Problems in the Hydrogeology of Hard Rocks of India

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INTRODUCTION

The terms hard rocks and fractured rocks are used interchangeably. In this group are included all those geological formations the drillability of which is low and the inter-granular porosity is practically absent e.g. igneous and metamorphic rocks as well as limestone, dolomites and cemented sandstone. Fractured rocks are characterized by secondary porosity due to the presence of joints, fissures, and foliation planes and solution cavities. In volcanic rocks, primary features like vesicles, flow contacts, lava tunnels, are also of significance. In limestone 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 groundwater occurs in isolated pockets.

Hard rocks widely occur in various parts of the world and cover about 20% of the land surface. In India, over two third of the surface area totaling about 2.40 million sq. km. is occupied by hard rocks regions and nearly 50% of the replenishable resources of groundwater occurs in these rocks. In certain parts of the hard rocks 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 and Rajashtan.

Fig.1 shows areas where detailed hydrogeological investigations have been carried out with international collaboration. 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, geo-hydrological investigations have indicated that the rocks everywhere are not so unpromising. Moreover, rapid methods of drilling by down-the-hole hammer have also facilitated the groundwater investigations and development work. Systematic geoexploration has also increased the rate of success in water well drilling in hard rock areas.

Studies on the hydrogeology of fractured hard rocks are being pursued for different purposes and with widely differing objectives, such as:

i) Development of safe groundwater supplies for domestic and irrigation purposes.
ii) Contaminant migration studies, in order to estimate the movement of pollutants through fractures etc.
iii) Tapping of geothermal resources involving estimation of extractable amount of hot fluids from the natural geothermal gradients.
iv) Development of petroleum and gas reservoirs.
v) Underground nuclear waste disposal.
vi) Construction of underground rock cavities for storing water, oil and gas etc. and underground passages such as tunnels.
vii) In several other geo-technical problems, e.g. stability of rocks slopes and seepage from dams and tunnels, triggering of earthquakes etc.

All the above studies require a clear under-standing and proper description of' the hydrological characteristics of fracture systems.

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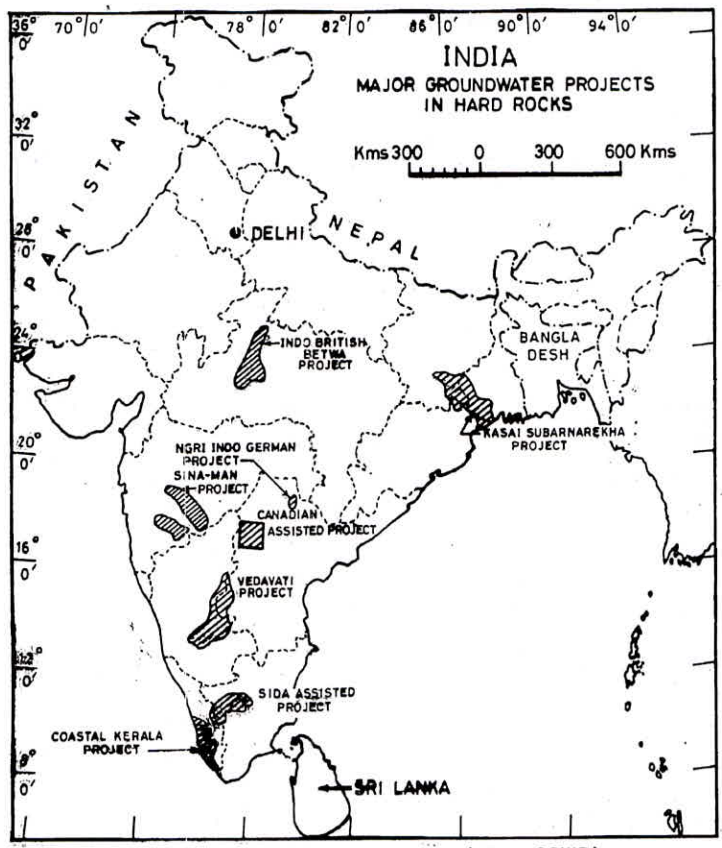

(After CGWB)

Figure 1. Major groundwater projects in hard rocks (after CGWB).

A comparison of the hydrogeological characteristics of porous and fractured rock aquifers is given in Table 1.

Table 1. Comparison of granular and fractured-rock-aquifers

Aquifer Characteristics	Aquifer Type	
	Granular rock	**Fractured rock**
Effective porosity	Mostly primary	Mostly secondary through joints, fractures etc.
Isotropy	More isotropic	Mostly anisotropic
Homogeneity	More homogeneous	Less homogeneous
Flow	Laminar	Possibly rapid and turbulent
Flow predictions	Darcy's law usually applies	Darcy's law may not apply, cubic law applicable.
Recharge	Dispersed	Primarily dispersed with some point recharge.
Temporary head variation	Minimal variation	Moderate variation
Water quality variation.	Minimal variation	Greater variation.

ROCK FRACTURES AND DISCONTINUITIES

Fractured rocks are characterized by various types of rocks discontinuities of various scales varying from few mm size joints to major fault zones and lineaments. The main rock discontinuities are foliation, fractures (joints), faults and lineaments. Foliation is a characteristic feature of metamorphic rocks. Along a fault, relative movement of rock mass takes place while long discontinuities extending over several kms are termed as lineaments. This results in strong heterogeneity in the mechanical and hydraulic properties of the rock.

Fracturing is caused by tectonic stresses , residual stresses ,contraction-cooling and dessication, unloading and weathering.

Genetically, fractures are classified as:

- *Shear fractures*-exhibit shear displacement, formed in conjugate sets.
- *Dilatational fractures* -tensile in origin.
- *Hybrid fractures*-have both shear and dilatational components.

Fractures and joints are also classified in relation to the rock structure, viz..

- *Strike joints*- strike of joints runs parallel to strike of bedding/ foliation.
- *Dip joints*- strike is parallel to dip direction of the rocks.
- *Oblique joints*- strike of joints is at an angle to strike of rocks.
- *Bedding joints*- parallel to bedding plane of sedimentary rocks.

Fractures and other discontinuities are he most important geological structures from the hydro-geological point of view as they facilitate storage and movement of fluids through them. On the other hand, some discontinuities, e.g. faults and dykes may also act as barriers to water flow.A number of factors including stress, temperature, roughness, fracture geometry and intersection etc. control the groundwater flow through fractures. For example, fracture aperture and flow rate are directly interrelated, non-parallelism of walls and wall roughness lead to friction losses, hydraulic conductivity of fractures is inversely related to normal stresses and depth beacause normal stress tends to close the fractures and reduce the hydraulic conductivity. Fractures parallel to the maximum compressive stress tend to be open , whereas those perpendicular to this direction tend to be closed.

Fracture permeability reduces with increasing temperature. As temperature increases with depth, thermal expansion in rocks takes place which leads to reduction in fracture aperture and corresponding decrease in permeability. Further, the fracture permeability also decreases by cementation, filling and weathering etc.

In view of the above, from hydrogeological point of view, including movement of contaminants, it is extremely important to study the structure of rock mass and quantify the pattern and nature of fractures etc.

Sheeting joins developed in granitic rocks due to weathering and unloading impart higher hydraulic conductivity horizontally. However at deeper level vertical fractures may be the main cause of ground water flow where K_h/K_v may be less then one.

Fractures, lineaments and faults can be studied in the field outcrops, and by aerial photographs, remote sensing as well as from bore hole surveys. Fractures have certain orientation, spacing, aperture, length etc. which are studied in rock outcrops in the field. Several sets of fractures are often developed in a rock mass. The number of sets of fractures in an area can be statistically determined by contouring the pole points and in rose diagram. The fracture network is recorded with the scan line method on the surface outcrops and subsequently analyzed statistically. As weathering and other surface process may affect the surface exposures and their fracture network, bore hole data will provide complementary information for the interpolation of fracture network and its attributes at depths. Later, this is compared with the data obtained from hydraulic tests on bore holes to get an idea about the hydraulic attributes related to the fracture set volumes .The combination of all these data helps generating the calculated hydraulic attributes of fracture networks for numerical modelling of fracture aquifers.

HYDROGEOLOGICAL CHARACTERISTICS OF THE HARD ROCK FORMATIONS OF INDIA

From the hydrogeological point of view, the hard rocks are broadly classified into the following four types:

- Igneous and metamorphic rocks excluding volcanic and meta-sedimentary rocks in the Precambrian shield and mobile belts: these rocks cover an area of roughly 100,000 km^2, extending from Kanyakumari in the south to Delhi in the north over a distance of about 3000 km and encompassing the greater part of Peninsular India,
- Volcanic rocks: These are mainly represented by the Deccan Traps of Cretaceous- Paleocene age occupying an area of about 500,000 km^2 in Central and Western parts of India. The Deccan Traps are of basaltic composition and consist of a number of flow units. Their maximum thickness is about 5 km along the western coast. The thickness decreases from the west towards east. The other suit of volcanic rocks is of Rajmahal traps of Jurassic age in parts of Bengal and Bihar in eastern India.
- Hard sedimentary rocks viz. Sandstones and shales (excluding carbonate rocks), covering an area of about 200,000 km^2 in Andhra Pradesh, Karnataka, Rajasthan, Madhya Pradesh, Uttar Pradesh, Bihar, Uttaranchal, Chattisgarh and Jharkhand.
- Carbonate rocks, mainly limestones, deposited in marine environments ranging in age from Pre-Cambrian to Tertiary.

The major groundwater provinces of India are shown in Fig 2. and their hydrogeological characteristics are given in Table 2.

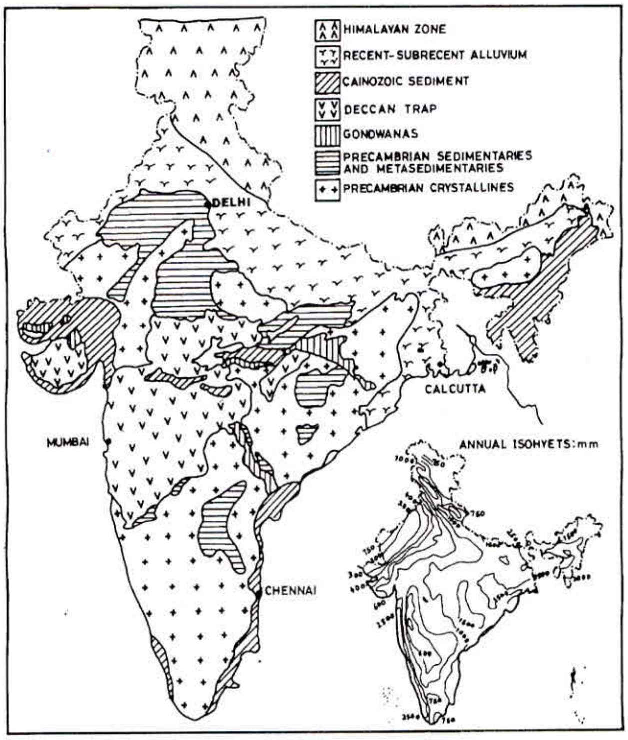

Fig. 2 Groundwater Provinces of India (after CGWB, 1989)

Table 2. Hydrogeological characteristics of major groundwater provinces of India

Groundwater Provinces/ Regions	Location	Lithology (age)	Main features of aquifers	Hydraulic properties T (m^2d^{-1})	Yield potential (m^3s^{-1})
Indo-Gangetic alluvium	Northern India covering an area of more than 1 million km^2	Alluvium with beds of sand, silt and clay with occasional beds of gravel, max. thickness more than 2000m (sub-Recent to Recent)	Shallow aquifers unconfined, deeper ones confined or of leaky type.	T=1000–5000 $S=10^{-4}–10^{-3}$	0.04–0.11
Cainozoic sedimentary basins	Eastern coast, NE India, and western parts	Unconsolidated to semi-consolidated sandstone, shales and limestones.	Deeper aquifer under confined condition; at places flowing wells.	T=500-5000 $S=10^{-5}–10^{-3}$	0.01-0.04
Deccan Traps	Central and western India covering an area of about 500,000 km^2	Basaltic lava flows generally flat lying, maximum thickness about 1500m in the western coast (Upper Creceous to Lower Eocene).	Main source of groundwater are: (a)weathered and fractured horizon, (b) inter flow spaces, (c) intertr-appeans (d) vesicular horizons.	T = 10-700 $S=10^{-3}-10^{-1}$	0.001-0.03
Gondwana Province	Structurally controlled basins mainly in central India.	Semi-consolidated sandstones and shales with coal seams(Carboni-ferrous to Lower Cretaceous)	Shallow aquifers unconfined, deeper ones confined.	T=50-500 $S= 10^{-3}-10^{-1}$	0.01-0.04
Precambrian sedimentary basins	Four discrete structural basins • Cuddapah • Raipur • Vindhyan • Western Rajasthan	Consolidated sandstones, shales and limestones (Proterozoic)	Intergranular porosity low; fractures are the main source of water in sandstone and shales; solution cavities in limestones.	T=5-500 $S = 10^{-3}-10^{-2}$	0.01-0.04
Pecambrian crystalline province	It occupies nearly half of the country in Central and South India.	Crystalline rocks, viz. Granites, gneisses and schists (Precambrian)	Weathered mantle (regolith) is the main source of water supply; fractures and lineaments also facilitate groundwater movement.	T = 5-50 $S = 10^{-1}- 10^{-2}$	0.001-0.005

The most common rock types are plutonic igneous and metamorphic rocks viz. granite, gneiss, charnockite, schist and phyllite of Archean age These rocks possess negligible primary porosity but are rendered porous and permeable due to the formation of secondary openings by fracturing, and weathering, The effect of lithology on permeability is not very clear A typical, weathered profile in a crystalline rock terrain is shown in Fig 3.

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 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 relative role of different fracture planes as groundwater conduits.

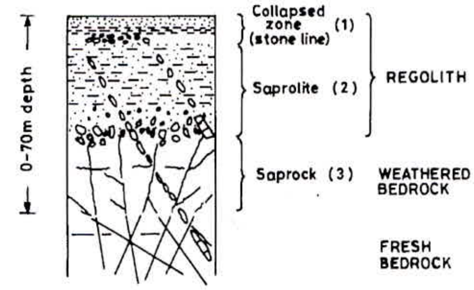

Fig. 3 Schematic weathered profile above crystalline basement rocks (after Wright and Burgees, 1992).

An overall decrease in well yield with depth is reported from various crystalline terrains (Fig.4). The optimum depth of wells is regarded between 50 to 60 m (Table 3). Generally coarse grained rocks viz. Pegmatites are more permeable lineament zones are found to be highly productive for the construction of bore wells. Weathered granites usually have lower permeabilities as compared with fractured rocks due to the development of secondary clay minerals.

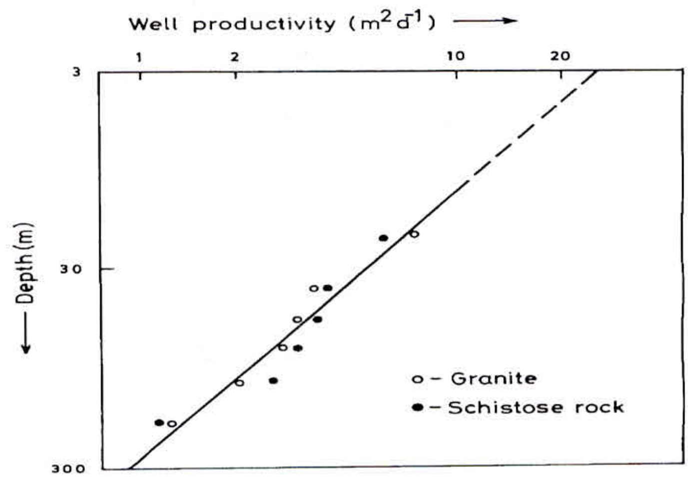

Figure 4 . Plot showing decrease in well productivity with depth in crystalline rocks of Eastern United States (after Davis and Turk, 1964).

In areas underlain by hard crystalline and meta-sedimentaries viz., granite, gneiss, schist, phyllite, quartzite, etc., occurrence of groundwater in the fracture system has been identified down to a depth of 60 m and even up to 200 m locally. In most of the granite-gneiss country, the weathered residuum, serves as an effective groundwater repository. It has been found that the deeper fracture systems are generally hydraulically connected with the weathered saturated residuum. The yield potential of the crystalline and meta-sedimentary rocks shows wide variations. Through 10cm to 15cm diameter bore wells, the fractured system generally yields from 10 m^3/hour and up to 100 m^3 /hour in the vicinity of structurally disturbed areas (Table 4).

Table 3. Data on optimum depth of wells in different regions and rock types

Region	Rock type	Optimum depth (m)
Cyprus	Gabbro	170-200
Satpura hills, India	Granite gnesiss & schist	45-60 45-75
Northern Carolina, USA	Granite	75-90
Kararnoja, Uganda	Gneiss & schist	30-92
Zimbabwe	Green stone and gneiss	40-80
Norway	Granite and gneiss	40-60

Table 4. Yield of bore wells in crystalline rocks

Rocks type	Region	Well yield (m^3 h^{-1})	Well depth (m)
Granite-gnesis	Southern and eastern India	15-80	3-10
Granite-gnesiss, Charnockite	Tamilnadu, South India	6-18.3	0-70
Granite and gneiss	Kwara, Nigeria	95	50-75
Granite and gneiss	Victoria, Zimbabwe	4.1	20-30
Gneiss (fractured)	Maharashtra, India	48	164
Granodiorite and Gabbro (fractured)	Lee Valley, USA	3.5-23	60-150
Pegmatite (fractured)	Karnatka, India	110	42
Quartz vein (fractured)	Bihar, India	55	137
Marble	Sri Lanka	2.4-24	-
Quartzite	Sri Lanka1	6-28.8	-
Schist	Connecticur, USA	4.16	33.4
Slate	Maine, USA	3.42	-

Factors Affecting Well Yield

Well depths in hard rocks usually range from 10 to 100 m as the probability of finding water bearing fractures decreases with depth. Studies in different parts of the world indicate that the following factors can be related to well yields (Singhal and Gupta, 1999, Moore et al., 2002, Faillace, 2003, Henriksen,2003):

- Rainfall regime and intensity.
- Size of the drainage area up-gradient of the well.
- Distance to the nearest water body.
- Well proximity to major fractures and lineaments.
- Narrow alluvial valleys in hard rock terrain and underlying weathered and fractured hard rocks can be a potential source of water supply.
- Topography and geomorphology have distinct influence on transmissivities and well yields. Steep slopes and sites on hill tops should be avoided for constructing borewells.
- Lithology doesn't appear to have any appreciable influence on well yield.

Groundwater flow in Fractured Rocks

The Darcy's law for flow in a single fracture can be written as :

$$V = K_f I$$

Where K_f is the hydraulic conductivity of the fracture, defined by

$$K_f = \frac{\gamma a^2}{12\mu}$$

Where a is the fracture aperture, γ is the specific weight of water and μ is the viscosity.

As the hydraulic conductivity (k), and permeability (k) are related by the expression.

$$K = \frac{\gamma}{\mu} k$$

Therefore, the permeability of the fracture, K_f, can be defined as:

$$K_f = \frac{a^2}{12}$$

By combining equation (1) and (2), the average velocity (Va) in the fracture expressed by a single parallel plate model is given by

$$\overline{V}a = \frac{\gamma a^2 dh}{12\mu dl}$$

Here it is assumed that the fracture walls are impermeable.

The transmissivity of fracture, T_f, equation (4) can be expressed as :

$$T_f = \frac{\gamma a^2}{12\mu} = K_f a$$

Many researchers also defined T_f as the hydraulic conductivity of fracture. The volumetric rate per unit plate (fracture) width (Q_f) will be

$$Q_f = \left(\frac{\gamma a^3}{12\mu}\right) I$$

The above equation is referred as the cubic law which is valid for laminar flow through parallel wall fractures with smooth surfaces. In natural conditions, these assumptions usually do not hold good. The validity of cubic law is discussed by several researchers (Lee and Farmer, 1993). Under field conditions, it is usually difficult to determine the representative distance between the fracture walls. At low applied stress, when the fractures are open the paralel plate approximation for fluid flow through fracture may be valid. However due to stress the contact area between fracture surfaces will increase and therefore variation in fracture aperture should be considered.

FLOW MODELS

Depending upon the porosities and permeabilities of the fractures and the matrix blocks, the fractured rock formation can be classified into (a) purely fractured medium, (b) double porosity medium, and (c) heterogeneous medium (Fig. 5). In a purely fractured medium, the porosity and permeability is only due to interconnected fractures while blocks are impervious. In double (dual) porosity medium, both fractures and matrix blocks contribute to groundwater flow but fractures are the main contributors. In a situation, when fractures are filled with clay or silty material, the fracture permeability is considerably reduced and such a medium is termed as heterogeneous.

K_f and K_m are the hydraulic conductivites of the fractures and the matrix, respectively. Sf and Sm represent the fluid storativities of the fractures and the matrix. A purely fractured media. B: fractured formation. C: double porosity medium. D : heterogeneous formation. In case B,C and D, the fracture coating or "skin" may be hydrogeologically significant.

In fractured rocks, the concept of porous medium can be applicable where the fractures are interconnected and the density of conductive fractures is high. When these conditions are not met, alternate conceptualizations mut be used. Some of the models describing flow in a fractured medium are :

- Double porosity model
- Equivalent porous medium (EPM) model and
- Discrete fracture network model

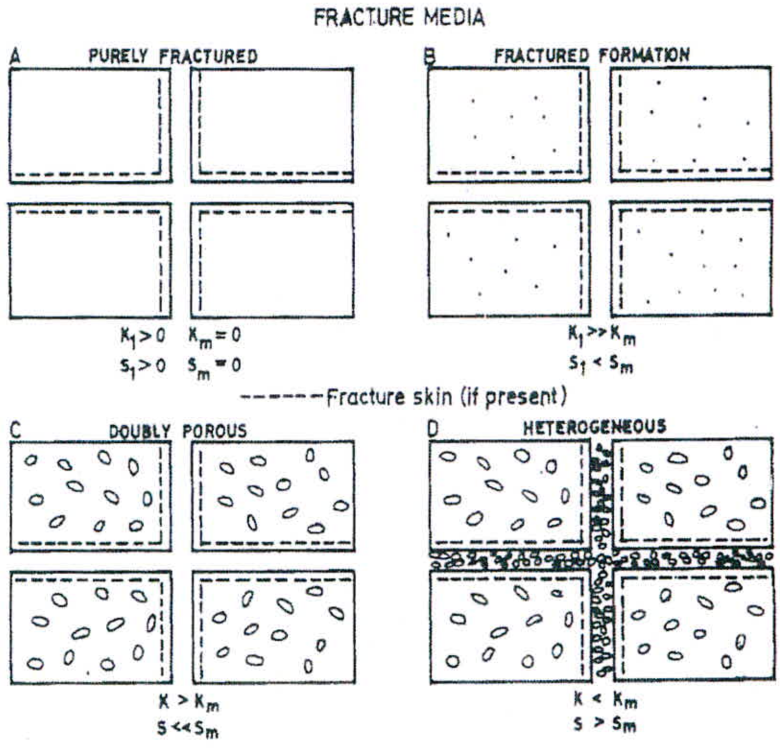

Fig. 5 Hydrogeological classification of fractured media (after Streltsova,1975).

It may be mentioned that various models require knowledge about characteristic features of individual fractures and thereby account for the heterogeneity. Therefore, careful mapping of fractures by surface and subsurface measurements is important. The level of details depends on the purpose for which the model is being developed. A greater accuracy is required for modelling solute transport as the heterogeneity of the fracture system greatly influences the travel time and solute concentration. It is also important to estimate the hydraulic properties of different fracture sets. Studies indicate that fractures parallel to the maximum compressive stress tend to be open, whereas those perpendicular to this direction tend to be closed (Anon,1996).

Choice of modeling strategy depends on information desired. The choice of simulation model should depend on conceptual model. If necessary hydrogeological data are lacking, sophisticated numerical models can not be justified. If sufficient data is not available, simple EPM model can be used for flow but not for transport.

Double Porosity Model

It is also known as dual porosity model. The behaviour of a fractured aquifer for regional groundwater investigations can be represented by a double-porosity model. The concept of double porosity model has been explained in detail by Streltsova-Adams (1978) and Gringarten (1982). The model assumes two regions – the porous block and the fracture, which have different hydraulic and hydromechanic characteristics. Three types of distributions of matrix block are considered – horizontal slabs (strata-type), spherical blocks and cubes (Fig.6). The fissured medium with horizontal fractures has been considered to be analogous to alternate aquifer-aquitard system (Boulton and Streltsova, 1978). 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 used by several researches in analyzing the behaviour of fractured oil reservoir (Anon, 1996).

In the double-porosity model, the porous blocks have high primary porosity but low hydraulic conductivity while the adjacent fractures have low storativity but high conductivity. The difference in pressure between the porous blocks and the fractures lead to flow of fluid from porous to adjacent fractures. Due to difference in the permeabilities of fractures and blocks, flow mechanism is different during early, long and intermediate times of pumping. The characteristics of a double (dual) porosity aquifer system are given in terms of K_f, K_m, S_f and S_m, where subscripts f and m are for fractures and matrix respectively. The otehr two parameters are storativity ratio (ω) and the transmissivity ration (λ). Storativity ration (ω) is the ratio of fissure to total system (blocks plus fissures) storativities and can be expressed as:

$$\omega = \frac{S_f}{S_f + S_m} \beta$$

Where S_f and S_m are the storativities of fractures and blocks respectively, and β is a factor depending on matrix block geometry which is taken to be equal to 1 for strata type. The transmissivity ratio, or interporosity flow coefficient (λ) (dimensionless) is given by :

$$\lambda = a r_w^2 \frac{K_m}{K_f}$$

Where a is the shape factor parameter depending on fracture and matrix geometry and r_w is well radius.

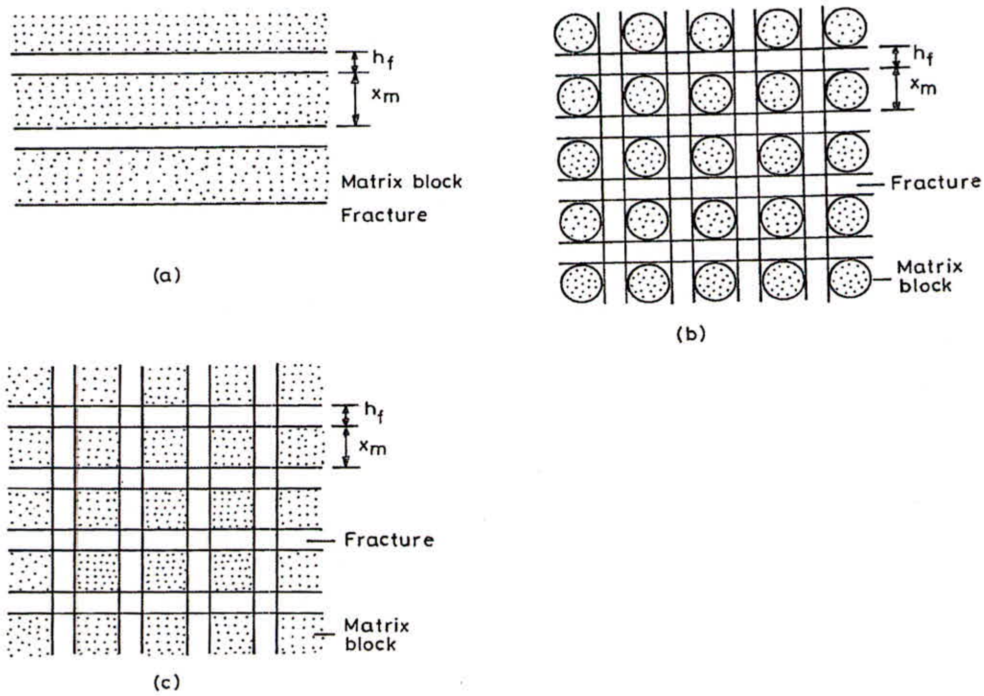

Fig. 6 Types of double porosity aquifers: (a) Horizontal fractures and matrix blocks; (b) Spherical matrix blocks, and (c) Cubical matrix blocks.

Equivalent Porous Medium Model

This is also known as equivalent continuum model. Here it is assumed that flow in a large volume of fractured medium can be similar to that of a porous medium especially when fracture density is high . In such cases conventional pumping test methods can be used.

Discrete Fracture Network Models

Network models are use fracture characteristics and heterogeneity of rocks mass based on field data. The hydraulic behavior of a discrete fracture aperture, length, density, orientation, connectivity of fractures and fracture filling material is discussed later. Two-dimensional and three-dimensional fracture network models have been suggested by Lee and Farmer (1993). These models evaluate flow in fractures or fracture sets with synthetic distributions of apertures, orientations, spacing and dimensions and take into account various surface roughness, flow channeling, and mixing phenomena at fracture intersections. The application of these theoretical models to natural systems has been limited. These models are useful where the area of interest is small – as in the study of the effect of radionuclide transport through fractures as a result of nuclear waste storage in geological formations over a long period of time. The disadvantages of the discrete modeling are that statistical information about fracture characteristics may be difficult to obtain.

Hydraulic Conductivity of Fractured Media

Fractures control the hydraulic characteristics of low permeability rocks, viz crystalline, volcanic and carbonate rocks. Also in some clastic sedimentary formations, fractures form the main pathways for the movement of fluids and contaminants.

In fractured rocks, a distinction can be made between hydraulic conductivity of fractures, K_f and of intergranular (matrix) material, K_m . As fractures form the main passage for the flow of water, the hydraulic conductivity of fractured rocks mainly depends on the fracture characteristics described earlier. Some important parameters which controls the permeability of fractured rocks are aperture, spacing, stress, infilling (skin), connectivity etc.

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 represents basaltic suite of rocks occupies an area of about 5 lakh km^2 (Fig. 3) . In U.S.A., the Hawaiian 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

- Vesicles
- Lava tubes and lava tunnels
- Interflow contacts

Secondary features

- Fractures and joints
- 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 soils and inter-flow spaces. In Deccan trap, red bole which represents weathered horizons, is 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. Volcanic rocks also show anisotropy. Horizontal hydraulic conductivity is several times higher than vertical conductivity due to inter flow spaces; K_h/K_v in some cases may vary between 20 to 100.

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 120 to 350 m^3 hr^{-1} to large diameter wells.

The hydrogeology 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 alternate pervious and impervious horizons. It is possible that vesicular or weathered or fractured basalt, forming aquifer horizon, may be sandwiched between two massive basalt units 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 well defined 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 200 to 20000 m^2/d and averaged about 5000 m^2/d . In the same tests S ranged between 0.02 and 0.06.

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.

The Deccan Trap lava flows are mostly horizontal and only occasionally are very gently dipping. It consists of a number of flow units, each varying in thickness from few meters to about 20 meters. Each flow unit is separated from the other by inter-flow spaces and intertrappean sediments which form important loci for groundwater.

Groundwater occurrence in the Deccan Trap is controlled by the contrasting water bearing properties of different flow units. The topography, nature and extent of weathering, fracturing, presence of vesicular horizon, intertrappeans etc. are the important factors controlling the occurrence and movement of ground water. Deccan Traps have usually low to medium permeabilities depending on the presence of primary and secondary porosity. Pumping tests have shown that under favourable conditions, bore wells yield about 10 to 70 m^3 /hr. At places Deccan Traps form multi-aquifer system where deeper aquifers occur under confined or semi-confined conditions.

The study of volcanic rocks from different parts of the world indicates that younger basalts are more permeable as compared with older ones due to the presence of vesicles, and lesser effect of metamorphism.

In Deccan Traps, based on tritium and water balance studies, recharge is estimated to be about 10 to 20% of the annual rainfall depending on topography, rock characteristics and rainfall

Rajmahal Traps, of Jurassic age occur in parts of Bihar and Bengal in Eastern India. They have comparatively low permeability. The yield of bore wells is reported to be about 8 m^3/hr.

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 of 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. Lime stones of Raipur basin in Chattisgarh/ Madhya Pradesh are also quite productive. However, everywhere carbonate rocks are not so productive.

Some of the problems related with Karst Hydrology are:

- Undesirable topography
- Instability of the ground
- Scarcity of perennial surface streams
- .Insufficient soil
- Mineralised water
- Undesirable permeability - at places very low and at other places very high
- Undesirable waste disposal environment.

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

A fracture trace is a 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 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 usually high as compared with well s located in the interfracture trace area.

The study of palaeokarsts (karsts formed in the geological past) are of importance from the point of view of groundwater development and storage.

Chalk, a type of limestone, poses interesting hydrogeological problems. It is porous but less permeable as compared with limestone and dolomite. However, in London basin, the chalk forms confined aquifer while interbed clay forms confining layers. Pumping tests have indicated varying permeabilities. High transmissivities are associated with anticlinal flextures, zones of fractured rocks and valleys. In carbonate rocks, specific capacity index values of wells of varying depths have been analyzed to determine the relative productivities/ permeahilities of various horizons.

Springs form the main source of water supply in karst areas. Some of the springs have high discharges (Table 5). Submarine springs are also typical features of karst areas as observed in Adriatic sea. These can be located by infra-red aerial photographs. A comparison of hydraulic conductivities of un-fractured and fractured carbonate rocks is shown in Table 6.

Table 5. Discharge values of some of the major karst springs (after Ford and Williams, 1989; Korkmaz, 1990; Bonacci, 1995).

Spring Location	Discharge (m^3s^{-1})			
	Mean	Maximum	Minimum	Basin areas (km^2)
Buna, Yugoslavia	40	440	2	-
Ljubjanica, Yugoslavia	39	132	4	1 100
Chingshuli, China	33	390	4	1040
Vaucluse, France	39	260	4.5	2100
Ombla, Croatia	25	106	4.0	800-900
Silver, USA	23	36	15.3	1900
Kirkgoz, Turkey	16	19	12	1800

In India, carbonate rocks (limestone, dolomite and marble) occur in discrete structural basins and range in age from Pre-Cambraian (Cuddapahs and Vindhyans) to Tertiaries. Among the carbonate rocks, limestone is the most common rock type. These rocks being soluble, develop solution cavities to varying extent. Such a process is known as karstification.

In India these rocks arc less karstified except some areas in Rajasthan e g., Borunda limestone in Jodhpur district, Raipur limestone in Chattisgarh and Kaladgis in Andhra Pradesh.Due to the presence of solution cavities, the carbonate rocks show two systems of groundwater flow with a time lag, a) rapid flow through fractures and solution cavities, and 2) diffused flow through intergranular spaces.

Table 6. Comparison of hydraulic conductivities (K) of unfractured and fractured carbonate rocks (after UNESCO, 1984)

Rock Type	K values of unfractured	K values of fractured rock rocks *(ms^{-1})* with one fracture per meter	
		Opening *(mm)*	K along the fractures *(ms^{-1})*
Limestone	10^{-13} - 10^{-12}	0.1	0.7×10^{-6}
	10^{-11} - 10^{-9}	4.0	0.5×10^{-1}
Dolomite	10^{-10}	6	1.6×10^{-1}
Chalk	10^{-7} - 10^{-6}	-	$10^{-5} - 10^{-4}$

Consolidated Sedimentary Rocks Sandstones and shales

Consolidated arenaceous and argillaceous sedimentary rocks in Cuddaph and their equivalents which are deposited during the pre-cambrian period. The formation consist of conglomerates, sandstone, shales apart from limestones and dolomite. The Cuddapaths and their equivalent were subjected to low grade metamorphism while the Vindhyans and their equivalents, which are younger than the Cuddapahs, do not show any significant effect of metamorphism. Therefore, Cuddapah rocks have generally low permeabilities as compared with the Vindhyans. The occurrence and movement of water in these rocks is governed by th bedding planes, fractures, weathering, topography and climate. They give moderate water supplies generally between 10 to 100 m^3 /hour. Shales wherever fractured can also be a source of water supply .

Estimation of Aquifer Recharge

Quantitative estimates of recharge to aquifers and changes in groundwater storage is important to manage the development of groundwater resources and to know the amount of groundwater that can be withdrawn without exceeding recharge. Readers may refer to Lloyd (1999) for the various methodologies which can be used for the estimation of recharge to aquifers.

The Govt. of India had constituted a Groundwater Estimation Committee which submitted a report in 1997 (GEC,1997) giving various approaches for estimation of groundwater recharge in the Indian context. However, it was later realised that the estimation of recharge in hard rock aquifers should be further looked into as the occurrence and movement of groundwater in these rocks is quite different than the porous media. Therefore another committee was constituted in 2002 whose report on the methodologies of groundwater recharge estimation in hard rocks is under preparation.

The hard rock terrain usually poses a different set of problems unlike porous rock areas, viz. rapid variation in hydraulic characteristics (T and S), both laterally and vertically. Demarcation of the boundaries of the groundwater basin in a hard rock terrain is also problematical. The water shed may be taken as an unit for recharge estimation as the watershed boundary will be a no flux boundary for groundwater also. The water shed may further be divided into various homogeneous zones depending upon their hydrogeological characteristics.

In hard rocks the most common methods for recharge estimation are:

- Water balance estimate
- Chloride profile method
- Chloride mass balance
- Hydrograph method
- Tritium injection method

Water balance estimates

The effective recharge is usually obtained by applying the following balance over a selected time interval Δt.

$$RE_{eff} = Q_{abstr} + S_y \Delta V + Q_{outflow} - Q_{inflow} \tag{1}$$

where, RE_{eff} = The effective recharge, Q_{abstr} = Pumpage from system or spring flow, $Q_{outflow}$ = Lateral flow to lower compartments, Q_{inflow} = Lateral flow from higher aquifers, S_y = Specific Yield, ΔV = Change in saturated storage volume(positive or negative)

For $\Delta V = 0$ and $Q_{outflow} = Q_{inflow}$, the effective recharge is equal to the abstraction over the time interval but if inflow and outflow do not cancel out, these components have to be estimated according to the Darcy's equation.

Chloride profile method

The chloride profile method is a promising and reliable technique for estimating average recharge. The method is based on the premise that the chloride introduced by precipitation is concentrated by evaporation losses, so that the chloride concentration attains a value determined by the natural equilibrium between input and losses. The recharge is derived from the equation.

$$RE = \frac{Cl_{rf}}{Cl_{gw}} R_f \tag{2}$$

where, RE = Recharge, Cl_{rf} = Chloride of rainfall , Cl_{gw} = Chloride of groundwater, and R_f = Rainfall

Hydrograph method

If the hydrograph of only one representative observation bore hole is being used in solving the following equation

$$(Re_{eff} - Q_{abstr}) = S_y \Delta V \tag{3}$$

the method is called the water level or the hydrograph method. In this case both recharge and S represent only point estimates.

Chloride balance

This method is found to be a useful complement in the drier regions (Lloyd, 1999). If monthly records of chloride concentration in rainfall and runoff are available, the rainfall intensity relationship can be examined to infer the rainfall–recharge relationship on a monthly basis. It would appear from an examination of the chloride concentrations in the runoff water that recharge conforms to an exponential relationship to rainfall.

Isotope techniques

Isotope techniques are being increasingly used for estimating recharge and also for understanding the recharge mechanism. Tritium(^{3}H) and other environmental isotopes viz ^{18}O,^{2}H,^{14}C and ^{32}Si have been commonly used as tracers and for dating of groundwater.

Injected tritium or 'tritium tagging' method has been used extensively in India for estimating recharge in porous and also in hard rock formations. If tritium is injected at any particular level, the vertical movement of this tagged water through the unsaturated zone can be monitored by measuring the concentration of ^{3}H at different depths by assuming piston-flow model. However, in fractured rocks, where preferential flow through fractures is more significant, recharge estimates by assuming piston-flow model may not give realistic values of recharge. In a recent study, Sukhija et al. (2003) have shown that preferential flow through fractures in hard rocks is more significant being on an average 75% of the total recharge.Estimates of recharge based on this technique from some hard rock terrains in India are given in Table 8.

Table 8. Rainfall recharge measurements in India using tritium injection method (after Ragarajan and Athavale, 2000).

Area	Rock type	Rainfall (mm yr^{-1})	Natural recharge derived		
			Median	Mean (mm yr^{-1})	Rainfall (%)
Godavari-Purna Basin	Basalt	652	50	56	8.6
Lower Maner Basin, A.P.	Sandstone and shale	1250	103	117	9.4
Noyil Basin, Tamilnadu	Granite	715	35	69	9.6
Ponnani Basin, Tamilnadu	Granite and gneiss	1320	24	61	4.6

Studies in the hard rock terrains covered with black cotton soil in basaltic terrain and red latiritic soil in granitic areas indicate that a minimal rainfall of about 246 mm and 412 mm are requested for the initiation of deep percolation in red and black cotton soil respectively.

Groundwater Quality

In crystalline (igneous and metamorphic) rocks the groundwater flow is mainly through fractures. Therefore, the contact area between water and rock matrix is less than in porous media. Further, the crystalline rocks contain usually silicate minerals which have comparatively low solubility. Therefore, in general groundwater in these rocks has relatively low salinity (TDS < 500 mg/l). However, in arid and semiarid regions, groundwater may have high salinity. In some eastern and western African countries, where arid conditions prevail, groundwater in crystalline rocks is brackish to saline with TDS in the range of 2000 to 6000 mg/l (Faillace, 2003).

At some places, as in parts of Andhra Pradesh and Rajasthan in India, groundwater in acidic igneous rocks (granites and pegmatite) and mica schists has fluoride contents more than the permissible limit (1.5 mgl^{-1}), which is mainly due to the presence of fluoride-bearing mineral, viz apatite, fluorite, biotite and hornblende in rocks. Among other trace elements, iron and manganese are common as a result of weathering of biotite and hornblende bearing rocks. In mafic and ultramafic rocks, chromium is quite prominent.

A vertical zonation in the water quality has also been reported from several crystalline rock terrains.Shallow groundwaters are usually of Ca-HCO_3 type. With increasing depth salinity increases and water tends to be of the Na-HCO_3 type and Na-Ca-Cl type (Gascoyne-etal, 1996, Bae etal. 2003) Fig.7. The quality of groundwater in deep-seated crystalline rocks is not only of geochemical interest but is also of importance for the disposal of radioactive waste and tapping of geothermal power.

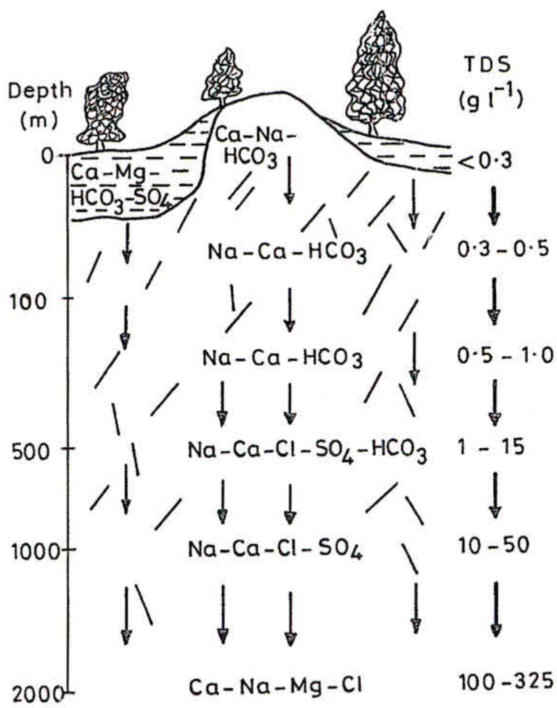

Fig.7 Schematic representation of the chemical evolution of groundwater with depth in plutonic igneous rocks (after gascoyne and kamineni, 1993)

Artificial Groundwater Recharge/Management of Aquifer Recharge

The term management of aquifer recharge (MAR), is now being increasingly used for artificial recharge to imply additional input of water underground besides natural infiltration (Dillon 2005: BGS 2006). The main purpose of MAR is to augment the groundwater resource. This also helps in checking pollution migration, seawater intrusion in coastal aquifers and land subsidence as mentioned earlier. It is also important in groundwater management as it provides natural storage for water for use during dry period. Artificial recharge has an additional benefit of lowering the salinity and temperature of groundwater which helps the industries where water is used for cooling purposes.

The main source of water for artificial groundwater recharge is the storm runoff and river water. Sewage and waste water is also being increasingly used for artificial recharge after necessary treatment. In India, excess monsoon water is used for this purpose.

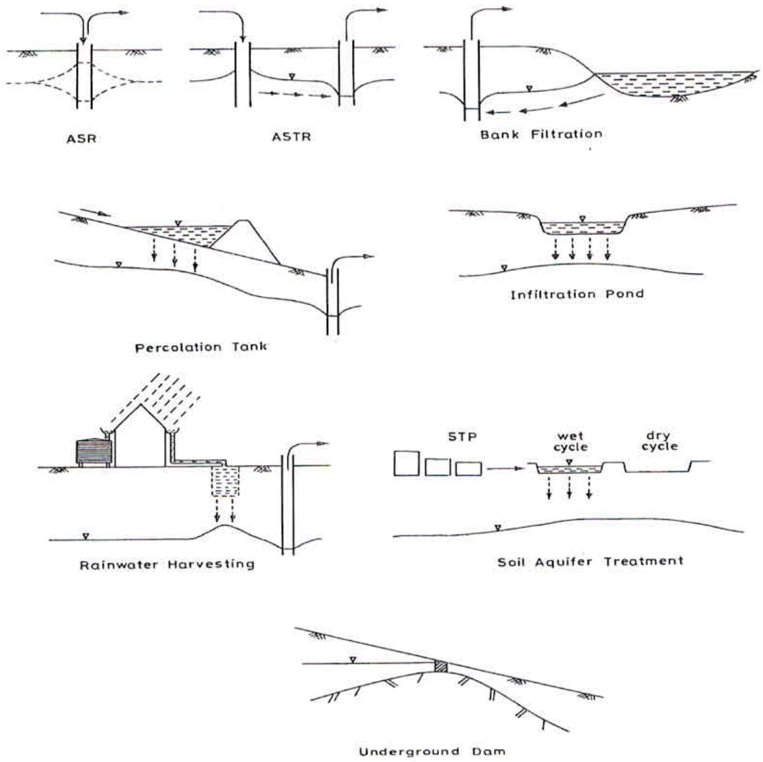

Fig.8 Schematic of types of management of aquifer recharge (After DILLON, 2005)

Techniques of MAR

The variuos techniques of MAR are site specific and the choice of a particular method depends on the nature of aquifers, their hydraulic conductivity and storativity, and quality of recharging water. Surface spreading methods are used in unconfined aquifers where the strata are permeable down to the zone of saturation, and water table is deep to provide adequate storage. Flood plains, alluvial fans and certain glacial deposits like eskers and moraines are suitable for recharge by spreading methods. Infiltration ponds are also constructed to recharge unconfined aquifer. These are made by excavation or by building dykes or levees e.g. in the Rhine valley, Germany.

A groundwater mound is formed due to infiltration. The shape and size of the mound depends upon basin size and shape, recharge rate and duration , depth of water table and aquifer parameters. The infiltration rate is initially high but usually decreases with time due to accumulation of suspended material, colloidal swelling, and by the growth of algae and bacteria. In order to maintain higher infiltration rates, the basin should be dried periodically to disrupt the growth of algae and bacteria. It also help in maintaining higher rates of infiltration with the development of shrinkage cracks.

Percolation Tanks

These are a type of infiltration basins built in the ephemeral river bed by providing a low earthen dam to store rain water. At places vertical shafts are also constructed in the percolation tanks to enhance recharge. Recharge by percolation (infiltration) tanks is an ancient practice of water conservation in the hard rock formations the world over (Singhal & Gupta, 2010). The capacity of a percolation tank usually ranges between 0.14 and 3.0 million m. Studies in crystalline rocks of south India indicate that the rate of infiltration from percolation tanks varies from 0.5 to 1.5 m d . initial rate of infiltration is high but it decreases with time due to silting .

In case of non perennial tank, the recharge rate are comparatively higher. This is due to the removal of silt by farmers during dry season which is used as manure. The recharge estimates from percolation tanks in Deccan basalts and granitic gneisses in India are reproted to range from 30% to 60% of impounded water depending on bedrock and climatic conditions. At some sites in the crystalline rock terrain in south India, groundwater level rose by 3-7 m in the vicinity of recharge ponds (BGS 2006). $\delta^{18}O$ data from a percolation tank in the basaltic rocks of central India show that the tank water contribution to the nearby wells is 50% and thereafter decreases with distance (Sukhija et al. 2002).

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