HYDROLOGY OF HARD ROCKS

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INTRODUCTION

In hard rocks are included all those geological formations the drillability of which is low and the intergranular porosity is practically absent e.g. igneous and metamorphic rocks as well as limestones, dolomites and highly cemented sandstones. The definition used in the UN-family for hard rocks is "Compact, non-carbonate, non-volcanic rocks". However, as secondary porosity due to fracturing and solution activity is the main controlling factor for the occurrence of ground water in carbonate and volcanic rocks also these rocks types have been included under the hard rocks.

The hard rocks are characterised by secondary porosity due to the presence of joints, fissures, foliation planes and solution cavities. In volcanic rocks, primary features like vesicles, flow contacts, lava tubes, lava tunnels, are also of significance. In limestones and other soluble rocks, solution cavities are the main cause of secondary porosity. Unlike sedimentary formations, the hard rocks generally represent anisotropic medium in which ground water occurs as isolated bodies.

In India, over two third of the surface area totalling about 2.40 million sq.km. is occupied by hard rocks. In certain parts of the hard rock terrain in India, as in the Western Ghats and in Assam rainfall is high (about 400 cm. per year) but over a greater part of the area rainfall is poor and these are drought prone areas e.g. Central Maharashtra, Telengana area of Andhra Pradesh and parts of Karnataka, and M.P.

In the past, the hard rocks were neglected as a possible source of groundwater. This was mainly due to their low permeability and high cost of drilling. However, in recent years, hydrological investigations have indicated that the rocks every where are not so unpromising. Moreover, efficient methods of drilling by down-the-hole hammer rigs have also facilitated the ground water investigations and development work. Systematic geo-exploration has improved the rate of success in water well drilling in hard rock areas.

Under the present stage of groundwater development in the country, it is necessary to evolve suitable methods of ground water exploration and assessment in hard rock formations and also the feasibility of artificial recharge especially in drought prone areas and in areas where there has been over development of groundwater resource.

Since 1947, i.e. after independence, there has been a serious attempt by the Central and State Govt. Organisations viz. Central Ground Water Board (CGWB), State Ground

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Water Deptts., Universities and other research institutes to evolve efficient and dependable methods of ground water exploration and assessment. In this connection, projects in collaboration with foreign agencies and some based on only Indian expertise have brought out very useful information on the hydrogeology of hard rocks.

Hydrology of Basalts

Basalts are the most common volcanic rocks present in different parts of the world and are of different geological ages. in India, Deccan Trap which represents basaltic suite of rocks occupies an area of about 5 lakh km^2. In U.S.A., the Hawaii an basalts and the basalts of Columbia snake river area (covering parts of Washington and Idoho States) have been studied in great detail from hydrogeological considerations.

The occurrence of groundwater in basalts in influenced by the presence of primary and secondary features as listed below:

Primary features:

1. Vesicles
2. Lava tubes and lava tunnels
3. Inter-flow contacts

Secondary features:

1. Fractures and joints
2. Weathering and laterisation

In hydrogeologic studies of volcanic rocks, close attention should be paid to the past geomorphological history of the area for determining the position of ancient valleys, buried soil and inter flow spaces. In Deccan trap, red bole which represents weathered horizons, are of importance.

The porosity of basalts may vary from less than 1% in massive basalts to an high as 85% in pumice. Porosity may be high on account of vesicles etc. but if these are not interconnected permeability will be low. It has been found that there is a general decrease in the permeability of basalt with increase in the age of rocks. This is primarily on account of formation of amygdales and metamorphism.

The hydrological characters of basalts also depend upon the type of eruption (central type or fissure eruption) and whether it was subaerial or submarine. The viscosity of the lava also controls the formation of vesicles which in turn influence the hydrological characteristics.

Pyroclastics associated with basalts differ in their hydrological characters depending on the particle size, sorting and cementing material. Reworked pyroclastics are quite permeable e.g. in California such a reworked formation yields 500 to 1500 gpm to large diameter wells.

The hydrology of basalts in different than other hard rocks. One of the main differences is that the various Basalt flow units can form a multi-aquifer system somewhat similar to a sedimentary rock sequence, having alternative pervious and impervious horizons. It is possible that a vesicular or weathered or fractured basalt, forming aquifer horizon, may be sandwiched between two massive basalts forming confining layers. The confined aquifer horizon is recharged either due to leakage from overlying aquifer horizons or from recharge in outcrop areas where there is somewhat large distance lateral continuity and flow units are low dipping. Therefore, in basalts, there may not be any relation between discharge and depth of well.

The permeability of basalts varies within wide limits. Pumping tests from Snake river basalts have given the transmissivity values ranging from 1×10^6 to 1.8×10^7 and averaged about 4×10^6 gpd/ft. In the same tests S ranged between 0.02 and 0.06. Specific capacity data from 238 production wells ranged from 6 to 22,000 and averaged about 2,100 gpm/ft. of drawdown.

Deccan trap basalts are not so productive. Pumping tests in basalts of parts of Ahmednagar district of Maharashtra have given values of transmissivity ranging from 15 to 150 m^2/day and of S from 0.01 to 0.13. Specific capacity of bore wells in Deccan Trap of Betul district, M.P. is found to vary from 0.2 to 8.1 pm/meter of drawdown.

Unit area specific capacity, obtained by dividing the specific capacity by the cross sectional area of dug well in basalts of Ahmednagar district varies from 1 lpm/meter/meter^2 in fractured basalts to 5 lpm/meter/meter^2 in vesicular basalts.

Red bole horizons which are of few cm to few meters in thickness at places occur between successive flow units. Red bole forms marker horizon for the purposes of correlation of different flow units and is also of significance from the point of view of ground water occurrence. At places it is fractured and forms good aquifer horizon while elsewhere it forms confining layer overlying the vesicular part of the flow unit. The latter forms confined aquifers and is a source of water for dug-cum-bore wells.

The Deccan Traps are also widespread in Madhya Pradesh, Uhl et al (1975) have analysed pumping test data from the basalts of Betul and Chhindwara distt. They have given specific capacity index values based on the well performance data. A comparison of the specific capacity index values of Deccan Traps with the basalts of Washington area in USA indicates that the latter have an order of magnitude higher values of permeability. Davis (1974) has tried to relate this variation in permeability with the age of basalts. Singhal (1985) has given a comparative account of the aquifer characteristics of basalts of varying ages from different parts of the world (Table 1).

The CGWB has carried out detailed hydrogeological investigation in the Betwa River Basin parts of M.P. and U.P.

Rajmahal Traps, which are of Jurassic age, have given high yield in parts of Purnea district in Bihar. Khan and Raja (1989) have discussed the ground water potentialities of Rajmahal traps of Sahebganj District, Bihar.

Hydrogeology of Plutonic and Metamorphic Rocks

The occurrence and movement of groundwater in plutonicigeous rocks and metamorphic rocks is governed by the Secondary features viz. joints, fissures, foliation planes and

Table 1 : Aquifer characteristics for some volcanic rocks

Country	Place/Area	Formation	Age	T(m^2/day)
EL SALVADOR	San Salvador	Lava flows	Pleistocene	1000-15000 (average 10,000)
		Pyroclatics		100
NICARAGUA	Pacific Coastal Region	Pyroclastics	Quaternary	120-3,500 (average 1,200)
AFGHANISTAN	Under Taruck Valley	Reworked tuffs		71
	Abe Istada Nahara basins	Reworked tuffs	Pleistocene	25-1000
SPAIN	Gran Canaria	Old Basalts	Miocene	5-20
	Modern Basalts	Post-Miocene		40-200
INDIA	Karnatak	Deccan Trap	Early Eocene	10-180
	Andhra	Deccan Trap	Early Ecocene	1-198
	Maharashtra	Deccan Trap	Early Eocene	0.1 to 500
U.S.A.	Snake River	Basalt		1×10^3- 1.8×10^5 (average 1×10^4)
	Oahu, Hawaii Basalt	Tholeitic	Pliocene	15,000 (in dyke free zone) 1,500 in the marginal dyke zone
	Nevada	Rhyolite and associated tuffs		17-1740
MORACCO	Oudja	Basalts		1.3×10^{-5} to 3×10^{-2}

weathering. In these rocks the permeability decreases with depth as both the intensity of weathering and width of fractures decrease with depth. The nature (permeability) of weathered material also varies depending on the lithology of rock types and climatic conditions. The maximum depth of weathering could be about 35 m.

Ground water exploration in such formations should be carried out with due considerations to lithological and structural studies of rock formations. Plotting of structural data viz. joints and poliation planes in Schmidt's equal area not is found to be useful in the design of wells in such rock formations.

Carbonate Rocks

In this area included limestones and dolomites. Thes rocks are characterised by solution phenomena which at places forms typical Karst features e.g. sink holes, dolinas, springs, lost rivers, caves etc. Very extensive hydrogeological work has been carried out in these rock types in different parts of the world.

The permeability of carbonate rocks varies considerably depending on the intensity of solution. The yield of wells also varies accordingly. The discharge from one single well from Vindhyan limestone in Borunda Village, Jodhpur district, Rajasthan, was found to be 500,000 lph for practically no drawdown. Pakhal limestones in Karimnagar dist. of A.P. have transmissivity of 775 m^2/d and S=0.12. Limestones of Raipur basin in M.P. are also quite productive. However, everywhere carbonate rocks are not so productive.

Some of the problems related with Karst Hydrology are given below:

1. Undesirable topography,
2. Instability of the ground,
3. Scarcity of perennial surface streams,
4. Insufficient soil.
5. Mineralised water,
6. Undesirable permeability - at places very low and other places very high.
7. Undesirable waste disposal environment.

The productivity of wells in carbonate rocks depends upon lithological, topographical and structural characteristics. Fracture trace studies are useful in the location of wells.

Specific capacity and specific capacity index (well productivity) studies in carbonate and other hard rocks is of help in determining yield characteristics of wells tapping aquifer horizons from varying depths. Khare (1981) has done such studies for the rock of the Raipur basin in M.P. He has shown that the most productive rock type in the area is limestone, followed by sandstone and shale. Wells tapping limestone show productivities between 0.02 and 5.93 lpm/m/m, while for sandstone and shale the productivity varies from 0.03 to 0.25 and 0.003 to 0.14 lpm/m/m respectively. Wells in limestones were grouped depthwise into 4 categories (i) 30-50 m (ii) 50-65 m (iii) 55-80 m, and (iv) over 80 m.

Productivity frequency plots indicated that, the highest productivity is shown by wells in the depth range of 30 to 50 m, while the deeper wells show lower productivity, indicating greater solution activity at shallower depths. Similar studies were also carried out for sandstones and shales formations.

Carbonate equilibria and hydrochemical studies in carbonate rocks are of help in determining the extent of saturation. Karstification and direction of ground water movement. Khare (1981) has also done such studies in the carbonate rocks of Raipur basin and has concluded that most of the ground waters from carbonate rocks are of under saturated to saturated nature with respect to calcium carbonate.

Importance of Fracture Studies

The following two types of tectonic fractures in crystalline rocks can be considered to be of importance from hydrogeological point of view.

1. Tensile fractures, related to brittle deformation
2. Shear fractures, related to brittle deformation.

Tensile fractures which are related to brittle deformation have high storativity because of the tensile origin. They, also form very good aquifers. Therefore this type of tectonic pattern should be taken into consideration in regional and local water development planning.

The storativity of shear fractures is a very complex quality. It appears that most, if not all shear fractures are tightly compressed by residual stresses. However, slightly dipping shears and thrust faults hold an unique position concerning the storativity of shears. At places thrust faults in hard rocks, are filled with gravely material and they have a good recharge from the surface on account of their low dip. At the construction of the tunnels and underground rock caverns, this type of fracture has been considered as the dangerous cause of influx of water.

In addition to above types of fractures, sheet joints which are horizontal and commonly developed in granites on account of load release are also of importance from hydrogeological consideration. These joints are closely spaced towards the top of the rock body and become widely spaced with depth.

Studies by CGWB in Noyil-Ponnani and Vattamalai Kari basins in parts of Tamil Nadu and Kerala States has shown that the yield of bore wells constructed in the tensile fracture zones varies from 3.6 to 221 lps while those located in the shear fractures ranges from 2.1 lps to 14.6 lps. (Raju, 1985). The yield of bore wells constructed in different type of fractures is shown in fig.1 indicating that tensile fractures are more productive than shear fractures. Therefore, proper analysis of fracture types in hard rocks can be of much help in the successful location of wells.

Hydraulic Fracturing

The problem of developing adequate ground water supplies from hard rock aquifers is wide spread. Over 25 percent of the land surface of the earth is directly underlain by plutonic igneous and metamorphic rocks. In many of these areas the only reliable source of water is from the hard rock aquifers. Inspite of using state-of-the-art exploration techniques, 15 to 30 percent of drilled wells fail to produce adequate supplies of ground water. This is often due to the fact that the bore hole misses the fractures which are usually vertical or steeply inclined.

Significant enhancement of low-yield wells has been achieved through hydraulic fracturing and well development. The procedure involves controlled injection of water and proppant into packer-isolated well bores with injection volumes and rates adjusted in accordance with aquifer responses to the fracturing procedures. In addition to fracturing, the well can be stimulated with other mechanical and chemical treatments e.g. high velocity jetting and acidizing.

Geophysical exploration in Hard Rock Formation

The major success in groundwater exploration using geophysical method has been achieved in hard rock areas where interpretation of filled data is less ambiguous. Electrical resistivity method and seismic refraction method of geophysical exploration are widely used in various forms to resolve many a problems of groundwater exploration. Even in these two, the seismic refraction method has severe limitations that no information can be obtained about a low velocity layer below a dense hard material. Also the seismic wave velocity does not respond to changes in salinity of groundwater. In addition to these limitations seismic methods are costly one. As such the electrical resistivity method is considered to be the cheapest and as direct method of exploration and exploitation of groundwater resources. It can be effectively used for determining the thickness of weathered/fractured bed rock, bedrock configuration and caverns in Carbonate rocks as well as to evaluate the aquifer parameters.

The success of geophysical exploration critically depends upon collection of accurate data and its proper and meaningful interpretation. As such the usage of electrical resistivity method for groundwater exploration may be viewed in the following context. (i) Development of indigenous instruments (ii) theory of reisistivity interpretation, and (iii) Groundwater exploration program.

The scientists from National Geophysical Research Institute, Hyderabad must be credited for development of a low-cost resistivity meter which generated tempo for groundwater exploration in India in a big way. Due to this fact now there are large number of manufacturers of resistivity instruments in this country. Important contribution from Indian geophysicists in the field of theory of resistivity data interpretation has come from Ghosh (1971a, 1972b), Das (1984), Sri Niwas and Israil (1987). Computer aided interpretation technique have added new weight in reliability and quality of resistivity data interpretation. Sri Niwas et.al.(1982) developed a fast automatic interpretation procedure using ridge regression inversion technique. Singhal (1984) used this programme effectively for interpreting resistivity data from Banda district. Singhal et.al. (1988) presented an integrated approach to aquifer delineation in hard rock terrains by taking a case study from the Banda District.

Patangey (1973) and Patangey et.al. (1977) have used resistivity data for groundwater exploration in granitic rocks of A.P. Verma et.al. (1980) have applied these methods to metamorphic terrain near Dhanbad in Bihar.

Remote Sensing

Remote sensing techniques comprising aerial and spaceborn sensors can provide vital information for exploration of groundwater resources. Major advantages in the use of these methods arise from synoptic overview, multi-spectral approach, near-orthographic and repetitive data coverages. The important features relevant for ground water studies, amenable to identification on remote sensing data products include: terrain features associated with recharge and discharge zones (such as rivers, canals, lakes, springs etc.), soil moisture anomalous vegetation, topography, regional geological setting, weathering, drainage characters and special landforms if any.

Remote sensing is considered as a forerunner in all exploration programmes. The integrative approach of 'satellite data - aerial photographic - geophysical - drilling' has been highly rewarding for ground water investigations. It saves time, cost and efforts.

In India, studies on these lines have been carried out at a number of institute and organisations, and different types of data sets have been employed in various investigations, such as:

1. Aerial photographs (black-and-white panchromatic) on scale of about 1:30,000 to 1:60,000.
2. Satellite images Landsat MSS, TM, IRS-LISS, SPOT, black and white and false colour composites.
3. Digital satellite data (CCTs) of Landsat MSS, TM, IRS-LISS, SPOT sensors, and computer enhanced products.
4. Miscellaneous satellite data such as Shuttle-Imaging Radar - A (SIR-A) images, MOMS-01, MKF-6 photography etc. (per availability).

Methodology of work is linked to the actual problem and terrain. Field data serve as important basis for interpretation and extrapolation.

A few selected examples of application in hard rock terrain are briefly mentioned below:

The hard rock terrains have ground water characteristics quite different from the soft rocks, and the main thrust of using remote sensing data in such studies, lies in the following:

- Regional appaisal
- Delineation of suitable landforms and weathered zones.
- Deciphering vegetation indicators
- Mapping of fracture traces and zones of secondary porosity.
- Inter-basinal linkages, if any.

Aerial photographs have been extensively applied in such investigations, with great benefit. The utility of satellite images and data is also undisputed (Sahai et. al. 1983).

Sharma 1983). In a number of studies, Landsat MSS data have been successfully used of delineating fractures, their intersection zones and areas of anomalous vegetation for demarcating sites for field geophysical surveys (e.g. Dewangan and Uday Shankar 1983). Gupta and Ganesh Raj (1989) utilised Landsat TM data for regional and detailed mapping of landforms and correlated these features with the well yield data.

In hard rock terrains, some of the landforms such as valley fills and buried pediments have greater potential for ground water than others; however, it may be difficult to distinguish between various such landforms on standard data products. Perumal (1990) developed a hybrid colour combination of processed Landsat MSS data (principal components and a computed brightness index CBRILL) to facilitate discrimination between such landforms.

The concept of integrated approach by Hydromorpho-geologic Survey has been found to be useful for groundwater targetting in alluvial as well as hard rock terrains (Roy, 1990). Pediment zonation and fracture mapping has been successfully used by IIRS geoscientists in targetting ground water in Karimnagar district, A.P., among others.

In many places, it has been found that wells located in deeper buried pediments and valley fills are more successful and yield good quantity of ground water.

GROUND WATER FLOW CHARACTERISTICS IN HARD ROCKS

There have been two approaches in modelling the fissured reservoirs-one model considers the fracture as a discontinuous system and the other assumes continuity and statistically homogeneous rocks and fluid properties.

Gringarten (1982) has given separate characteristic pressure-drawdown curves for well tapping single vertical fracture and horizontal fracture. Two parameters i.e. fracture permeability (K_f) in the direction parallel to the fracture, and matrix permeability (K_m) are considered. The response at both pumping well and observation wells are shown. The shapes of the horizontal fracture curves are sufficiently different from that of the vertical fracture curves.

The behaviour of a fissured aquifers is different than a homogeneous one which can best be represented by double porosity, multilayer, and composite models.

Double-porosity Model

The concept of double-porosity model has been explained in details by Streltsova-Adams (1978) and Gringarten (1982). The model assumes two regions - the porous blocks and the fracture which have different hydraulic and hydromechanic characteristics. The block consists of fine pores which are separated from fractures. The blocks supply fluid to the fractures and act as uniformly distributed source. Such an approach with some modifications has been also widely used by many workers in analysing behaviour of fractured oil reservoirs.

The difference in the rate of the pressure redistribution (the rapid, almost instataneous response of fissures to pressure change and the delayed reaction of the porous blocks) results in a pressure differential which drives a subsequent flow from the porous blocks to the fissures. In the double-porosity model, the porous blocks have primary porosity and low permeability while the adjacent fractures have although low volume but high permeability. These differences in porosities and permeabilities have been considered in developing flow models in fractured rocks. The differences in pressure between the porous blocks and the fractures lead to flow of fluid from porous blocks to adjacent fractures.

In the earlier solutions given by various workers, (Gringarten, 1982), it was assumed that the fissure compressibility is negligible (due to the low volume of the fracture) and that the flow of fluid from blocks to fractures was occurring under pseudo-steady-state conditions.

It has also been shown that the flow mechanism is different during early, long and intermediate times of pumping. At early times, flow from the matrix block is essentially zero. At long times, the fractured reservoir behaviour is equivalent to that of a homogeneous porous medium with a permeability equal to the fissure permeability, and a porosity -compressibility product equal to the arithmetic sum of that for each medium. Gringarten (1982) has also shown that the hydraulic diffusivity (n) depends upon the shape of the matrix blocks. Two types of distributions are considered as horizontal slabs and as spherical matrix blocks.

Bourdet and Gringarten (1980) have given log-log and semi-log type curves for the fissure pressure in a double porosity fractured reservoir. It may be noted that the type curves are indentical to the time-drawdown curves for unconfined aquifer given by Boulton. Therefore, there could be a possibility of misinterpretation of tests data if information about the geohydrological system is not known otherwise.

Other aspects investigated regarding double porosity model is the effect of inner boundary condition (well bore storage and skin) and outer boundary conditions.

Boulton and Streltsova (1978) have studied the flow conditions in a fractured unconfined aquifer. They have shown that double porosity effect are notable at the early times and unconfined aquifer effects at later times due to delayed drainage effect. Therefore, the late time drawdown curves from unconfined double-porosity aquifer will merge with those for conventional unconfined aquifers.

ANALYSIS OF PUMPING TEST DATA AND DETERMINATION OF AQUIFER CHARACTERISTICS

The three common type of wells in hard rock formations of India are large diameter dug wells, bore wells and dug-cum-bore wells. As the hard rocks are anisotropic and heterogeneous in character, the ground water flow mechanism in such rocks is quite complicated. The type of ground water structure on which pumping test is carried out is also of importance in the choice of a particular method for the analysis of test data. The analysis of pumping test data from bore wells and large diameter wells is discussed separately.

BORE WELLS

The bore wells are usually of 6 cm to 9 cm in diameter and 30 to 60 m in depth.

Rushton (1989) has shown from a study in granites in Hyderabad area that after one hour of pumping from deeper bore well tapping fractures, the water level in shallow piezometer tapping weathered horizon starts to fall and the decrease in ground water head continues after the pump is switched off. The decrease in shallow piezometer continues until it is of the same magnitude as the observation well in the fractured zone; only then does recovery commence indicating that the water is drawn from the weathered zone. (Fig. 1) Rushton (op. Cit) is of the view that in fractured rocks, the following characteristics may be determined:

a. Horizontal hydraulic conductivity and confined storage coefficient of the fractured zone.

b. Effective vertical hydraulic conductivity and confined storage weathered and fractured zone.

c. Horizontal hydraulic conductivity and specific yield of the weathered zone.

The above parameters can be determined by a variety of methods. Rushton (op. Cit) has suggested that these parameters can be determined by (i) Leaky aquifer theory (ii) Neuman's unconfined aquifer theory, and (iii) Numerical model which has been devised for horizontal flow in the individual aquifers and vertical flow between the aquifers.

The conventional Jacob's straight line method has been used earlier by many workers to determine aquifer parameters in hard rocks.

Ballukraya et.al. (1989) have analysed pumping test data from bore wells in charnockites from Tamil nadu. The drawdown data from pumping well show three segments. The first segment is attributed due to dewatering of storage water in the bore hole, the second segment represents flow predominantly from the weathered rock zone, while the third segment is the result of flow from fractures which are under confined condition. A comparison of values of T and S obtained by using. Their Recovery Method, Walton's Leaky aquifer method and Neuman's unconfined aquifer method are given. It is recommended that test data from pumping well are more representative for determining aquifer parameters after making necessary corrections for well losses.

Sridharan et al (1989) have discussed the applicability of double porosity model for fractured aquifers. They have suggested that the ground water flow in such formations is similar to leaky confined aquifers.

Singhal et.al. (1987) and Mishra et.al. (1989) have used the double porosity model for determing aquifer characteristics of a variety of hard rocks from Karnataka. The time-drawdown curve with values of aquifer parameters for test on one such well is given in Fig.2. The data curve had the best match with the Streltsova's double-porosity type curve. It was also observed that the data form observation wells in the neighbourhood of pumping well are more representative.

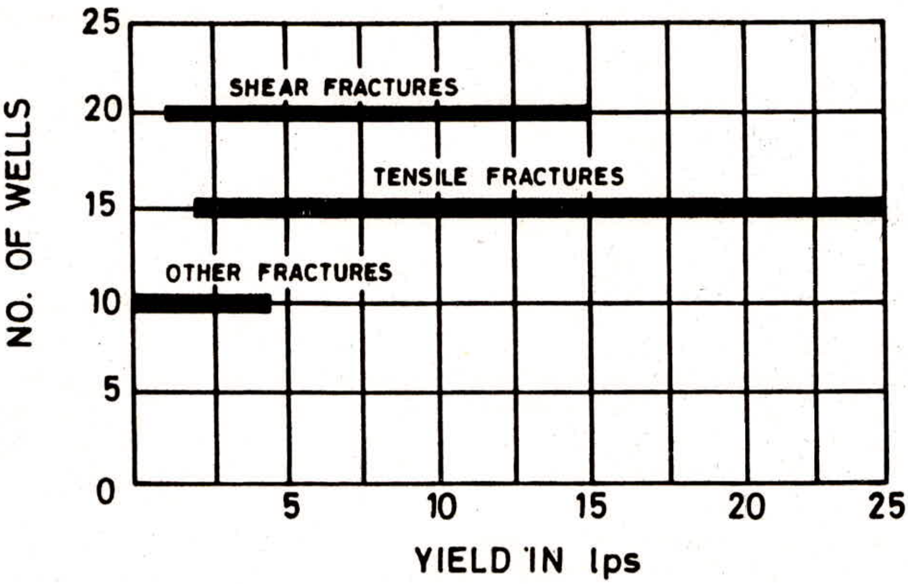


FIG. 1 _YIELD OF BOREWELLS CONSTRUCTED IN DIFFERENT FRACTURE ZONE

(After Raju, 1985)

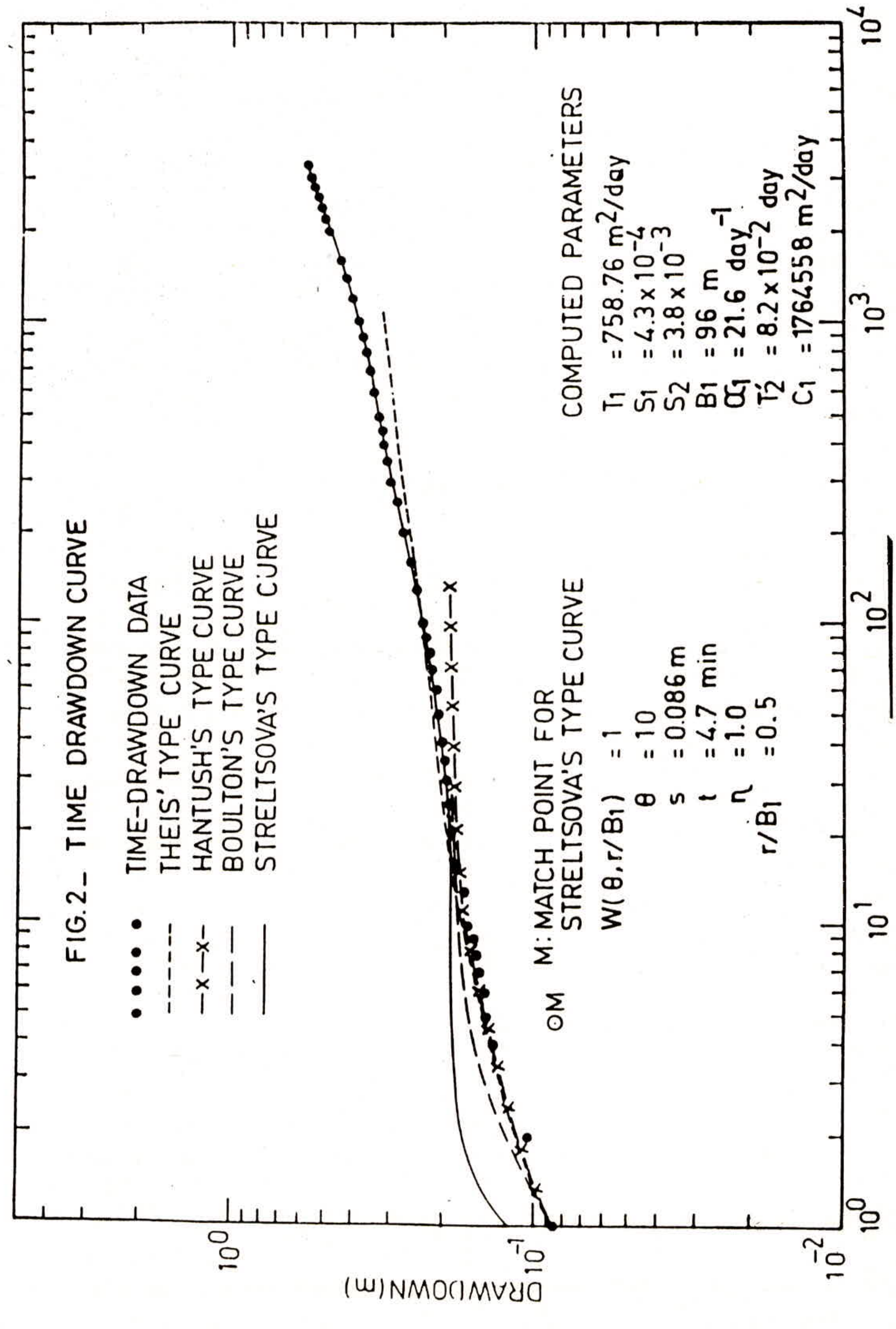


FIG.2_ TIME DRAWDOWN CURVE
TIME-DRAWDOWN DATA
THEIS' TYPE CURVE
HANTUSH'S TYPE CURVE
BOULTON'S TYPE CURVE
STRELTSOVA'S TYPE CURVE
M: MATCH POINT FOR STRELTSOVA'S TYPE CURVE
W(θ, r/B1) = 1
θ = 10
s = 0.086 m
t = 4.7 min
η = 1.0
r/B1 = 0.5
COMPUTED PARAMETERS
T1 = 758.76 m2/day
S1 = 4.3 x 10-4
S2 = 3.8 x 10-3
B1 = 96 m
α1 = 21.6 day-1
T2' = 8.2 x 10-2 day
C1 = 1764558 m2/day
DRAWDOWN(m)
TIME (min)
10-2
10-1
100
100
101
102
103
104
M

HYDRAULICS OF LARGE DIAMETER WELLS

Dug wells of large diameter are the primary source of ground water extraction not only in India but also in other Asian and African countries, where the hard (crystalline) rocks are predominant. At present there are over 9 million dug wells in our country. The wide use of large diameter wells is mainly due to their low cost of construction and the simplicity of maintenance and operation. They are also ideal in hard rock formations as they provide necessary storage for water during recuperation. Therefore, due attention has been paid by research workers to have a better understanding of the hydraulics of large diameter swells to make the structures more efficient and also to determine the aquifer parameters from pumping tests on such wells.

The main problems in analysing pumping test data from large diameter well are:

a. Effect of well storage
b. Variation in discharge with time
c. Development of seepage face in unconfined aquifer
d. Partial penetration of well
e. Anisotropic nature of the aquifer

Due to the above reasons, the conventional methods based on Theis' equation are not suitable for analysing flow to large diameter wells. Analytical and numerical solutions of steady and unsteady flow to a well storage have been developed by several workers. A description of all these methods is beyond the scope of this paper. However, a brief account of the important contributions made in the Indian context is given below.

Papadopulos and Cooper (1967) were the first to provide a method which predicts the drawdown due to pumping from a large diameter well assuming constant discharge.

Sammel (1974) suggested that the pumping rate must be kept small enough to prevent the development of seepage face at the pumped well so that the flow in the aquifer must be similar to flow in a confined aquifer.

Kumaraswamy (1973) gave a recovery formula for fractured formations. However, it is often difficult to obtain the required data for the fractures.

Rushton and Redshaw (1979) have given a numerical method solving Their differential equation by a discrete space-time numerical model. This method has advantage that many necessary conditions can be included in a single numerical solution. Rajagopalan (1983) has also given a mathematical model. Rushton and Singh (1983) have developed type curves quite similar to those of Papadopulos and Cooper using numerical approach for constant as well as variable abstraction rates. It may be possible to compute transmissivity reasonably by this method but the estimation of storativity is questionable. The assumed linear variation of well discharge with drawdown may introduce errors because in field, the variations of well discharge with drawdown are not strictly linear.

Athavale et.al. (1983) have suggested a constant discharge device for aquifer tests on large diameter wells.

Patel and Mishra (1983), Chachadi (1989) and Chachadi et.al. (1990) have used discrete Kernel approach to analyse pumping test data from large diameter pumping wells and observation wells. The effect of both production well and observation well storages on drawdown and recovery at the face of the production and observation well and at any point in the aquifer have been analysed. The variable abstraction rate has also been considered in these studies.

One of the puzzling features of the pumping tests in fractured rocks is rise in water levels during pumping in the observation wells as well as in the pumping well. The following four hypotheses can be put forward to explain such phenomena:

1. Release of water from storage in the porous aquifer matrix of a double-porosity medium does not occur immediately in response to pumping, and the delayed release of this water could result in local increase in water level in the fracture system. This hypothesis Alone is probably insufficient to explain water level increases in the pumping well.
2. Deformation of the fracture system as result of pumping may decrease the storage capacity of the fractures.
3. Water stored in isolated cavities (e.g., formed by dissolution along joints) may be released into the fracture system only after pumping distorts the fractures or the distribution of hydrostatic pressure, or cleans out sediment filled fractures, opening new conduits for flow from the cavities.
4. Water removed from the pumping well may have been discharged to the ground surface above fractures in hydraulic communication with the pumping well, recharging the aquifer during the test.

SPECIFIC CAPACITY

Specific capacity determined from both recovery data on dug wells and drawdown data from bore wells can be used to compare the hydraulic characteristics of aquifers in hard rocks. Unit area specific capacity and specific capacity index values have been used to demonstrate variations in well yields depending on the well dimensions and vertical variation in permeability (Krupanidhi, et.al., 1973, Singhal 1973, Khare 1981, Angadi 1989). It has been usually observed that specific capacity index in hard rocks decreases with increase in depth. This criteria is of help in determining the optimum depth of wells. The specific capacity values for some hard rocks in Karnataka are given in Table 2.

Well Spacing

The over exploitation of groundwater can be avoided by specifying:

a. the density of wells, and

b. the spacing between adjacent wells

Singhal and Singhal (1989) have used two approaches for this purpose. One uses the pumping test data to develop a graphical relation between the duration of pumping and corresponding radii of influence in different hard rock terrains using groundwater flow equations. The second approaches based on groundwater recharge data to compute well density such that the total draft does not exceed the annual groundwater recharge.

Table 2: Specific capacity of dug wells in different hard rocks formation (after Singhal and Singhal, 1989)

Formation	Sp.capacity (lpmin/m) C	Unit Area sp.capacity= =(c/Area) (lpmin/m/m^2)	Sp.capacity index (lpmin/m/m^2) =c/2π rh)
Basalt	20.4-364	0.35-5.04	0.16-3.02
Limestone	30.4-348	0.53-19.83	0.16-14.14
Shale	28.4-39.3	0.53-1.22	0.26-0.37
Gneiss	15.5-228.6	0.23-10	-
Sandstone	54.3	0.97	0.60
Laterite	582.2	12.57	5.10

The present norms of well spacing adopted by nationalised banks for loaning purposes are uniform for granular formations and hard rocks. In view of the different characteristics of unconsolidated and crystalline rock formations, it is necessary to evaluate separately the minimum spacing of wells in hard rock aquifers.

The radius of influence approach takes into account the formation characteristics i.e. T and S, to compute the well spacing. Table 3 gives the results of above two approaches for determining well spacing and well density. This table indicates that the recharge method gives a range of values between 190 to 492 m with the maximum well density in the range of 5 to 35 wells per sq.km.

Table 3: Spacings in Different Formations: (after Singhal & Singhal, 1989)

Formation	Radius of Influence Approach well spacing (m)	Recharge Well spacing (m)	Approach Well density (per km^2)
Greywackes	110-136	224-448	6 to 25
Basalt & related rocks	170-256	370-417	7 to 9
Limestones	126	415	7
Gneisses, Granites Charnockites	134-382	191-492	5 to 35
Literates (coastal areas)	130-275	190-225	25 to 35

Well Economics

Studies have been also carried out to determine the relative economics of dug-, dug-cum-bore and bore wells. The results obtained by Singhal and Singhal (1989) are given in Fig.3. This figure indicates that for lower groundwater discharge (upto 22,000 m^3/year), dug wells are more economical than other types of groundwater structures. However for higher discharges, bore wells are preferred. The dug-cum-bore wells will be useful as revitalisation structures. The higher economics of bore wells over dug wells has also been advocated from the studies carried out by the C.G.W.B. under the Vadavati Project as described later in this paper.

Artificial Groundwater Recharge

In areas where there is excessive lowering of water levels, artificial methods of groundwater recharge are adopted. These techniques are in vogue mainly in alluvial and other unconsolidated formations. However, on account of greater development of ground water in hard rock areas in the recent years, attempts are also being made to adopt effective methods of recharge in such formations. A brief account of these methods in the Indian context is given below. The choice of a particular method and its effectiveness would depend upon the hydrogeological characteristics viz.

a. Lateral and vertical continuity of aquifers.

b. Direction of groundwater movement.

c. Interconnections between aquifers tapped by various types of ground water structures.

d. Hydraulic characteristics of aquifers.

Percolation Tanks

Percolation tanks have been used for artificial ground water recharge in the hard rock formations in basalts, granites and other crystalline rocks in states of Tamilnadu, Karnataka, A.P., and M.P. Romani and Sharma (1989) have given a detailed account of percolation tanks constructed in Jhabua district of M.P. where the rock types are Deccan basalts and Bagh beds. Geological mapping of different flow units and the contact between Bagh beds and the underlying Archaeans was of importance in delineating effective zone of recharge and thereby in the location of suitable sites for the percolation tanks. Pardhasaradhi (1989) has described the effectiveness of percolation tanks from Siva and Man river basins in Maharashtra where the rock types are Deccan traps. Rate of seepage from these tanks was computed to vary from 15 to 75 mm/day during the period of observation from Aug'78 to March'79. Some of the problems associated with the location and effectiveness of these type of structures are the following:

1. Lithological mapping and deliniation of affective zones of recharge and their lateral continuity.
2. Probable area of influence and location of abstraction wells.
3. Soil conservation measures in the catchment area with a view to control salutation of tank.

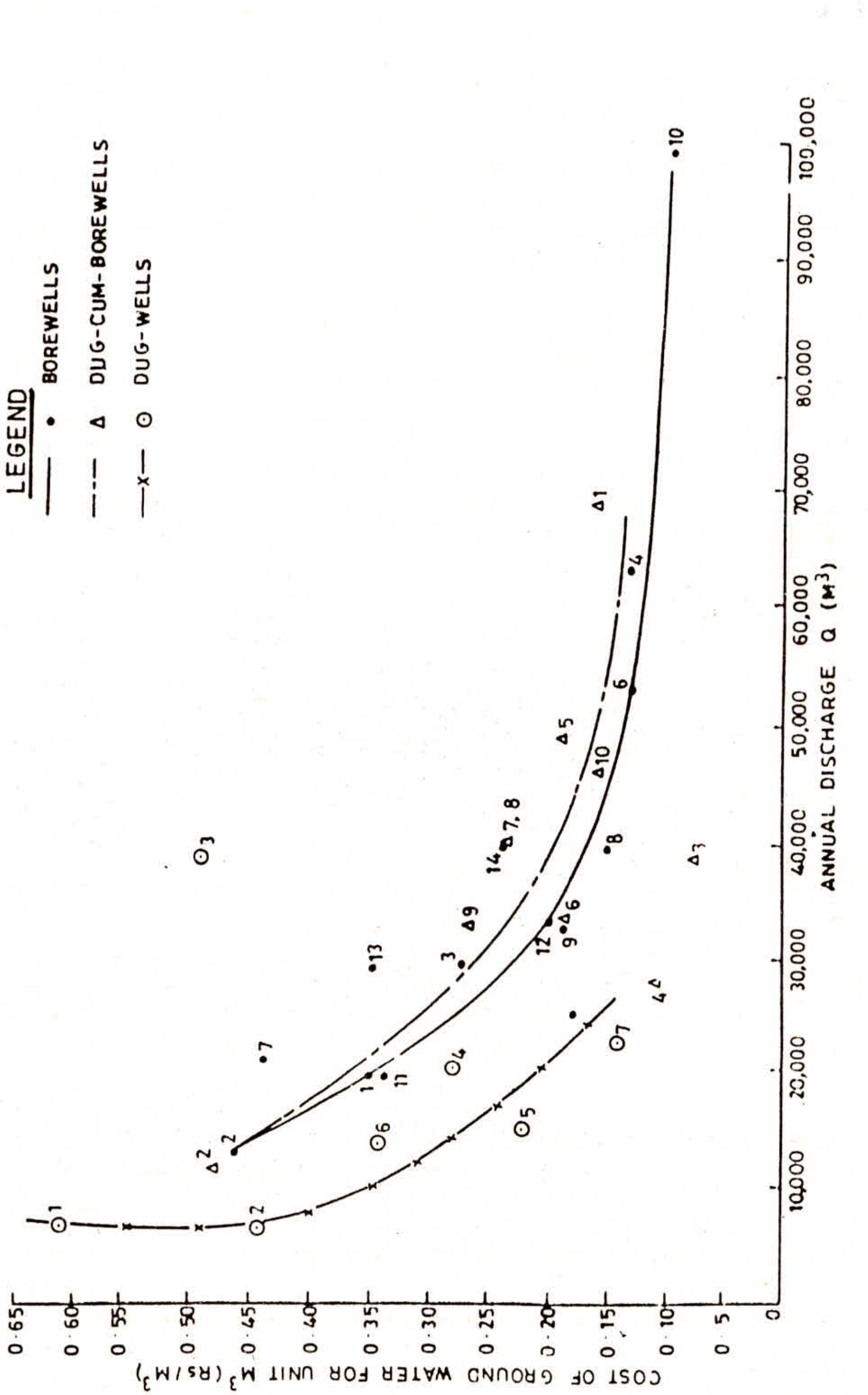


FIG. 3 PLOT OF COST PER UNIT VOLUME OF GROUNDWATER Vs ANNUAL DISCHARGE FOR DIFFERENT GROUNDWATER STRUCTURES

Subramanyam and Prakasam (1989) have deşcribed various methods of artificial recharge in drought prone areas of Andhra Pradesh. These methods are;

1. Percolation tanks
2. Check dams
3. Percolation canals

Checkdams were found quite effective in limestones and other hard rock areas with steep slopes and they serve the twin purpose of ground water recharge and soil conservation. However, in zones with gentler slopes, percolation tanks generally perform better than Checkdams and are also cost effective (Subramanyam and Prakasam, (op. Cit.).

Percolation through canals was made effective by release of water periodically in canals and other natural channels in Anantpur distt. of A.P. The area is underlain by Tadipatri shale of Cuddapah Group. The ground water levels rose by as much as 12 m.

Ground Water Dams

A ground water dam is an impervious subsurface structure (duke) which checks the lateral out flow of ground water thereby augmenting the ground water availability in scarcity areas. The construction of such structures has been practiced in the past in many countries (Brazil, North Africa, Japan and elsewhere). In India, the oldest example is perhaps from Ottapalam in Palghat distt. of Kerala. Recently the CGWB has also constructed groundwater dams at other places in Palghat distt. in Kerala (Sinha and Sharma, 1990).

The subsurface dam or dyke can be ideally located across narrow valleys having a 4 to 8 m thick cover of sandy soil underlain by heard impervious bed rock. The soil cover forms the storage reservoir for ground waster.

The wall of the dam can be thin and is usually made of materials like clay, bitumen, polythene sheets etc. The dyke need not project above the ground surface. It may be completed within one meter or so of the land surface. The stored water can be taken by dug well or infiltration gallery constructed upstream of the dyke.

Sinha and Sharma (op. Cit.) have given a detailed account of the design and criteria of site selection for these structures.

The private dam constructed at Otlapalam in 1962-64 is made up of a 4-inch plastered brick wall. It has a length of 155 m and has a depth of 5 to 9 m. The catchment area of the dam is about 10 ha and water is used for irrigation of 3.2 ha of paddy during October-December, and 1.2 ha of paddy during the dry season.

A subsurface dam was built in Octacamund, Tamilnadu, in 1981. It is made of plastic sheets.

In 1979 a subsurface dam was constructed by CGWB at Govt. Seed Farm, Ananganadi, Distt. Palghat, Kerala. It has a catchment area of 20 ha. The bedrock area of 20 ha. The bedrock consists of gneisses and granites.

Recharge through Wells

This method of artificial recharge has been practiced in Rajasthan and M.P. The Agriculture University at Indore has alsos carried out sub studies.

EVALUATION OF GROUND WATER RESOURCES-SOME CASE STUDIES

The Central Ground Water Board, Govt. of India has carried out systematic evaluation of ground water resources in some hard rock areas of India. The following projects were taken up by CGWB:

1. Ground water project in Andhra Pradesh and Karnataka (area 11,620 sq.km.) 1971-75; in collaboration with Govt. of Canada.
2. Vedavati-River Basin project in parts of Karnataka and Andhra Pradesh (Area 24,000 sq.km.) 1974-79.
3. Sina and Man river Basin project in Maharashtra (Area 16,680 sq.km.) 1975-79.
4. Noyil, Amaravatai, Ponnani River Basin project in Tamil Nadu and Kerala (Area 6,300 sq.km.) 1975-79, (with assistance of Swedish Intl. Development Agency).
5. Upper Betwa River Basin project in Madhya Pradesh and Uttar Pradesh (Area 20,600 sq.km.) 1975-79, in collaboration with Govt. of United Kingdom.
6. Project on Ground Water Studies in coastal Kerala (Area 24,000 sq.km.) 1983-87 (with the assistance of SIDA).
7. Project of Ground Water Studies in Kasai and Subernarekha River Basins in Bihar, West Bengal and Orissa (Area 26,960 sq.km.) 1984-88; with the assistance of UNDP.

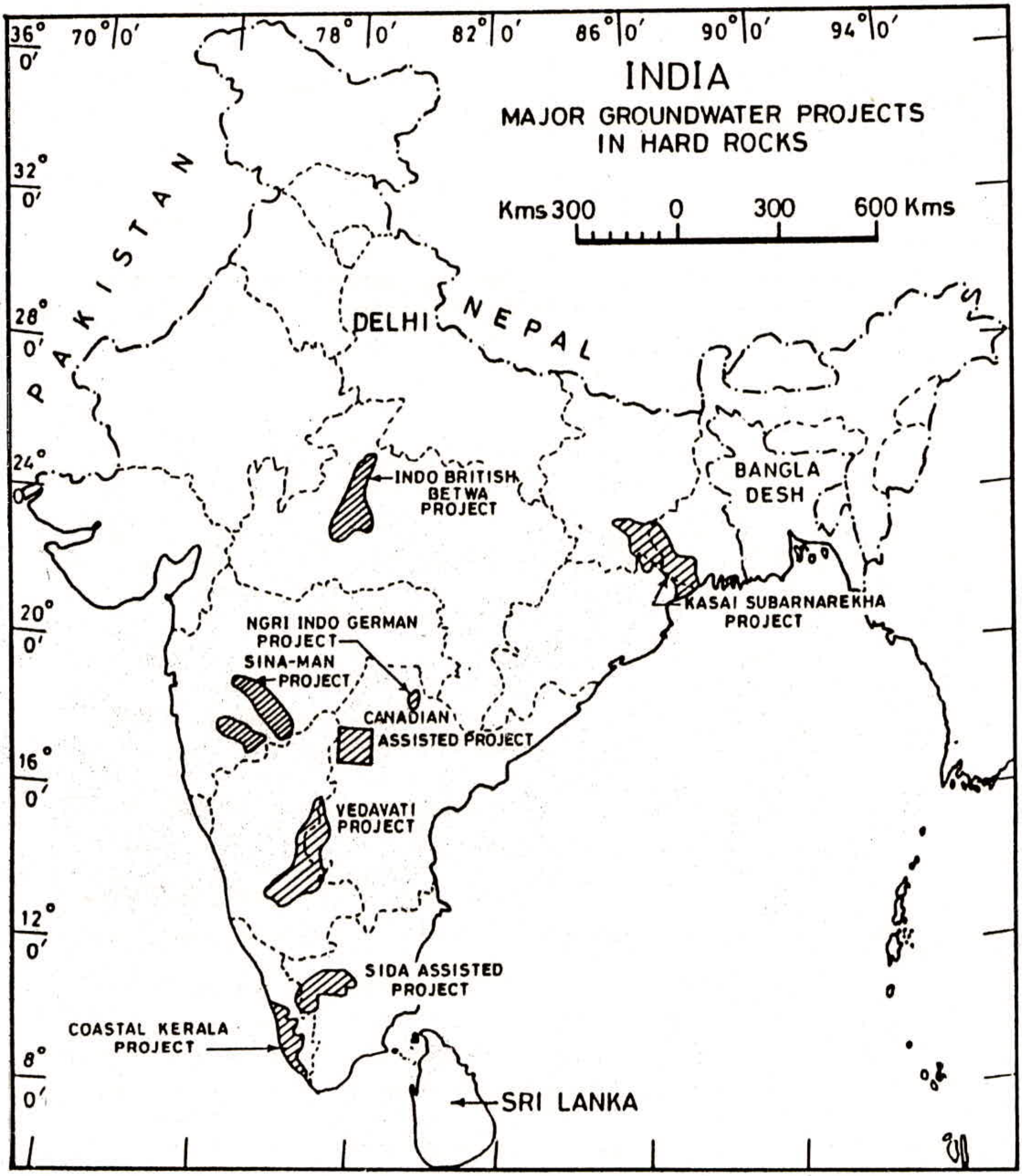
Pathak (1985), Baweja (1985) and Raju (1985) have given an account of the main findings of some of the above projects.

In addition to above, National Geophysical Research Institute (NGRI) in collaboration with Govt. of West Germany, investigated a part of Lower Maner River Basin in Warangal and Karimnagar districts of A.P.

The location of the above project areas is shown in fig.4 and the main findings of some of these projects are described below.

Ground Water Project in Andhra Pradesh and Karnataka

The Central Ground Water Board - Canadian Associated Ground Water Project (CGWB-CAGP) was a joint Indo-Canadian Project designed to develop methods of groundwater-resource evaluation in hard rock areas, using hydrogeological mapping and water balance techniques. The project area comprised 11,620 sq. Kilometers lying between 77° 30' and 78° 30' East longitudes and 17° and 18° North latitudes. It covered parts of Medak, Hyderabad and Mehboobnagar districts of A.P. and small parts of Bidar and Gulbarga districts of Karnataka State.



(After CGWB)

FIG. 4.

The area is occupied with Peninsular Gneisses (Granites, and migmattites etc.) and Basalts. These rocks are weathered to varying extent and are covered at places with red soil and block cotton soil. Hydrogeological maps wsere prepared demarcating groundwater recharge and discharge areas.

Studies indicated that the average dynamic groundwater reserves in the area was approximately 8.3 per cent of the average annual precipitation. Static groundwater reserves ranged from 15 percent of the average annual precipitation in groundwater discharge areas to 50 percent of the average annual precipitation in recharge areas. Safe well yields in granitic and basaltic terrains were also computed.

The hydrochemical studies indicated that the major ions in most groundwaters are within the prescribed limits recommended by Indian Standards. Only nitrate concentration was high enough, on a local scale, to be a health hazard.

Vedavati River Basin Project

The Vedavati River Basin Project was taken up by the Central Ground Water Board to develop suitable methodology and hydrologic parametric indices for a typical hard rock basin with a view that this could be applied to similar hydrogeologic environment elsewhere in the country. The basin is located in a hard rock environment of the drought prone rainshadow region in the peninsular India covering dparts of Karnataka state and Andhra Pradesh. This project was entirely equiped as manned by the Indian personnel. The field work was done from August, 1974 to June, 1979.

A number of thematic maps were prepared representing the available groundwater, its quality, type of well structure required and optimum pumpage levels in addition to the basic parameters involved for water resources estimation and management.

The project area comprises predominantly of three rock groups (1) Peninsular Gneissic complex, (2) Younger Granites, and (3) Dharwar Super Group of metamorphic rocks. The thickness of weathered zone varies from a few cm. in upland (recharge) areas to more then 30 m in valley protions (discharge areas). The transmissivity of fractured granitic aquifer ranges from 3 to 331 m^2/day, whereas the transmissivity in schistose formation ranges from 7 m^2/day to 67 m^2/day.

The 10 years average rainfall approximated to 600 mm over the project area. The average recharge due to precipitation was estimated to be 10 percent of the average annual rainfall. The recharge due to the canal and tank seepages and return flow irrigation was approximately 379 KCM i.e. nearly 2 to 3 percent of the annual average rainfall or 19 to 20 percent of the total surface irrigation input.

The average maximum dynamic reserve in the area was estimated to be 1560 MCM which is 10 percent of the average annual rainfall. The safe well yields ranged from 1 ham/year to 30 ham/year.

The main objective of study was to improve the methodology of groundwater resources evaluation and establish parameteric indices for optimum development of these scarce resources and bring out necessary user oriented maps. The following studies were made (CGWB, 1980).

1. Annual replenishable recharge.
2. Effect of drought on ground water system.
3. Isotope studies to estimate infiltration rates and groundwater dating.
4. Mathematical modelling for regional ground water simulation and optimal utilisation.
5. Resistivity surveys including vertical electrical soundings and profiling.
6. Exploratory drilling including pumping tests to study the system response in time and space.
7. Ground water budgeting and estimation of safe yield for the basin.

The study indicated that an additional 34,715 wells can be put to obtain an additional 1248 MCM of groundwater per annum, creating irrigation potential for an additional 100,000 crop hectares, and drinking water facilities to nearly 3,690 villages.

A multi-disciplinry drainage basin approach in the resource evaluation was adopted.

The following findings are of interest:

1. The transmissibities can be classified under (i) fractured rock transmissivities, and (ii) fractured blowk transmissivities. The former have transmissivity values in the range of 50 to 350 m^2/day, whereas the latter have values in the range of 5 to 40 m^2/day.
2. Specific yield in granitic areas varies from 4 percent (upper reaches) to 1 percent (in lower reaches) and 0.5 (lower reaches) to 2.5 percent (upper reaches) in schistose terrain.
3. In the uplands, the recharge from rainfall in estimated to be 10 to 15 percent, while in valley portions it is only 1 to 5 percent depending upon the soil type and land slopes.
4. A density of one observation well in 266 sq.km. was suggested to study the recharge pattern.
5. For Vedavati basin, it was determined that a mimimum amount of 310 mm of rainfall has to occur before its effect is observed in the rise of water table.
6. The effect of drought on ground water levels could not be precisely established. Water level hydrographs indicated that upper parts of the basin will be much more sensitive to the drought effect than that of the lower slopes.
7. Stable carbon 13/14 and environmental tritium studies have indicated that ground water in shallow horizons is of recent age but at deeper levels (more than 40 m.b.g.1) the ages are found to be 3000 to 4000 years. This indicates poor communication and low permeability.
8. Tritium injection studies have indicated about 10 percent recharge from rainfall in upper reaches while in lower parts of the basin it is from 4 to as low as 1 percent of rainfall.

9. A density of 80 wells/sq.km^2 and a well spacing of 110 meters has been suggested for the Vedavati basin.

10. The cost benefit analysis of dug wells and bore well indicate that these two types of structures cost more or less the same (Rs.9000) but the average annual yield of bore well (46000 m^3/year) is 6 $^1/_2$ times that of dug well (7573 m^3/year). Further, investment cost per cubic meter of water extracted per year by more well (Rs.0.36) is 4 times less than the dug well (Rs.1.46). As per estimates the cost of bore well in Karnataka was Rs.30,000 including the cost of submersible pump.

Sina and Man River Basin Project in Maharashtra

It represents a typical Deccan basalt terrain where investigations by Central Ground Water Board were carried out during the period 1975-79.

The net long term annual dynamic groundwater recharge in the Sina and Man basin is worked out to be 23.75% and 18.4% of the annual rainfall respectively (Pathak, 1985). The yield of wells from shallow aquifer varies from 2 to 14 lps while from deeper aquifers yield is only 0.25 to 2 lps.

Noyil-Amravati-Ponnani River Basin Project

The project area is 6,300 sq.km. situated in the southern part of Indian Peninsula in the districts of Coimbatore in Tamil Nadu State and Palaghat in Kerala State. It covers the drainage basins of Noyil river and Vattamalai Karai stream (a major tributary of Amravati river) and the upper recharges of Ponnani river.

The average annual rainfall varies from about 600 mm in the eastern parts to more then 2000 mm in the western parts.

The area is underlain by a variety of high grade metamorphic rocks viz. schists, gneisses, charnokites and granites. The rocks are characteristed by several systems of fractures. The prominent ones are in the form of lineaments which can be mapped from the study of aerial photograsphs and satellite imageries. Raju (1985) has given a detailed account of the fracture patterns and their importance in the occurrence of ground water. They also control the surface drainage pattern.

The yield of bore wells constructed in the tensile fracture zones varied from 3.6 to 221 lps while those located in the shear fractures ranged from 2 to 15 lps. On the other hand, bore holes which are located away from the tectonic fractures have given low yields ranging from 0.2 to 4.6 lps. The yield of wells located in the tensile fractures are such higher than that of shear fractures (Raju, 1985). The study also revealed that there is no definite indication of decreasing density of fractures with depth and water bearing fractures have been encountered at depths between 150 m and 211 m.

Upper Betwa River Basin Project

The basin covering parts of Madhya Pradesh and Uttar Pradesh consists of Deccan Traps, Vindhyans and Bundelkhand granites.

The pumping tests on shallow dug wells have indicated permeabilities of the weathered basalt to be in the range of 0.2 to 10.7 m/day. The transmissivity is usually less than 10 m^2/day. The yield of bore wells in Deccan Traps varies from 10 lpm to 570 lpm for drawdown of 5 to 10 m. However, in a few exploratory bore holes good amount of water has been found at deeper depths (195 to 198 m) at the contact of Deccan Trap and the Vindhyan formations (Pathak, 1985).

Indo-German Collaboration Project on Exploration and Management Studies of Ground Water Resources (1974-79)

This project was a collaborative programme between B.G.R., Hannover, Germany and N.G.R.I., Hyderabad, India. The Lower Maner River basin located in Warangal and Karimnagar districts of A.P. was selected as a 'pilot basin' for integrated studies under this collaborative project. The basin covers an area of 1600 sq.km. and forms a part of the main Godavari rift Valley, comprising granites (Archeans), Pakhal limestones and dolomites (pre-Cambrians), Sullavai sandstones and quartzites (pre-Cambrian), Talchir sandstones and shales (upper Carboniferous), Barakar sandstones (Lower Permian), Kamthi sandstones (Triassic) and Kota Shales and sandstones (Jurassic).

Systematic hydrogeological investigations were carried out involving resistivity survey, well inventories, drilling, pumping tests, hydrochemical studies, estimation of recharge using tritum injection method.

An attempt was made to assess the total groundwater resources of the area and to predict trend of future development with the help of RC analog and mathematical modelling.

The total recharge to the phreatic aquifer of the basin was estimated to be 152 + 15 million cubic metres (mcm), out of a total precipitation of approximately 2000 mcm for the year 1976. This amounts to about eight percent of the average annual rainfall of 125 cm, over the basin (Athavale, et.al., 1978).

CONCLUSIONS

Although in recent years, investigations have been carried out on various aspects of the hydrogeology of hard rocks, however, there are still many gaps in our knowledge. Some of the aspects which are of greater relevance to our country are as follows. These should be looked into for proper utilisation of ground water resources of hard rock terrains.

1. Applicability of geophysical and remote sensing methods of ground water exploration.
2. Ground water flow mechanism in fractured media.
3. Well hydraulics and determination of aquifer and well characteristics.
4. Design of groundwater structures to suit different geohydrological conditions.
5. Hydraulic fracturing and other methods of augmentation of well yields.
6. Artificial recharge
7. Estimation of dynamic and static resources.

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