schist with linear to arcuate hills have low groundwater yield and act as recharge zones. The low lying areas of these hills were mapped as structural valley with phyllite/schist formations and these have moderate to good yield of 57000 - 80000 lpd. Flood plains with similar formations also possess moderate to good groundwater potential. Valley fills with phyllite/schist lithology and bed material comprising of boulders, cobbles, pebbles, gravels, sand and silt have groundwater yield more than 80000 lpd.

The study reveals that remote sensing interpreted data in conjunction with secondary data provide important clues for groundwater targeting.

Table 1. Groundwater prospective in Bagidora tehsil of Banswara district.

Geomorphology	Lithology	Structure/ Formation	Yield (lpd)	Quality	Probability
Structural Hill (SH)	Phyllite/ Schist	Linear or arcuate hills with some definite trend	< 20000	Poor to Moderate	Poor to Nil
Structural Valley (SV)	Phyllite/ Schist	Linear or arcuate valley between high relief controlled by structure	57000-80000	Moderate to Good	Moderate to Good
Flood Plain (FP)	Phyllite/ Schist	Unconsolidated material like gravel, sand, silt etc. normally flat surface adjacent to stream/ river	57000-80000	Moderate to Good	Moderate to Good
Valley Fill (VF)	Phyllite/ Schist/Basalt	Constitute boulders cobbles, pebbles, gravel sand, silt, etc. deposited by stream/ valley	> 80000	Moderate to Good	Good to Very Good
Pediment (P)	Phyllite/ Schist/	Gently sloping smooth surface of erosional bed rock between hills & plain	< 20000	Poor to Moderate	Poor to Nil
Buried Pediment (BP)	Phyllite/ Schist/Basalt	Flat & Smooth surface of buried pediment with varying over burden of weathered material	20000-80000	Moderate to Good	Moderate to Good
Dissected Plateaus (DPT)	Phyllite/ Schist/Basalt	Deep gullies with gently sloping land developed due to stream/ river erosion on plateau	< 20000	Poor to Moderate	Poor to Nil