INTRODUCTION TO HYDROGEOLOGY

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Introduction

`Water is a prime natural resource, a basic human need and precious National asset. Estimation of water resources is therefore, a prime requisite for planning and development. Planning of Water resources require adequate knowledge about the region and its geology. It is a known fact that about 65% of the total land area is covered by hard rocks. Both surface and groundwater are to be used conjunctively to meet the water requirements of the area, which often became more acute due to recurring droughts. Due to the wide distribution of hard rocks in Central and Southern India the whole behavior of the nature and hydrologic process varies from other parts of the country due to the unique nature of hard rocks, i.e., they devoid of primary porosity but have been rendered porous due to weathering and fracturing. The weathering zone is extensive within depths of 10 to 20 m but is localised down below with increase in fracture porosity. The calcareous members like clay gneisses and marbles have been subjected at places to solution.

Definition of `Hard Rock'

Among the geologist and hydrogeologist, still there is no consensus in defining the `Hard Rocks'. In general, Hard Rocks are those geological formations with very low drillability and further, the inter-grannular porosity is practically absent. Larsson et al (1987) defined `hard rocks' as igneous and metamorphic, non-volcanic and non-carbonate rocks. Gustafson and Krsany (1993) accepted the same approach. Yet, hydrogeologists may feel inefficiency of such definition and its limited content due to the fact that, other rock types (especially well cemented sedimentary rocks often occurring in areas built also by crystalline rocks) may be characterized by the same geological environment as crystalline rocks. Moreover, it is often impossible to define exact geological boundary between `hard rocks' and some other rock types. In most of the hydrogeological studies the term `Hard Rock' is used in a wider sense, rather vaguely. Recently, Gustafson (1993) proposed that the term `hard rock' might, from a groundwater exploration point of view, include all rocks without sufficient primary porosity and conductivity for feasible groundwater extraction.

Hydrology of Hard Rock Area

Rock types and Aquifers

Several factors can provide a basis for classifying rocks – but as a starting point it is usual to group all rocks into three main types, depending on their origin. These are igneous rocks, sedimentary rocks and metamorphic rocks, and most of the world's largest groups are of sedimentary origin. Igneous and metamorphic rocks are far less important as source of ground water.

Igneous and Metamorphic Rocks

Igneous rocks are formed by the cooling and solidification of molten material derived from the earth's interior. They occur as intrusives amidst other rocks, as extrusives on the surface, or as large bodies or plutons. The intrusives include sills and dykes of dolerite and pegmatite, the extrusives include basalt and rhyolite ejected on the earth's surface from volcanic vents, and the plutonic rocks include coarse textured igneous rocks as granites, diorite and pyroxenite, ranging in composition from acidic to basic depending on the silica content. Metamorphic rocks are derived by the alteration of other rocks due to heat and pressure, such as, from sand stone to quartzite, shale to slate, limestone to marble. The gradation from igneous to metamorphic rock may be imperceptible, as between granite gneiss, gneissic granite and granite. Rocks with well-developed schistosity and lineation are more resistant to ruptural deformation, while homogenisation into a granitoid type seems to make the rock brittle, as indicated by the higher frequency of joints in granite than in gneiss.

Sedimentary Rocks

Sedimentary rocks are formed as a result of deposition of particles which are often derived from the weathering and erosion of other rocks. The nature of the process means that particles will be deposited with space between them; the size of these voids will depend on the sizes of the particles, and how well sorted they are.

Aquifer Characteristics and Well Yields

Barring the volcanic rocks, igneous and metamorphic rocks usually have porosities less than 1%, the voids being minute, generally isolated and inconsequential from a practical point of view. On weathering and fracturing, the rocks acquire higher porosity, which may reach 30% or more in the case of granite, gabbro, basalt and schist in some cases highly weathered granites may attain a porosity as high as 56.6% (Morris and Johnson, 1967). Estimations by various methods show comparatively low values of specific yield, a range of 2-4% being common for granite, gneiss and schist.

Volcanic rocks include basalt, rhyolite and tuff. Commonly, they consist of several successive flows of variable thickness and lateral extent. A typical flow unit consists of lower dense and massive horizon., passing upwards into a vesicular, amygdaloidal or jointed horizon. The distinctive geohydrological feature of volcanic rocks is the presence of significant primary porosity in the form of vesicles, lava tubes and occasional tunnels formed due to escape of gases. Secondary porosity is developed due to fracturing during cooling of the lavas, tectonic disturbances, and weathering. The vesicular porosity of basalt is considerably reduced by filling up with minerals like zeolites and silica to form amygdales. The basic varieties, such as basalt, are more productive than the silicious varieties like rhyolite as the former contains more large openings in definite pervious horizons between successive flows, besides being more susceptible to weathering. Also, one flow may be separated from the other by sedimentary beds deposited during quiscent periods between successive eruptions.

ZONE OF SATURATION

The upper surface of the zone of saturation is called the water table or phreatic surface, which separates the zone of saturation from the overlying vadose zone. The lower limit of the zone of saturation extends to depths at which the interconnected openings filled with water are so little that they have no practical significance. The width of the zone of saturation may be small in areas underlain by consolidated rocks with joints tapering at shallow depths, or may be several thousands of meters in areas underlain by a thick sequence of sedimentary rocks.

Nearly, all geologic materials near the Earth's surface contain voids. In unconsolidated sediments, these voids are the spaces between grains. In consolidated rocks, voids consist of fractures and fissures. The volume of water contained in a rock depends on the percentage of voids in a given volume of rock, or the porosity. The ease with which water travels through a given material depends on the size of the voids and their degree of interconnection, or the permeability.

Development of Fissures and Joints

In any discussion of the hydrology of fractured crystalline and argillaceous rocks, one must first consider the structural nature of the rock mass. Fractures also called joints, are planes along which stress has caused partial loss of cohesion in the rock. It is relatively smooth planar surface representing a plane of weakness (discontinuity) in the rock. Conventionally, a fracture or joint is defined as a plane where there is hardly any visible movement parallel to the surface of the fracture; otherwise, it is classified as a fault. A fracture is any break in a rock matrix, regardless of its size. Single small fractures are commonly termed as crack or fissure. If the rock on either side of a fracture indicates that there has been some displacement along the fracture, the fracture plane is termed as a fault. Faults are most common in the deformed rock of mountain ranges, suggesting either lengthening or shortening of the crust. Movement along a fault may be horizontal, vertical or a combination. The most common types of faults are normal, reverse and lateral. Fracture zones measures from less than a meter to tens of meters in width and are generally filled with broken and crushed rocks. Depending upon the rock type this material may be embedded in a clay matrix.

There are different types of fractures which depends upon the causes of formation, rock type and past stresses incurred. Causes of fracture not only limited to magmatic or seismic activity , but also to shrinkage of the rock due to temperature drop or moisture loss, weathering and load release due to erosion of overlying material. Regardless of the nature of origin, fractures can have a dominant effect on both the quality and quantity of water moving through the subsurface. Because the extent of weathering varies from one rock type to another, and rock type, it is almost impossible to generalise on the hydrogeological properties of these rocks. Large variations within a single rock types are possible over small areas, so that detailed investigations are necessary before any predictions can be made as to well yields or the amount of water likely to enter an excavation. Extrusive rocks tend to be more variable than the intrusive rocks. When fractures are more or less continuous throughout the bed rock, and seem to have well-defined pattern bearing a relationship to each other or to other elements of rock mass, the fractures are called joint. A joint is a fracture along which no movement has taken place. Probably all consolidated rocks contain joints. When fractures are more or less continuous throughout the bed rock, and seem to have well-defined pattern bearing a relationship to each other or to other elements of rock mass, the fractures are called joint.

Joints are discontinuous in their own planes, but when the ratio of joint spacing is large, they form continuous network for flow. In a rock mass dominated by joints, the hydraulic characteristics are to an unknown degree is as a result of the interconnections of the different joint sets. Joints are variably distributed in rock bodies. In some cases, hard rocks are cut with joints exhibiting no apparent regular pattern (local joining), where as in others, most of the joints are oriented in certain directions. The directions of large joints and even fractured zones can be most clearly traced in areas where normal faults, reverse faults and other fractures occur (regional tectonic fracturing). In such cases, as well as on the sharp crest of the anticlinal highs and synclinal lows, on extensive fracturing can usually be seen over a large distances.

The most prominent zones of tectonic fracturing are confined to anticlinal crests found in folded regions, younger oblique joints and faults are also found in such areas.The process of weathering produce joints primarily by means of the temperature effect on the rock, as well as by chemical and physical action on flowing water. Temperature fluctuations are known to be of a limited vertical extent (the yearly temperature changes reach the depths of 20 m to 30 m); therefore the joints produced by weathering rapidly decreases with depth within the upper 30 to 50 m in most cases. The highly dense joint sets of the above origin can be observed in the upper portions of the hard rock massifs. The joints in rocks may be either open or filled (mineralised), the fill being represented by sandy-clay material or vein minerals (quartz, calcite, pyrite, nickel silicates, copper ores etc.). Joints of tectonic origin are most commonly subjected to mineralization. The character and extent of jointing depend also upon the composition

In the case of joints and fractures, the occurrence and movement of groundwater is controlled by the fracture pattern. The fracture porosity forms the main criteria in defining the ground water flow system. Fractured zone generally constitute the potential aquifers and therefore the geometry of the fractured aquifer system assumed considerable importance while exploring the groundwater in hard rock terrain. Hence, the exploration, development and management of groundwater in the hard rock basaltic terrain are very important. Groundwater in these regions occurs under unconfined and semiconfined conditions. The presence of vesicles, fractures, zeolites, intertrapean redboles and tuffaceous formations give rise to varying magnitude of porosity in the basalt. The aquifer transmissivity ranges from 2 to 140 sq. m /day., the higher values of which were noticed over fractured and jointed basalt. Aquifer resistivity ranges from 10 - 30 ohm m over alluvium and 20-60 ohm m over weathered basalt (Narayanpethaka et al., 1997).

Basic Aquifer parameters and function

Water stored in aquifers is usually in motion, flowing slowly under gravity, until it discharges to a spring, stream, lake, or ocean, or is taken up by plants, or is extracted by wells.

Storage Functions:

The main properties of an aquifer related to its water-storage functions are discussed in the following sections.

Total Porosity (θ): The ***porosity*** is the measure of the void spaces of the water-bearing formation and is expressed quantitatively as the percentage of the total volume of the geologic medium occupied by pores or fractures. It is defined mathematically by the equation:

$$\theta = 100\frac{V_v}{V}$$

where, θ is the porosity (percentage), V_v is the volume of void spaces in a unit volume of rock, and V is the unit volume of rock, including both voids and solids. Typical porosity values of several geological sediment types are listed in table....

Sediments	θ **(%)**	**Sediments**	θ **(%)**
Clay	45-55	Sandstone	5-30
Silt	35-50	Limestone/ dolomite	1-20
Sand	25-40	Shale	<1-10
Gravel	25-40	Fractured, solid rocks	<1-10
Sand-gravel, mixed	10-35	Vesicular basalt	10-50
Glacial till	10-25	Dense, solid rock	<1

Void Ratio (V_r): The ***void ratio*** of a porous material is the ratio of the volume of void space to the volume of its minerals.

$V_r = V_v / V_m = \theta /(1 - \theta)$

Specific Yield (S_y): ***Specific Yield*** is the quantity of water that a unit volume of unconfined aquifer releases by gravity. It is defined mathematically by the equation:

$$S_y = 100\frac{V_g}{V}$$

where, S_y is the specific yield, V_g is the water volume drained by gravity force, and V is the volume of bulk sample.

The specific yield of sediments and rocks is generally determined in situ by aquifer-test or pumping-test methods, such as the Theis-curve procedure or Neuman's semi-logarithmic method. Aquifer-test procedures involve a well from which water is pumped. Water level drawdown is recorded at different rimes, after pumping is started in one or more nearby observation wells.

Specific yield of sediments and rocks can also be determined by laboratory methods. In this case, one must be sure that the saturated samples remain undisturbed and must be allowed to drain for very long period of time (months) before equilibrium is reached. The ratio of the volume of water drained to the volume of the rock sample is the specific yield. Table..... lists representative specific yield ranges for selected materials.

Sediments	**Specific Yield (%)**
Clay	1-10
Sand	10-30
Gravel	15-30
Sand and Gravel	15-25
Sandstone	5-15
Shale	0.5-5
Limestone	0.5-5

Specific Storage (S_s): ***Specific storage*** is the amount of water stored or expelled by the compressibility of the mineral skeleton and pore water per unit volume of a confined aquifer and per unit change in head. Specific storage has a dimensions of (1/L) and has value on the order of 10^{-3}.

Storativity or storage coefficient (S) of a confined aquifer is the product of the specific storage (S_s) and the aquifer thickness (b). The storativity of most confined aquifers is between 10^{-3} and 10^{-5}. The storativity for an unconfined aquifer is usually taken to be equal to the specific yield. The specific yield of most alluvial aquifers is between 10 to 30 percent.

Specific Retention (S_r): *Specific Retention* is the amount of water that a unit volume of an earth material can retain the pores by molecular attraction and capillarity, after gravity drainage. It is defined mathematically by the equation:

$$S_r = 100\frac{V_r}{V}$$

where, S_r is the specific retention, V_r is the volume of water retained against gravity and V is the bulk volume of the sample.

Since the specific retention represents the volume of water retained in the pores against gravity drainage, it may be evaluated by the following expression,

$$S_r = \theta - S_y$$

Darcy's Law

In the mid-nineteenth century, Henry Darcy, made the first systematic study of the movement of water through a porous medium. Darcy found experimentally that the discharge, Q is proportional to the difference in height of the water, Δh, between the two ends and inversely proportional to the flow length L.

Flow of groundwater except through coarse gravel and rockfill is laminar and the flow is governed by ***Darcy's law***, which states that the velocity in a porous medium is proportional to the hydraulic gradient.

$V = ki$,

Where, $i = \Delta h/L$, is the hydraulic gradient or head loss in length L, k is the coefficient of permeability

$Q = A\,ki$

$= wb\,ki$

or, $Q = T\,wi$

where, A = wb, the product of width of aquifer to its thickness, T is the transmissivity of the aquifer, T = kb

Transmissivity of the aquifer is the flow capacity of an aquifer per unit width under unit hydraulic gradient.

In aquifers containing large diameter solution openings, coarse gravel, rock-fills, and also in the immediate vicinity of a gravel packed well, flow is no longer laminar due to high gradient and exhibit nonlinear relationship between the velocity and hydraulic gradient.

Methods of estimating Hydraulic Properties of rocks

Hydraulic properties of rock materials can be estimated by several techniques in the laboratory and in the field. The values obtained in the laboratory are not truly representative of the formation. However, the advantage of laboratory methods is that they are much less expensive and less time consuming. Laboratory methods are based on both indirect and direct methods.

In unconsolidated material, hydraulic conductivity can be determined from grain-size analysis. The hydraulic conductivity of unconsolidated material is found to be related empirically to grain-size distribution by a number of investigators. Hazen, as far back as 1893, developed the empirical relationship between hydraulic conductivity (K) and effective diameter (de)

$K = Cde^2$ where C is a coefficient based on degree of sorting (uniformity coefficient) and packing. If K is in cm/s and de is in cm, the value of C in equation ranges between 45 in very fine poorly sorted sand to 150 in coarse well sorted sand; a value of C = 100 is used as an average. Effective diameter, (de), is the diameter of the sand grain (d10) such that 10% of the material is of smaller size and 90% is of larger size. It can be estimated by plotting the grain-size distribution curve. Uniformity coefficient, being the ratio of d60 to d10, is a measure of the degree of sorting. One of the well-known equations for determining hydraulic conductivity by indirect method is the Kozeny –Carmann equation which depends on factors such as pore tortuosity factor, pore shape factor, specific surface area and void ratio.

Direct Methods

These involve use of various types of permeameters – constant and variable head types. In these methods, the rate of fluid flow through the specimen and the hydraulic gradient across the specimen and the hydraulic gradient across the specimen are measured. Darcy's law can be used to calculate hydraulic conductivity. When the conductivities are very small, steady stae flwo can be achieved by taking small lengths of samples in the flow direction and using large hydraulic gradients. Falling head permeameters are also used for estimation of hydraulic conductivity of both coarse grained and tight formations. In low permeability formations such as hard rocks, use of gas permeameters are commonly used particularly in oil industry. Compressed air is the most satisfactory fluid in most cases. The advantage of using gases is that they have low viscosity and they do not react significantly with the rock material in the dry state.

Packer Tests

A Packer test, also known as an injection test, is used in an uncased borehole to determine the hydraulic conductivity of the individual horizon by isolating it with the help of packers. This method is widely used for estimating the hydraulic characteristics of fractured rocks in various geotechnical and waste disposal investigations. In a packer test water is injected under pressure into the test section. The borehole should be flushed beforehand to remove coatings from the wall of the borehole in order to get reliable results. The following three types of packer test could be used in fractured rocks, depending on details of the information required.

(a) Standard Lugeon test, which gives average hydraulic conductivity.
(b) Modified Lugeon test, which gives directional hydraulic conductivity on the basis of relative orientation of the test hole to the system of fractures.
(c) Cross-hole hydraulic test

Tracer injection Tests

Tracer tests are a valuable tool for determining flow characteristics, viz. groundwater flow direction, flow rates and basin boundaries in fractured rocks because the interpretations of these tests do not assume the continuum approach. The in-situ measurement of hydraulic conductivity can also be made by using a tracer. The tracer used for such a purpose should be inexpensive, easy to detect and safe. A variety of tracers, non-radioactive and radioactive, can be used.

Slug Tests

A slug test involves sudden injection of a known volume of water into a well and a measurement of fall of water level with time. Alternatively a known volume of water can be withdrawn and the rise of water level noted. Slug test are suitable in rocks of low permeability and in weathered hard rocks. Slug tests can also be used in fractured rocks when fractures are uniformly distributed.

The advantage of a slug test is that it is cheap, as it requires less equipment and manpower and the duration of the test is also relatively short. It can be carried out even if nearby wells are being used. However, slug tests cannot replace the conventional pumping test methods as the latter have several additional advantages.

The duration of the slug test depends on the permeability of rocks- it has to be larger in low permeability media. The well radius also influences the duration of the slug test. In low permeability formations , it is necessary to have boreholes or standpipes of small diameter in order to reduce the duration of the test.

Pumping Test

In a pumping test, a well is pumped at a known constant or variable rate. As a result of pumping, water level is lowered and a cone of water table depression in an unconfined aquifer and cone of pressure relief in a confined aquifer is formed. The difference between the static (non-pumping) and pumping water level is known as drawdown. As pumping advances, the cone of depression ex[ands until equilibrium conditions are established when the rate of inflow of water from the aquifer into the well equals the rate pumping. The distance from the centre of the pumped well to zero drawdown point is termed as radius of cone of depression ®. In an ideal uniform, isotropic and homogeneous aquifer, the cone of depression will be symmetrical and the contours of equal drawdown will be circular or near circular. In contrast, in a fractured aquifer, due to anisotropy, the plotted drawdown cone, based on data from a number of observation wells, will be linear, highly elongated or irregular; the longer axis will be parallel to the strike of fracture conducting water.

The slope of the cone of depression and its radius is large, as compared with aquifers of low transmissivity.

Hydrogeological Provinces of Hard Rocks in India

Nearly 65 % of the total land area of the country is occupied by hard rocks. About 54% of the population of the country resides in these regions. Nearly 50 % of the annual replenishable reserve of groundwater occur in these rocks.

A hydrogeological province may be defined as ground water basin having a large aerial extent with specific and definable hydrologic environment and geochemical characteristics. On this basis all geological formations taken as aquifers and in relation to the type of void space present in them and probable form of regional flow system leading to a common drainage outlets are grouped under a single hydrogeological province, i.e. hard rocks.

The hydrogeological sub-province within the major group can be delineated based on the rock type, topography, regional hydraulic conductivity and climatic factors (Fig)

(1) Basalt sub province (The basalt sub province occupies nearly 5,12,000 sq km. Out of the total hard rock area of 22,39,000 sq km in India).
(2) Granite sub province (including gneiss),
(3) Schist sub province (including metamorphic)
(4) Lime stone sub province,
(5) Laterite sub province.

Hydrogeological Investigations Carried out

In general the groundwater potential of hard rocks is poor, through relatively high yields may be obtained in restricted locations under favourable circumstances of topography and rainfall. The zone and the frequency of openings in fractured rocks are normally restricted to shallow depth resulting in low void ratio and hydraulic conductivity. Exceptionally carbonate rocks develop solution channeling with high hydraulic conductivity and yield, particularly in zone of past and present water table fluctuations. The drainage d3eveloped in individual lava flows during intertrappean periods give rise to productive zones, under favourable conditions of topography with high conductivity and yield.

The hydrology and groundwater resources in Deccan Traps have explained by many hydrologists. As per the wok done by State Department of Mines and Geology, Karnataka (1975), the black trap is hard, compact and is traversed by joints in shallow depth. Joints had persisted only upto 10 - 15 m depth. Beyond this depth, the rock becomes more and more compact and presence of such massive variety of trap was noticed approximately from 630.6 m contour and below. Weathering extended hardly 0.5 to 1.0 m depth. The depth for the water in the well varied from 2 to 10 m. While, the pink trap appeared to be better aquifer. They are weathered to an average depth of 12 to 15 m and were having more blowholes and amygdoloidal structures which were filled by secondary minerals like zoeolites and silica. More of fractures and fissures were noticed which helps to retain water percolation, after rainfall. Pink t raps are seen at an approximate altitude of 660.6 to 675 m above M.S.L. and extended approximately upto 630 m contour. The depth of water table in such formation varied form 6 to 12 m depending upon the topography.

In the Deccan trap, the ground water occurs under water table conditions in weathered and jointed traps, and under confined conditions in the zeolitic and vesicular traps wherever they are overlain by hard traps. Depth of weathering in general varied from 2 m to 18 m. Wells ranged in depth from 3.7 to 17.8 m bgl and depth to water table ranged from 1.10 to 16.2 m bgl. The yield of dug wells ranged from 20 cu. m / day to 250 cu. m /day for the pumping period of 2 to 8 hrs. Wells in valleys nearer to nallas and in zeolitic traps yielded better. The inflow rate varies from 0.58 lpm / sq. m to 1.2 lpm / sq. m for recuperation period varies from 1380 minutes to 1175 minutes and in vesicular trap the inflow rates of 1.1 lpm / sq. m to 1.2 lpm / sq. m for recuperation period of 70 minutes and 1260 lpm. The transmissivity figures obtained by the Pappodopulos and Cooper method ranges from 21.5 sq. m /day to 150 sq. m /day.The specific capacity of the wells ranges from 2.42 to 19.13 cu. m /h/m and unit specific capacity in the range of 0.039 to 0.1995 cu. m /h/m. Deccan trap does not contribute appreciably to tube well yield, and the contained water can be tapped only by constructing large-diameter well. In most cases, this zone is entirely shut off by the lining in a tube well. The saturated fractures and joints found in the relatively unweathered bedrock at greater depths are capable of yielding a substantial quantity of water. The fractures and joints are mostly horizontal in nature and interconnected with a network of joins and fissures. The yield from these zones is not readily affected by seasonal changes. In the granite and genesis of south India, such saturated zones are normally encountered at depths ranging from 10 to 50 m. In tectonically disturbed areas, they may even occur at greater depth of 100 m or more. These saturated zones areas usually weathered and have a small vertical extent of a few tens of centimeters. The normal yield of a tube well tapping such zones is around 5.5 cu. m/h. Very low yields of about 450 -900 liters /hour are frequent where as quite large yields up to 90,000 liters /h have been reported from a few isolated tube wells. In the consolidated or fissured formation, the occurrence of ground water is restricted to weathered residue and fracture zones having secondary porosity, and the yield is above20 cu. m /h in the Mesozoic and Paleozoic formations , while it goes down to 5-20 cu. m /h and even below 5 cu. m /h in the Precambrian and Archean formations.

Intensive exploratory drilling in igneous and other hard rock in parts of peninsular India have showed that the openings at greater depth, becomes less pronounced and less abundant and in some cases they are not favourable for movement of ground water . Relatively higher yields from hard rocks are obtained within 40 to 50 m. Depth from surface. Optimum depth drilling beyond which is normally not warranted is about 100 meters while rock type is commonly of secondary importance to the control of weathering and structure. The geometry of the fracture or joint sets is determined by the types of the rock and the stress to which they have been subjected, besides the effect of weathering and relief which makes the void space constituting the system progressively larger on approaching the surface. The topographic conditions and the rainfall regime maintain a high level of saturation in the hard rocks. Thus topographic lows and high rainfall will offer better advantage, although latter factors are insufficient to ensure favourable conditions. Every situation must be considered in the light of the relative influence of the controlling factors. Nevertheless, the water table and the top of the flow system will show generally sympathetic relationship to the topography. The degree of sympathy will be governed by the hydraulic conductivity, the closer water table and topography relationship.

Other Field Methods

Seepage meters can be an extremely useful tool for measuring fluid flux at the ground-water/surface-water interface (Lee and Cherry, 1978). Tracer tests have been used to study physical, chemical, and biological processes in the subsurface. Physical parameters such as dispersion, average linear velocity, porosity, and variation in hydraulic conductivity have been obtained from tracer tests. The tracer tests by Sudicky, et al. (1983) and Sutton and Barker (1985) show that ground water velocity can vary substantially over small scales. In the experiments, small slugs of contaminants. broke into discrete parts that moved at different velocities. Also, Sudicky, et al. (1983) and Freyberg (1986) used tracer tests to describe how the apparent dispersivity value increases with the scale of the problem. Pickens and Grisak (1981) were able to demonstrate that when the concentration breakthrough curves obtained with the point samplers are analysed, this dispersivity parameter is small (0.007 m). In addition, Palmer and Nadon (1986) and Taylor, et al. (1988) suggest that electrical resistivity can be coupled with the execution of single-well injection tracer tests to obtain information about variation in hydraulic conductivity.

Geophysical techniques are recognised as useful tools in characterizing waste sites. Surface geophysical techniques used include gravity, infrared imagery, ground penetrating radar, induced electrical polarization, resistivity, magnetometer, reflection seismics, and electromagnetic surveys. Borehole methods include geothermetry, electrical methods, acoustic methods, and nuclear logging techniques. Surface geophysical techniques such as resistivity, conductivity, seismic refraction, and VLF can be useful in identifying lithology changes in the subsurface, depth to water table, and depth to bedrock.

REFERENCES

Anderson and Burt, T. P., 1990. Processes studies in Hillslope Hydrology.

CSIRO Disc Permeameter: Instructions Manual, 1988. CSIRO, Canberra, Australia

Freeze, R. A. and J. A.Cherry, 1979. Groundwater Prentice Hall, Inc., Englewood Cliffs, NJ.

Freyberg, D. L., 1986. A Natural Experiment on Solute Transport in a sand aquifer. 2. Spatial moments and the advection and Dispersion of Nonreactive Tracers. Water Resources Research, Vol. 22, pp.2031-2046.

Klute, A. and C. Dirksen, 1986. Hydraulic Conductivity and Diffusivity:Laboratory methods. In. Methods of Soil Analysis, Part I, Physical and Mineralogical Methods, A Klute, Editor. Agronomy, No. 9, Part I, American Society of Agronomy, Inc., Soil Science Society of America, Inc., Madison, WI, pp. 687-734.

Lee, D. R. and J. A. Cherry, 1978. A Field Exercise on Ground water Flow using seepage meters and mini piezo-meters. Journal of Geological Education, Vol. 27, pp. 6-10.

Palmer, C. D. and R. L. Johnson, 1989. Determination of Physical transport parameters. Transport and Fate of Contaminants in the subsurface.Seminar Publication, EPA.

Perroux, K. M. and White, I. 1988. Designs for disc Permeameters. Soil Sci. Soc. America J. 52:1205-1215.

Philip, J. R., 1957. The theory of Infiltration:The infiltration Equation and its Solution. Soil Sci. 83:345-357.

Reynolds, W.D., Elrick, D. E. and Clothier, B. E., 1985. The Constant Head Permeameter:Effect of Unsaturated flow. Soil Sci. 139:172-180.

Soni B., S. L Srivastava and B.K.Purandara, 1993. Measurement of Field saturated Hydraulic Conductivity. National Seminar on Hydrological Hazards-Prevention and Mitigation.

Soni B, B. K Purandara, S. L. Srivastava and N. Varadarajan, 1991-1992. Estimation of hydrological soil parameters for malaprabha and Ghataprabha sub-basins

Sudicky, E. A., J. A. Cherry and E. O. Frind. 1983. Migration of Contaminants in Ground water at a land fill: A case study. 4. A natural gradient Dispersion Test. J. of Hydrol. Vol. 63, No. ½, 81-108.

Sutton, P. A. and Barker, 1985. Migration and Attenuation of Selected Organics in a sandy aquifer—A Natural Gradient Experiment. Ground water, Vol. 23, No.1, pp. 10-16.

White, I. and Sully, M. J., 1987. Macroscopic and microscopic capillary length and time scales from field infiltration. Wat. Resour. Res. 23:1514-1522.

Wooding, R. A., 1968. Steady infiltration from a shallow circular pond. Water Resour Res. 4:1259-1273.

Pickens, J. F. and G. E. Grisak, 1981.Scale Dependent Dispersion in a Startified Aquifer. Water Resources Research, Vol.17, pp 1191-1212.

Palmer, C. D. and R. L. Nadon, 1986. Radial.Injection Tracer Experiment in a confined Aquifer, Scarborough, Ontario. Groundwater. Vol. 24, pp322-331.

Taylor, K., F. Molz, and J. S. Hayworth, 1988. A single well Electrical Tracer Test for the determination of Hydraulic Conductivity and porosity as a Function of Depth. Proceedings