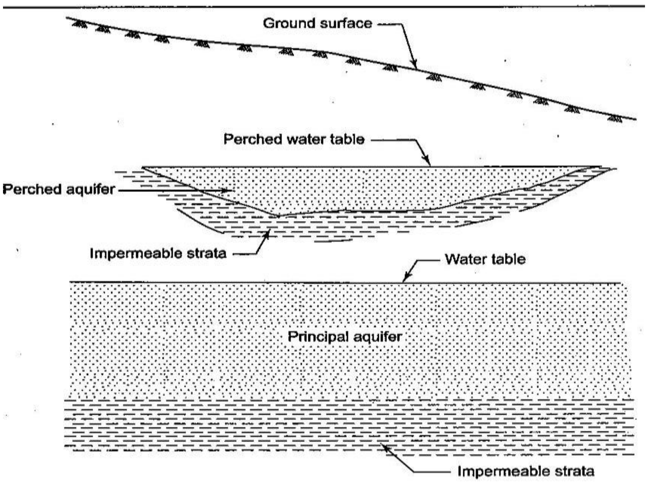
and they may not have sufficient storage to support significant well production. Therefore, perched aquifers are not the target of a groundwater exploration.



AQUIFER CHARACTERISTICS

The properties of aquifer that influence well performance are depth and extent of the aquifer, number of aquifer exposed to the well and the hydraulic properties of the aquifer. An aquifer performs two functions, such as storage and conduit. The properties of aquifer may be expressed in terms of its hydraulic conductivity (permeability), transmissibility, storage co-efficient and specific yield. In case of semi-confined aquifer, two additional properties such as leakage factor and hydraulic resistance are also important.

1. Porosity

Porosity of a porous medium (soil or subsurface formation) is defined as the ratio of the volume of voids (V_v) in a porous medium to the total volume of the porous medium (V).

$$\eta = V_v / V$$

2. Effective Porosity

It is defined as the portion of void space in a porous material through which fluid (liquid or gas) can flow. In other words, it is the fraction of total porosity which is available for fluid flow. It is also called 'kinematic porosity'.

$$n_e = \frac{\text{Volume of water able to circulate in the porous medium}}{\text{Total volume of the porous medium (soil or aquifer material)}} \qquad (3.2)$$

3. Hydraulic Conductivity / Co-efficient of Permeability

It is measure of aquifer's ability to transmit water under a hydraulic gradient. The rate of flow of groundwater to a given hydraulic gradient is dependent upon the hydraulic conductivity of the aquifer.

Def.: The rate of flow of water in lit./day through a horizontal cross-sectional area of 1 m^2 of aquifer under a hydraulic gradient.

The first rational analysis for movement of water through sand was done by Henri Darcy. He proposed that the relationship expressed in the equation which formed the basis of all studies of flow through porous media.

Darcy's law states that the rate of flow of water through a column of saturated sand is proportional to the difference in hydraulic head at the ends of the column and inversely proportional to the length of the column.

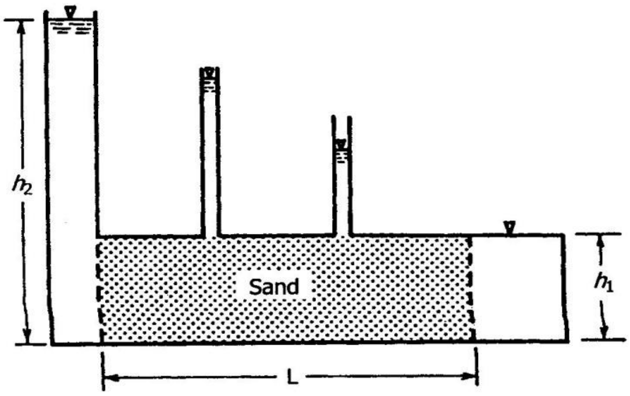


Fig. 5.13. Definition sketch for Darcy's Law.

$$V \propto \frac{(h_2 - h_1)}{L}$$

$$V = K \frac{(h_2 - h_1)}{L}$$

Where, $h_2 - h_1$ = Difference in hydraulic head at points of measurement 1 and 2.
l = Distance between the two points h_1 & h_2. In m.(Length of section)
V = Velocity of Flow (m/day)
K = Hydraulic conductivity (m/day)

The difference in hydraulic head ($h_2 - h_1$) divided by the distance L along the path of fluid flow is called hydraulic gradient i. The slope of watertable or the piezometric surface is the hydraulic gradient under the ground water movement take place.

$$V = Ki$$
$$Q = V \times A$$
$$= KiA$$

Where, Q = Volume of water discharged in standard length of time (m^3/day).
A = Cross-sectional area through which water moves (m^2)

The values of hydraulic conductivity for different aquifer materials are given below.

Sr. No.	Aquifer Material	Hy. Conductivity K (m/day)
1	Clay	$< 10^{-6}$
2	Silt	$10^{-5} – 5 \times 10^{-4}$
3	Silty Sand	$10^{-4} – 2 \times 10^{-3}$
4	Fine Sand	0.001 – 0.05
5	Mixed Sand	0.005-0.01
6.	Clean Course Sand	0.010 – 1.00
7.	Clean Gravel	1 - 100

Validity of Darcy's Law

The Darcy law is valid for the groundwater flow condition when head loss is directly proportional to the velocity of flow. Such a flow condition exists when the groundwater flow is laminar. That is, the Darcy law is valid for laminar flow only.

To check the validity of the Darcy law, a non-dimensional number called Reynolds Number is used. Reynolds Number (R_e) is given as:

$$R_e = \frac{\rho V d}{\mu} = \frac{\text{Inertial Force}}{\text{Viscous Force}} \qquad (4.11)$$

Where, ρ = density of the fluid, V = flow velocity, d = characteristic length, and m = dynamic viscosity of the fluid.

Experiments have shown that the Darcy's law is strictly valid for $R_e<1$, but it doesn't depart seriously up to $R_e = 10$ (Ahmed and Sunada, 1969). Hence, in practice, the Darcy's law may be applied to flow conditions that exist when $R_e \leq 10$. Fortunately, most natural groundwater flow occurs with $R_e \leq 1$, and hence the Darcy's law is generally applicable**.**

4. Transmissibility

The magnitude of flow through any vertical section of an aquifer is estimated if the thickness (b), average hydraulic conductivity (k) and the hydraulic gradient(i) at the section are known. Transmissivity (T) of an aquifer system describes how transmissive an aquifer is in moving water through its pore spaces.

Definition: the rate at which water is transmitted through a unit width of the aquifer under a unit hydraulic gradient is called *transmissibility*. OR It is defined as the product of hydraulic conductivity (K) and the saturated thickness (b) of the aquifer.

According to Darcy's law, $Q = Kib$ (a = w x b = 1 x b)

In above equation, the product of the term k and b may be used to represent the water transmitting capacity of the entire thickness of the confined and semi-confines aquifer which may be termed as *transmissibility*.

$$Q = Ti \text{ (for unit width)}$$
$$Q = Tiw$$

Where, Q = groundwater flow rate (discharge), K = hydraulic conductivity of the aquifer, b = saturated thickness of the aquifer, w = width of the aquifer, i = hydraulic gradient, and T = transmissibility of the aquifer.

5. Co-efficient of Storage / Storability

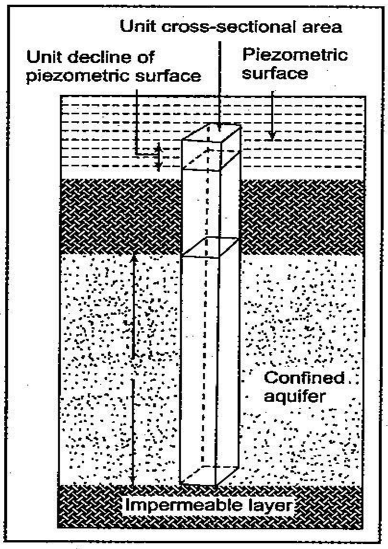
The storage properties of confined and semi-confined aquifer are expressed by the co-efficient of storage S.

It is defined as the volume of water release from or storage into aquifer per unit surface area per unit change in the hydraulic head..

Water recharged or discharged from an aquifer represents a change in the storage volume within the aquifer. In confined aquifer, the co-efficient of storage is a result of compression of aquifer and expansion of the contained water as a result of reduced pressure due to pumping. The value of S ranges from 0.00001 to 0.001(10) for confined aquifer.

6. Specific Storage

The 'Specific Storage' (S_s) of an aquifer is defined as the volume of water released from (or taken into) storage per unit volume of an aquifer per unit change in hydraulic head.



ig. 2.2 Definition sketch of storage coefficient

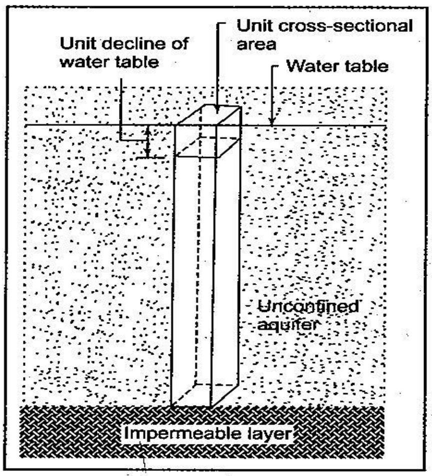


Fig. 2.3 Definition sketch of specific yield

7. Specific Yield

Specific yield is the ratio of the volume of water which a rock is yield after being saturated by gravity to the volume of rock. The specific yield (S_y) is the property of an unconfined aquifer.

Typical values of porosity and specific yield for different geological materials

Sl. No.	Type of Geological Material	Porosity (%)	Specific Yield (%)
1	Coarse Gravel	28	23
2	Medium Gravel	32	24
3	Fine Gravel	34	25
4	Coarse Sand	39	27
5	Medium Sand	39	28
6	Fine Sand	43	23
7	Silt	46	8
8	Clay	42	3
9	Fine-grained Sandstone	33	21
10	Medium-grained Sandstone	37	27
11	Limestone	30	14

$$S_y = \frac{\text{Volume of Water Drained}}{\text{Total Volume of Saturated Rock}}$$

The concept of specific yield as apllied to a confined aquifer is equivalent to its storage co-efficient. Under un-confined aquifer conditions, the groundwater is derived from the storage by the gravity drainage of the voids in the portion of aquifer that has been unwatered by pumping.

When water is drained from an aquifer by gravity force, only a part of the total volume of water stored in its pores is released. The quantity of water that a unit volume of the aquifer will yield when drained by gravity is called its specific yield. The quantity of water that a unit volume of aquifer retains when subjected to gravity force is called specific retension. The sum of specific yield and specific retension equals the porosity of aquifer.

8. Specific Retention

Specific Retention of a soil or aquifer material is defined as the ratio of the volume of water retained after saturation against gravity to its own volume.

$$S_r = \frac{\text{Volume of Water Retained}}{\text{Total Volume of Saturated Rock}}$$

Porosity = Specific Yield + Specific Retension

The values of specific yield for different aquifer materials are given below

Sr. No.	Aquifer Material	Specific yield (%)
1	Uniform Sand	30 %
2	Alluvial	10 - 20 %
3	Gravel	15 - 30 %
4	Sand and Gravel	15 – 25 %
5	Sand Stone	5 – 15 %

9. Hydraulic Resistance (c)

Hydraulic resistance is a property of semi-pervious layer of semi-confined aquifer. It characterises the resistance of the semi-pervious layer to upward and downward leakage.

Def.: it is the ratio of saturated thickness b of the semi-pervious layer and the hydraulic conductivity K of the semi-pervious layer for the vertical flow.

$$c = \frac{b}{K}$$

When the value of c becomes infinity, the layer is considered to be impervious. When the value of c equals to or near to zero, the layer is considered an aquifer. The value of hydraulic resistance of a semi-pervious layer is evaluated on the basis of the pumping test data using the following equation,

$$c = \frac{B^2}{Kb}$$

Where, c = hydraulic resistance (days)

B = Leakage factor (m)

K = hydraulic conductivity (m/day)

b = Thickness of the horizontal pervious layer confined between horizontal semi-pervious and impervious layers (m)

The value of c ranges between 100 to 1000000 (10^2 to 10^6) minutes.

10. Leakage factor (B)

It is also a property of semi-confined aquifer. It determines the distribution of leakage into the semi-pervious layer. The value of Leakage factor is evaluated on the basis of the pumping test data using the following equation,

$$B = \sqrt{Kbc}$$

High values of leakage factor indicate a great resistance of the semi-pervious strata (layer) to flow, as compared to the resistance of the aquifer itself.

GROUNDWATER INVESTIGATION / GROUNDWATER EXPLORATION

As we know that groundwater is widely distributed beneath the earth, but its occurrence is confined to only certain geologic formations and structures. As the occurrence of groundwater cannot be seen from the earth's surface, a variety of techniques are used to explore/investigate groundwater.

The exploration of groundwater can be done from the earth's surface or above-surface locations, which is known as surface investigation. Groundwater exploration can also be done using equipment/instruments extending underground, which is known as subsurface investigation.

Surface investigations of groundwater usually do not provide quantitative data/information concerning aquifers or groundwater as obtained from subsurface investigations. Correct interpretation requires supplemental data from subsurface investigations to verify the findings of surface investigations. Although the surface investigations of groundwater provide an incomplete picture or qualitative information of hydro geologic conditions below the ground, they are usually less expensive and less time consuming than the subsurface investigations (Todd, 1980).

Surface Methods of Groundwater Exploration

The surface methods of groundwater exploration can be classified into two major groups: (a) geologic methods (also called 'reconnaissance methods'), and (b) geophysical methods. Geologic methods involve interpretation of geologic data or geology related data and field reconnaissance using 'Test pits and trenches', 'Adits', 'Continuous Cone Penetrometer' and 'Auger'. They represent an important first step in any groundwater investigation. On the other hand, geophysical methods are 'Electric resistivity method', 'Seismic methods', 'Gravity method', 'Magnetic method', and 'Remote sensing techniques' (Todd, 1980), of which 'Electric resistivity method' is most widely used for groundwater exploration.

Geophysical Methods

Geophysical methods are scientific measurements of differences in physical properties within the earth's crust. Some of the geophysical methods are briefly described below.

1. Electric Resistivity Method

Among all surface geophysical methods of groundwater exploration, the electric resistivity method has been applied most widely for groundwater investigations, even these days. Electric resistivity of a rock formation limits the amount of current passing through the formation when an electric potential is applied. If a material of resistance R has a cross-sectional area A and length L, then its resistivity can be expressed as:

$$\rho = \frac{RA}{L}$$

The unit of resistivity is Ohm-meter (W-m). Resistivity of rock formations varies depending on the material density, porosity, pore size and shape, water content, water quality and temperature (Todd, 1980).

Electric resistivity methods are based on the response of the earth to the flow of electrical current. In these methods, an electric current is introduced into the ground by two current electrodes, and the potential difference is measured between two points using potential electrodes suitably placed with respect to the current electrodes. The potential difference for unit current sent through the ground is a measure of the electrical resistance of the ground between the probes.

The measured current (in amperes) and potential differences (in volts) yield an apparent resistivity (ρ_a) over an unspecified depth. If the spacing between electrodes is increased, a deeper penetration of electric field occurs and a different apparent resistivity is obtained (Todd, 1980). In practice, various standard electrode spacing configurations/arrangements are adopted, but mainly two types of electrode configurations known as Wenner electrode arrangement (Fig. 7.1) and Schlumberger electrode arrangement (Fig. 7.2) are most commonly used in resistivity surveys.

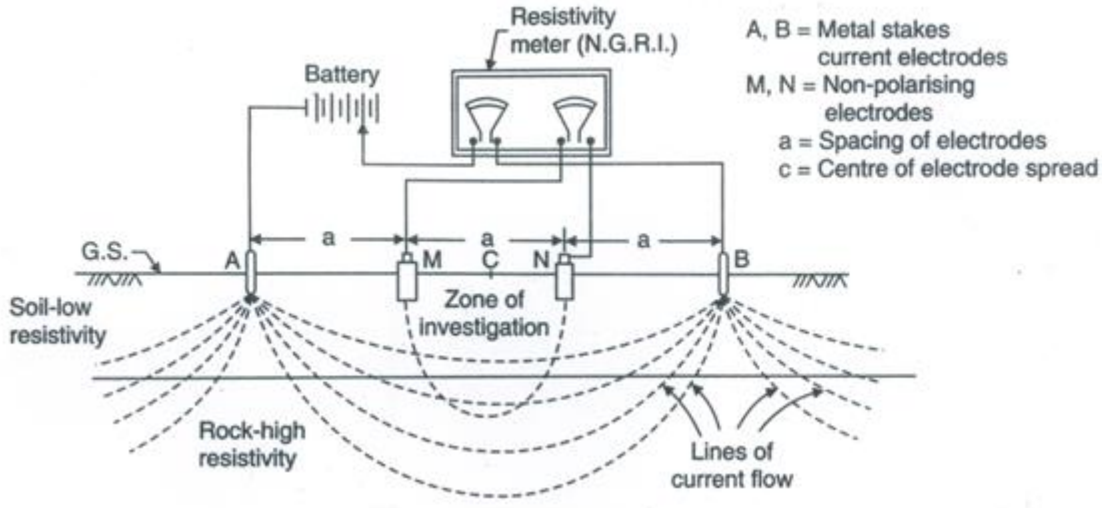


Fig. 7.1. Schematic view of the electrode arrangement.

Electric resistivity surveying is carried out by using an Electric Resistivity Meter. Two commonly used ER meters are: NGRI Resistivity Meter and Terrameter.

Finally, the salient advantages of the electric resistivity method are (Todd, 1980):

(i) Its portable equipment and the ease of operation facilitate rapid measurements;
(ii) It frequently aids in planning efficient and economic test-drilling or well-drilling programs;
(iii) It is especially well adapted for locating subsurface saltwater boundaries, because the decrease in resistance due to the presence of saltwater becomes apparent on a resistivity-spacing curve;
(iv) It can be used for delineating geothermal areas and estimating aquifer permeability; and
(v) It can also be used for defining areas and magnitudes of polluted groundwater.

However, the limitation of the resistivity method is that the factors like lateral geologic heterogeneities, buried pipelines, cables, and wire fences can disturb the electric field close to the electrodes, thereby invalidating resistivity measurements.

2. Seismic Methods

Seismic techniques involve the measurement of seismic waves travelling through the subsurface. Since seismic techniques require special equipment and trained persons for operation and data interpretation, they have been applied to a relatively limited extent for groundwater investigations. Three most commonly used seismic methods are: (i) Seismic refraction, (ii) Seismic reflection, and (iii) Seismic surface wave analysis.

Seismic Refraction Method

The principle of seismic refraction surveying is based on the fact that shock waves travels through different earth materials at different velocities. Seismic refraction method involves the creation of small shock at the earth's surface either by impact of a heavy instrument or by a small explosive charge and measuring the time required for the resulting sound or shock wave to travel a known distance.

Shock waves are produced by setting off an explosive charge in a shallow hole or by striking the ground with a heavy hammer. A seismic graph is used to detect and time the arrival of shock point. Comparison of the velocities measured at various distances between the shock point and detector instruments provide a basis for estimating the sub-surface geologic conditions.

The refraction method assumes that the velocity of seismic waves increases with depth, and hence the layers must be thick enough and should have velocity contrast to be resolved. This method is suitable where the velocity of shock wave increases with depth. This method can provide data up to a depth of 100 m. For deep measurements, it may require explosives as a source of energy.

3. Remote Sensing Techniques

Remote sensing from aircraft or satellite has become an increasing valuable tool for understanding subsurface water conditions. Remote sensing techniques offer many types of investigations about an area without causing any damage to the sites.

Aerial photographs and satellite images taken at various electromagnetic wavelength ranges can provide useful information about groundwater conditions. Other non-visible portions of the electromagnetic spectrum hold promise for a whole array of imaging techniques that can contribute to hydro geologic investigations/surveys. Fractures and faults appear on aerial photos and satellite images as tonal variations in surface soils caused by the difference in soil moisture. Fracture patterns and other observable surficial features obtained from remote sensing data serve as interpretive aids in groundwater studies because they can be related to the porosity and permeability of subsurface formations, and ultimately well yield.

The RS technology, with its advantages of spatial, spectral and temporal availability of data covering large and inaccessible areas within a short time, has emerged as a powerful tool for the assessment, monitoring and management of groundwater resources.

Subsurface Methods of Groundwater Exploration

Detailed and comprehensive examination of groundwater and conditions under which it occurs can be made by subsurface investigations only. Subsurface investigations are conducted by a person or a group of persons on the earth's surface who operate the equipment/instruments extending underground through a borehole which provides direct access to subsurface formations and groundwater.

Various subsurface methods of groundwater exploration can be classified into three major groups: (a) Test drilling, (b) Borehole sensing (sometimes it is also called 'television logging'), and (c) Geophysical logging.

Test drilling provides information regarding subsurface formations in a vertical line from the ground surface, whereas the borehole sensing provides more detailed information about the borehole, geologic strata, and well casing and screen. On the other hand, geophysical logging techniques provide information on physical properties of subsurface formations, groundwater quality, and well construction.

At the end, it is worth mentioning that apart from the above-mentioned subsurface investigation techniques, there are some other important subsurface investigation methods which can provide important information about the hydro geologic conditions and the dynamics of groundwater in a basin. These methods are: tracer tests for groundwater flow; groundwater-level monitoring for flow directions and aquifer conditions; pumping tests for aquifer parameters, well parameters, well yield and well evaluation; groundwater-level fluctuation measurements for analyzing spatio-temporal changes in groundwater storage, groundwater behaviour and surface water-groundwater interaction; and groundwater sampling for water-quality assessment.

2.WATER WELLS

WATER WELLS

Water well is a hole or shaft, usually vertical, excavated into the earth for bringing groundwater to the surface (Todd, 1980). Wells also serve other purposes such as for observation/exploration, artificial recharge and disposal of wastewaters

TYPES OF WELLS

Wells are classified according to........

1) The type of aquifer supplying water to the well:

- a) Gravity well / percolation well: The well which derives its water from an unconfined aquifer is called gravity well.
- b) Artesian well / cavitation well: The well which derives its water from a confined aquifer is called artesian well.

2) The depth of the well:

- a) Shallow well: The wells having a pumping water level is less than or equal to 6 m are classified as shallow well.
- b) Deep well: The wells having a pumping water level is greater than 6 m are classified as deep well.

3) The method of construction of the well

- a) Open well / Dug well: Open wells are dug down from the water bearing strata. They derive water from the formation close to the ground surface. The open excavation is usually circular or rectangular in shape. Generally, the circular shape is adopted for open wells in alluvial and other such formations because of its greater structural strength. In case of circular wells, the diameter varies from 1.5 to 6 m. The open wells of larger size and rectangular in shape are preferred in hard-rock formations to facilitate larger amount of groundwater inflow into the well. The depth of open wells varies from a few meters to about 50 m. The large diameter of the wells permits the storage of large quantities of water in the well.

Usually two types of wells are constructed, lined (masonry) and unlined, depending on the characteristics of the underground formations at the well site. A typical masonry well constructed in alluvial or semi-consolidated formations. A typical dug well is constructed in hard rock formations. The top portion along the soil mantle is usually lined with bricks or stones. A majority of irrigation wells in India are open wells, drawing their water mostly from shallow unconfined aquifers.

b) Dug-cum-bore well: sometimes a confined aquifer lies beneath a dug well. In such cases the yield of well can be appreciably increased by boring a hole through the impermeable bottom and reaching the artesian aquifer. The small borehole (size ranging from 4 to 15 cm) is drilled through the bottom of the dug well up to the water-bearing formation lying below the well-bottom.

Usually, only one bore is drilled at the centre of the dug well constructed in unconsolidated formations. However, in hard-rock formations, the number of bores may range