GROUND WATER AVAILABILITY IN HARD ROCK AREAS

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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 pratically absent e.g. igneous and metamorphic rocks as well as limestones, dolomites and cemented sandstones. 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 media in which ground water occurs in isolated pockets.

In India over two third of the surface area totalling about 2.40 million sq.km. is occupied by hard rocks. About 54 percent of the population of the country resides in the hard rock regions and nearly 50 percent of the replenishable resources of ground water occurs in these 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 some parts in Karnataka. The status of ground water development as in March, 1983 in hard rock areas of India is given in Table 1.

In the past, the hard rocks were neglected as a possible source of ground water. This was mainly due to their low permeability and high cost of drilling. However, in recent years, geohydrological investigations have indicated that the rocks everywhere are not so unpromising. Moreover, rapid methods of drilling by down-exploration has also increased 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 determining aquifer and well characteristics in hard rock formations and to develop methdology for evaluation of ground water resources. Norms for ground water assessment in hard rock areas are given in Table 2.

Hydrogeology of volcanic rocks

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 respresents basaltic suite of rocks occupies an area of about 5 lakh km^2. In U.S.A., the Hawawaiian basalts and the basalts of Columbia Snake river area (covering parts of Washington and Idaho States) have been studied in great details from hydrogeological considerations.

The occurrence of groundwater in basalts is 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 as 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 or 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 1500g pm to large diameter wells.

The hydrology of basalts is 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 alternate 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 1×10^5 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 0.1 to 5 gpm/ft. 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 x 1 pm/metre/$metre^2$ in fractured basalts to 5 lpm/metre/$metre^2$ in vesicular basalts.

Hydrogeology of Plutonic and Metamorphic rocks

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

Groundwater 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 foliation planes on Schmidt's equal area net is found to be useful in the design of wells in such rock formations. Shape of cone of depression and base flow from streams are of help in determining the role of fracture planes as groundwater conduits.

Carbonate Rocks

In this are included limestones and dolomites.These 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 district 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 at 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.

A fracture trace is natural linear feature extending for less than a mile long that is visible prominently on an aerial photograph. These features are dark or light lines in the soil, alignment of vegetation, topographic sags, aligned gaps in ridges, linear drainage and other similar features. They are mapped by many people and they are regarded to be the surface manifestations of vertical zones of fracture concentrations. Specific capacity indices of wells situated near or on single fracture trace or intersection of two or more fracture traces are high as compared with well located in the interfracture trace are (Siddiqui and Parizek, 1971).

The study of palaeokarsts is of importance from the point of view of ground water development and recharge such a study has been made in Kuwait.

Chalk which is a type of limestone poses interesting hydrogeological problems. It is pervious but less permeable as compared with limestone and dolomite. However, in London basin, the chalk forms confined aquifer while clay forms confining layers. Pumping tests have indicated varying permeabilities. High transmissivities are associated with anticlinal flexures, zones of fractured rocks and valleys.

In carbonate rocks, specific capacity index values of wells of varying depths have been analysed to determine the relative productivities/permeabilities of various horizons (Walton, 1970).

Carbonate equilibria studies in carbonate rocks are of interest from hydrochemical point of view and in predicting development or reduction of solution phenomena.

Aquifer Characteristics and Hydraulics of Wells

The three important hydrological properties of a formation are total porosity, permeability and specific yield or storage coefficient. The determination of these parameters help in the design of wells and as well as in the computation of ground water budget.

In hard rocks the permeability is very heterogeneous due to the presence of joints, fissures and solution cavities. Therefore, it becomes doubtful whether those methods which are used for computing formation characteristics in isotropic and homogeneous rocks can be used in fissured rocks also. This of course would depend upon the extent to which the heterogeneity has been developed. In those cases where jointing and solution activity has given rise to uniform development of secondary porosity and permeability of the whole rock mass, the usual pumping test methods and interpretation can be used. However, in cases where jointing and solution has imparted greater heterogeneity, special consideration should be given to these feature, as they influence greatly the symmetry of the cone of depression. In such cases permeability parallel to the strike of fractures or foliation planes will be several times more than across it.

Papadopulos (1967) has given an analytical solution for such a case and the same was also verified by an electric analog model. Sever (1967) also found a similar shape of water table contours, at the end of a 30 hr. pumping test in the mica schists where the cone of depression developed around a pumped well tapping steeply dipping planar opening was elliptical with the long axis parallel to the strike of the planar openings. It also has a steeper gradient along the dip of the openings.

However, snow (1969) has assumed a parallel plate model for ground water flow in a fractured media and therefore it is required to have an accurate description of fracture geometry to know the ground water flow in fractured rocks. It is, of course, often difficult to have accurate and reliable data of fracture pattern as is required in snow's approach.

Sammel (1974) has reviewed various methods of form analysing concept for fissured rock masses which are highly heterogeneous. A fissure-block pressure relationship has been assumed. A 'two-layered' concept has been suggested one representing the solid blocks units and the other by fracture units. A fractured porous medium containing two kinds of porosity, pore and fracture, with a fluid flow from the primary blocks (pores) into fractures, has been suggested. Two conceptual models have been considered. The first one is the double porosity medium, consisting of block masses of primary porosity separated from each other by many randomly distributed fisssures. The second is a porous medium containing aligned flat fissures of high permeability extending horizontally without a limit.

Wells

The ground water structures in hard rocks are dug wells, dug-bore well and bore wells. The dug wells are usually rectangular in cross-section. The length varies from 5 to 10 m and the width varies from 3 to 5 m. Depth of dug wells varies from 10 m to 20 m. However, in some parts of south India viz. in Coimbatore district of Tamil Nadu, dug wells in gneissic formations are as deep as 35 m.

Dug-cum-bore wells are constructed to tap deeper horizons by providing one or two bore holes from the bottom of the dug wells. The bore holes are of 5 cm to 7.5 cm diameter and 15 to 20 meters depth. At times these bore holes tap aquifers under confined conditions.

Bore wells are usually of 10 cm to 14 cm diameter and their depth varies from 30 m to 100 m.

Specific capacity, unit area specific capacity and specific capacity index values are found to be useful criteria for computing hydrogeological characteristics of hard rocks and in predicting the performance of wells.

Drilling in hard rocks is presently done most effectively by 'down-hole hammer' air rotary method.

Experience shows that yield per unit depth of well penetration generally decreases as depth increases. Drilling beyond an optimum depth may add to total yield, but the cost account of decrease of porosity and permeability with depth. This implies that unit cost of water from more shallow wells. Economics factors, therefore, largely determine optimum well depth in crystalline rock aquifers. Davis and Turk (1964) and other have plotted data of well yield per foot of well penetration in the aquifer as a function of well depth. These figures clearly show that permeability generally decreases with depth. The analysis provides a basis for estimating optimum and economic depths for drilling water wells in crystalline rocks, and optimum depth depends largely upon cost fractors.

Campbell and Lehr (1973, p.251) have made following conclusions regarding water-bearing characteristics of igneous and metamorphic rocks:

(1) The water bearing characteristics of most crystalline rocks are primarily controlled by weathering and structure. Rock type alone is commonly of secondary importance.

(2) In the absence of geological and geophysical guidance, when drilling in crystalline rocks, highly variable amounts of water are encountered. In unweathered rocks, from 5 to 15 per cent of the wells are failures, median yields are less than 8 gpm and about 10 percent of the wells will have yields of 50 gpm or more.

(3) Water production per foot of well decreases rapidly with an increase in well depth. This decrease is roughly tenfold between depths of 100 and 1,000 ft.

(4) The optimum depth of water wells in crystalline rocks is determined largely by economic factors, unless the geologic structure is known in detail.

(5) Although extensive economic studies have not been made in many of the hard rock areas, rough estimates suggest that the depth of single domestic well should be less

than 50to 80 m, and wells of larger production should be less than 280 m. Additional research is obviously needed on both drilling parameters and production factors involded in developing ground water from igneous and metamorphic rocks.

Effects of drought on ground water

The definition of drought is somewhat difficult. It may be defined as a period in which rainfall is sufficiently less than the average rainfall to cause substantial reduction on normal water supplies. Thus, what is drought in a humid area could be a bounteous season in an arid area. Conversely, normal season in an arid area would be disastrous in a humid area (Williamson, 1978).

It is a common experince that drought causes an increase demand for bore wells and a greater demand for technical advisory services. There may be also greater risks in ground water exploration. Under such an emergency programme of bore well construction for ground water supplies during the drought period 1969-70 in Western Australia, underlain by Precambrian granites, gneiss and meta sediments, the success rate was only 10%, the criterion of success being a yield in excess of 4.5 m/day and saline content less than 11,000 mg/l. In India, the NABARD has put the criteria of a successful well in Karnataka as 1.5 lps.

In drought effected areas, there is a general trend of decline in ground water levels which can be attributed to a combined effect of low to negligible recharge coupled with increased draft. Although desirable, but in such circumstances it may be difficult to sort out the relative effects of the drought and the increased draft.

There will also be an increased time-lag between rainfall and recharge, under drought condition. The lag will depend upon rainfall pattern, antecedent soil moisture condition, soil type, hydraulic conductivity, evapotranspiration and depth to water table. Studies in the Upper Hunter River Valley, New South Wales have indicated that the time lag of a long period of drought (1933/45) was such that it was only in 1948 that the water levels in alluvium at a depth of about 9 m commenced to recover.

Chapman (1963) has developed the concept of storage/flow ration for different parts of a basin to determine the nature of ground water level fluctuation. According to Chapman (1964)'if the ratio is sufficiently large to damp out fluctuations in recharge, the hydrology becomes a relatively simple problem of steady flow analysis. A ratio of 50 years in the arid zones and rather less in more humid areas is generally sufficient for this purpose. Conversely if the ration is small, say five years or less, lack of recharge due to drought will have marked effect on ground water level'.

The storage/flow ratio is usually expressed in years. For a unit width of the aquifer, the storage-upgradient of a selected section is given by the product of thickness and length of the aquifer and its specific yield, the flow is given by the product of the thickness of the aquifer and its hydraulic conductivity and hydraulic gradient (Williamson 1978).

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 basins have been investigated :

1. Vedavati-River basin in parts of Karnataka and Andhra Pradesh
2. Sina and Man river basins, Maharashtra
3. Betwa river basin, in Madhya Pradesh and Utter Pradesh
4. Noyil, Ponnani and Amaravathi river basin in Tamil Nadu and Kerala

Vedavati River Basin

It is a drought prone rain shadow region of Peninsular India covering parts of Karnataka and Andhra Pradesh. The main objective of study was to improve the methodology of ground water resources evaluation and establish parametric 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 ground water 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 project period was August, 1974 to March, 1980. The study indicated that an additional 34,715 wells can be put to obtain an additional 1248 MCM of additional 100,000 crop hectares, and drinking water facilities to nearly 3,690 villages.

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

The following findings are of interest:

(1) The transmissivities can be classified under (i) fractured rock transmissivities and (ii) fractured block 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 58 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 reacharge from rainfall is 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 minimum 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. 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 metres 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 or bore well (4600 m^3/year) is 6$\frac{1}{2}$ times that of dug well (7573 m^3/year). Further, investment cost per cubic meter of water extracted per year by bore well (Rs.0,36) is 4 times less than the dug well (Rs.1.46). As per present estimates the cost of bore well in Karnataka will be Rs. 30,000 including the cost of submersible pump.

(2) Sina and Man River Basins, Maharashtra

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

The net long term annual dynamic ground water 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.

(3) Betwa River Basin

The basin covering parts of Madhya Pradesh and Uttar Pradesh consists of Deccan Traps, Vindhyans and Bundelkand 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 faries from 10 lps to 570 lps for drawdown of 5 to 10 m. However, in a few exploratory bore wells 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).

(4) Noyil, Ponnani and Amaravathi Basins

They represent typical gneisses and granites of the pre-Cambrian Shield in Tamilnadu and Kerala States.

The yield of bore wells in tensile fracture zones varies from 3.6 to 22 lps while those located in shear fractures ranges from 2 to 14 lps. Those wells which are located away from fracture zones have yield ranging from 0.2 lps to 4.6 lps (Pathak, 1985). The tensile fractures exhibited long distance (5km) hydraulic continuity during pumping test.

The construction of sub-surface dykes/dams was found to be useful for ground water conservation extension drilling in dug wells increased there yield considerably.

Ground water resource estimates in India

There could be several techniques to compute the ground water recharge viz. ground water level fluctuations, analysis of base flow aquations, hydrologic budgeting, tracer techniques, ground water modelling etc.

There have been several attempts to estimate ground water recharge for different parts of India as given in Table 3.

Table 1: STATUS OF GROUND WATER DEVELOPMENT IN HARD ROCK AREAS

Irrigation potential in million hectares (Area) G.W. Resource in million hect-metres (Volume)

State	Ultimate	Development upto 3/83	Percent
1. Andhra Pradesh			
Resource	3.66	0.74	20
Potential	2.20	1.17	53
2. Karnataka			
Resource	1.30	0.18	15
Potential	1.20	0.45	38
3. Kerala			
Resource	0.69	0.09	13
Potential	0.30	0.04	13
4. Madhya Pradesh			
Resource	5.95	0.49	8
Potential	3.00	1.13	38
5. Maharashtra			
Resource	3.45	0.66	12
Potential	2.00	1.17	59
6. Tamilnadu			
Resource	2.69	0.99	37
Potential	1.50	1.17	78

Table 2: NORMS FOR GROUND WATER ASSESSMENT IN HARD ROCK AREAS

I.	Recharge due to rainfall (Percentage of normal rainfall)		
1.	Granitic Terrain	- Weathered and fractured	10 to 115%
2.	-do-	- Unweathered	5 to 10%
3.	Basalts	- Vesicular and Jointed	10 to 15%
4.		- Weathered	4 to 10%
5.	Phyllites, limestones, sandstones quartzites, shales, etc.		3 to 10%
II.	Specific yield		
1.	Granites		2 to 4%
2.	Basalts		1 to 3%
3.	Laterites		1 to 3%
4.	Weathered phyllites, shales, schists and associated rocks		1 to 3%
5.	Limestones		3%
6.	Highly Karstfied limestone		7%

Table 3: GROUND WATER RECHARGE ESTIMATES AS CALCULATED/GIVEN BY VARIOUS AGENCIES

IN MILLION M^3 PER YEAR

S.No.	Name of State	Department of Agriculture	A.R.L.C.	World Bank (Mr.Barber)	Planning Commission	Irrigation (1972) Comm.	Raghva Rao (1969)	Pathak (1981)
		Recharge	Recharge	Recharge	Recharge	Recharge	Recharge	Recharge
1.	Andhra Pradesh	16.50	30.85	29.50	31.53	21	13.93	18.5
2.	Assam	5.25	N.E.	11.60	7.23	20	13.5	9.96
3.	Bihar	24.00	20.01	28.70	26.63	26	17.7	20.28
4.	Gujarat	11.25	11.27	13.00	7.84	12	8.26	10.9
5.	Haryana	9.00	10.27	9.90	9.05	4	2.83	6.1
6.	H.P.	0.38	N.E.	N.E.	N.E.	1	0.73	0.5
7.	J and K	1.13	N.E.	2.50	N.E.	5	3.24	0.2
8.	Karnataka	9.00	9.72	9.10	10.26	12	8.10	9.3
9.	Kerala	2.25	7.05	7.10	8.75	7	4.37	8.3
10.	M.P.	18.00	42.75	43.40	5.15	32	21.62	57.3
11.	Maharashtra	18.75	22.93	22.90	7.79	15	10.20	25.6
12.	Manipur	N.E.	N.E.	N.E.	0.37	-	-	0.08
13.	Meghalaya	N.E.	N.E.	N.E.	6.60	-	-	0.2
14.	Nagaland	N.E.	N.E.	N.E.	0.14	-	-	0.03
15.	Orissa	11.25	13.31	32.60	12.57	19	12.96	20.6
16.	Punjab	17.50	9.79	15.80	11.54	8	5.59	9.3
17.	Rajasthan	10.00	32.17	17.60	6.94	4	2.75	23.8
18.	Sikkim	-	N.E.	N.E.	N.E.	-	-	-
19.	Tamilnadu	13.50	18.24	18.40	12.89	14	9.31	14.1
20.	Tripura	N.E.	N.E.	N.E.	0.60E.	-	-	0.6
21.	U.P.	72.00	61.49	74.10	38.37	43	28.75	71.2
22.	West Bengal	18.75	21.57	21.60	16.01	19	13.04	12.2
	Total:	258.51	311.80	357.80	200.26	262.0	176.82	319.05

(after Sinha, 1983)

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