Applied Hydrogeology G412

Lecture.1

Introduction

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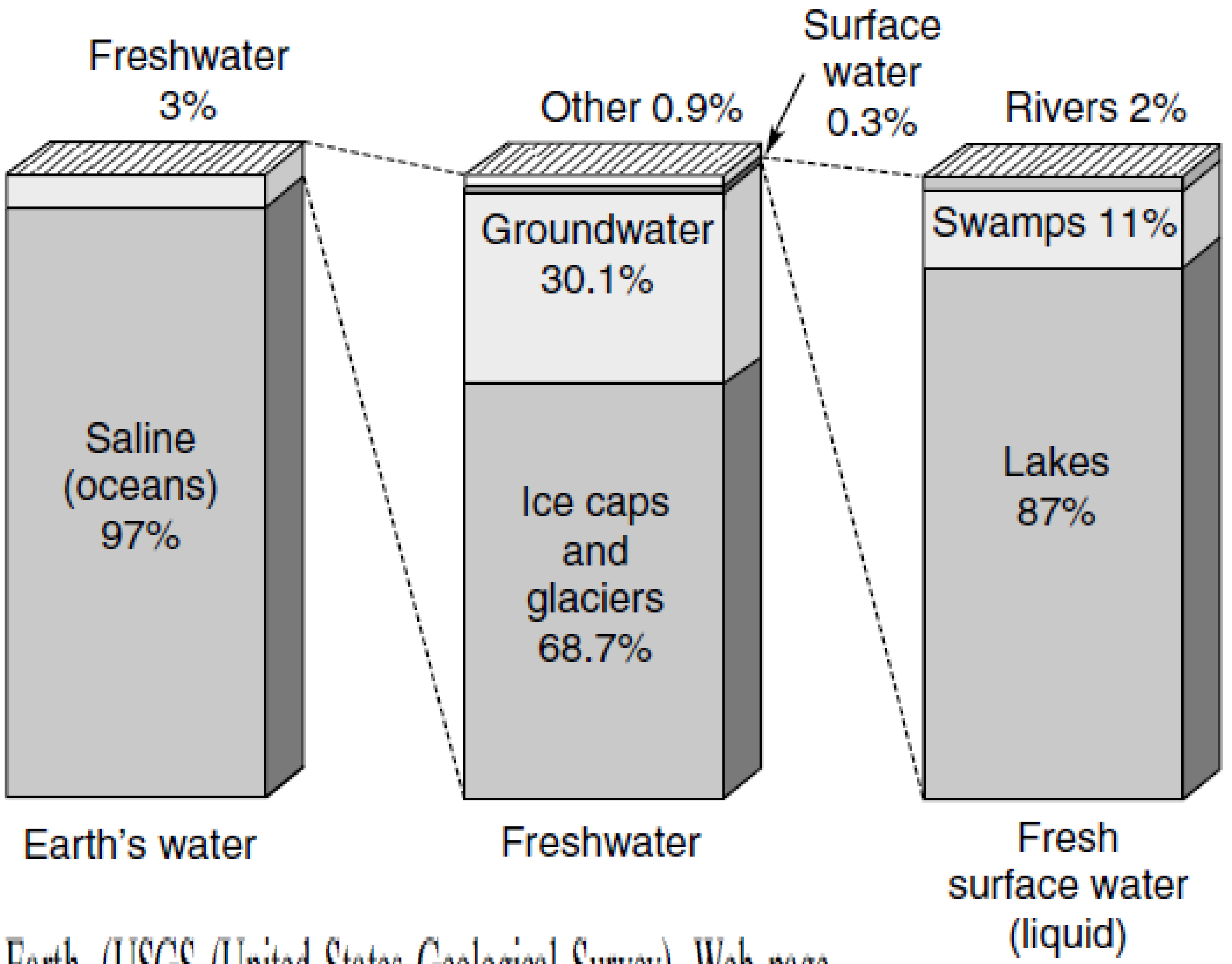
Groundwater as a natural resource

Groundwater is an important natural resource. Worldwide, more than 2 billion people depend on groundwater for their daily supply. A large proportion of the world's agriculture and irrigation is dependent on groundwater, as are a large number of industries. Whether groundwater or surface water is exploited for water supply is largely dependent on the location of aquifers relative to the point of demand. A large urban population with a high demand for water would only be able to exploit groundwater if the aquifer, typically a sedimentary rock, has favorable storage and transmission properties, whereas in a sparsely populated rural district more limited but essential water supplies might be found in poor aquifers, such as weathered basement rock.

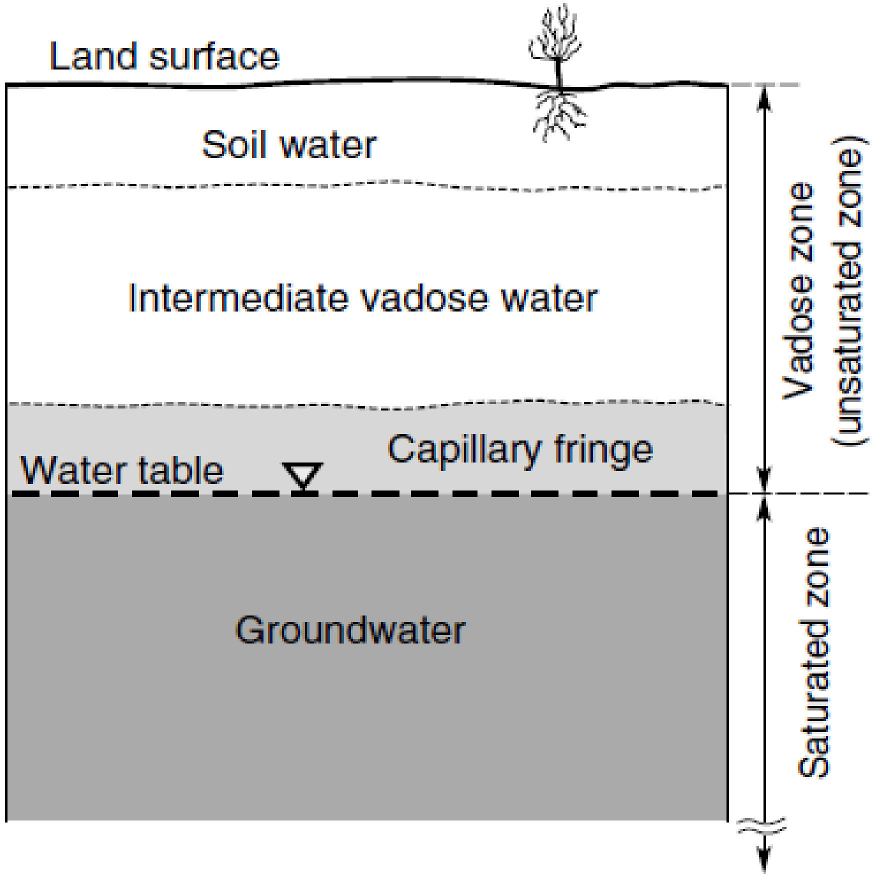


Distribution of water on Earth. (USGS (United States Geological Survey), Web page http://ga.water.usgs.gov/edu/waterdistribution.html, accessed on November 12, 2005.)

- **TYPES OF WATER BELOW GROUND SURFACE**

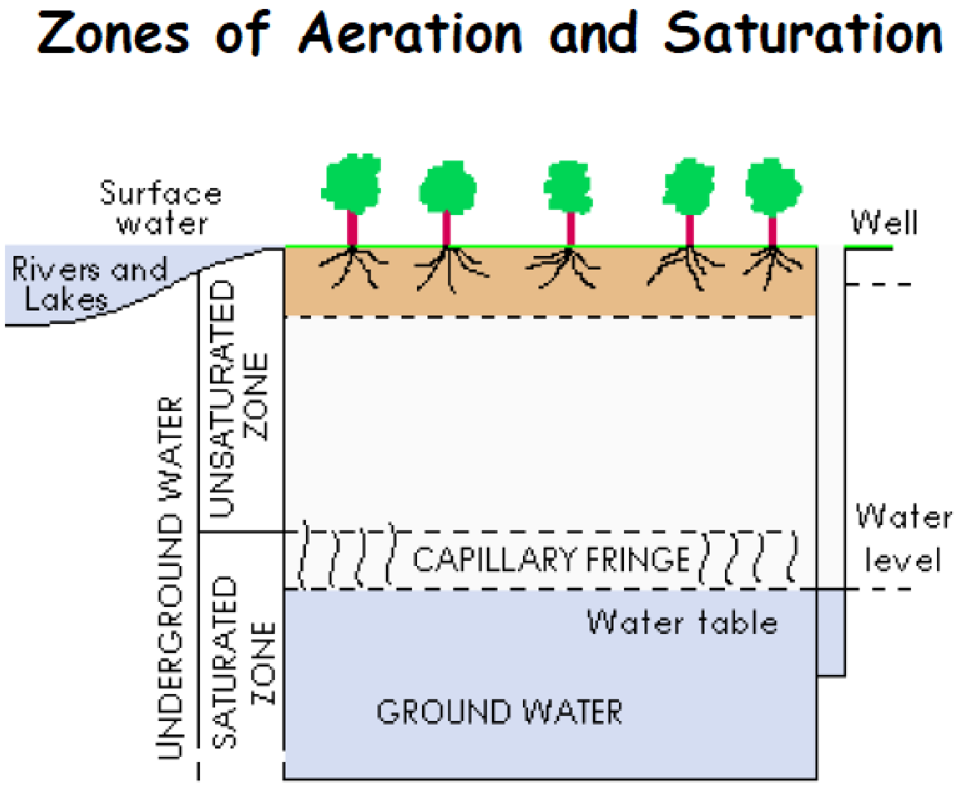
- Water in the subsurface, from the practical hydrogeologic perspective, can be divided into two major zones: water stored in the unsaturated zone, also called vadose zone or zone of aeration, and water stored in the saturated zone

- Soil pore space in the vadose zone is filled with both air and water, in varying proportions, depending on the soil type, climatic and seasonal conditions.



This zone may be divided, with respect to the occurrence and circulation of water, into the uppermost zone of soil water, the intermediate zone, and the capillary fringe immediately above water table.

The capillary fringe is a zone directly above water table and contains capillary interstices some or all of which are filled with water that is continuous with the water in the zone of saturation but is held above that zone by capillarity acting against gravity



Water Table

Represents the top of saturated zone

Represent the upper limit of unconfined aquifer

Depressed version of topography

GEOLOGIC CONSIDERATIONS

- Study of water bearing geological layers is important before any major water abstraction from the groundwater reservoirs. The proportion of solids (particles) and voids (pores, fractures, solution cavities) in any rock body defines its worth for water storage and yield capability, i.e., its water release potentiality. Voids and solids are present in any rock mass as mutually exclusive combinations, which give the rock ability to store fluids (water, gas, oil, air) in the voids. Rock masses may be potential reservoirs provided that the voids are interconnected.
- The term reservoir has a broad meaning and in general, it can be defined as "any material body, which can store and release fluid." Reservoir does not necessarily mean that it can transmit water at demand levels. The proportion of interconnected pores present in the whole bulk of the rock mass further defines the permeable or impermeable nature of the reservoirs.
- Depending on the genesis of voids as porous, fractured, or karstic, the geological formations are regarded as fluid (groundwater, oil, and gas) reservoir. The sedimentary rocks such as sandstone, clay, and limestone are potential groundwater reservoirs. The igneous and metamorphic rocks (if not fractured) like granite and gabbro are not significant groundwater reservoirs.

- Depending upon the geometrical interrelationships (size, shape, orientation, interconnection, etc.) among pore spaces, the permeable reservoirs are further classified into porous, karstic, and fractured media. Porous medium can be categorized broadly into fine- and coarse-grained formations.

- **AQUIFER PARAMETERS**

1. Porosity
2. Specific yield and retention,
3. Hydraulic conductivity (coefficient of permeability),
4. Transmissibility (transmissivity)
5. Storage coefficient and specific storage

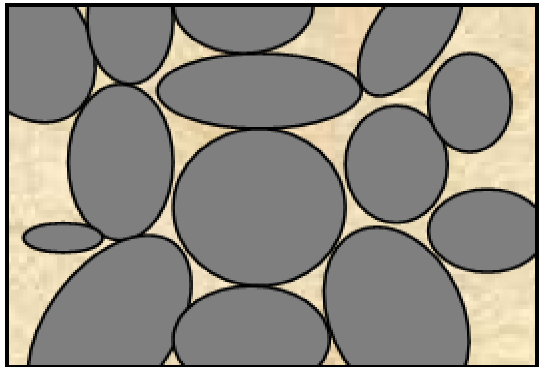
- **POROSITY AND EFFECTIVE POROSITY**

- Porosity (n) is the percentage of voids (empty space occupied by water or air) in the total volume of rock, which includes both solids and voids:

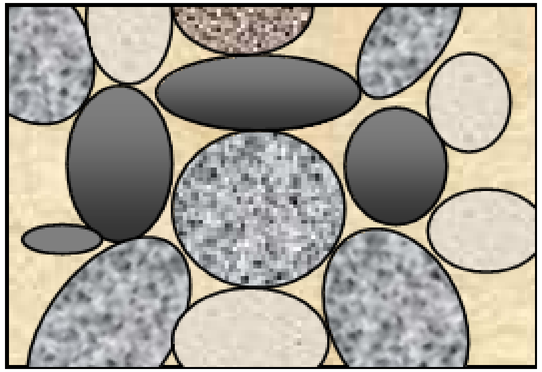
$$n = \frac{V_v}{V} \times 100\%$$

where Vv is the volume of all rock voids and V is the total volume of rock (in geologic terms, rock refers to all of the following: soils, unconsolidated and consolidated sediments, and any type of rock in general).

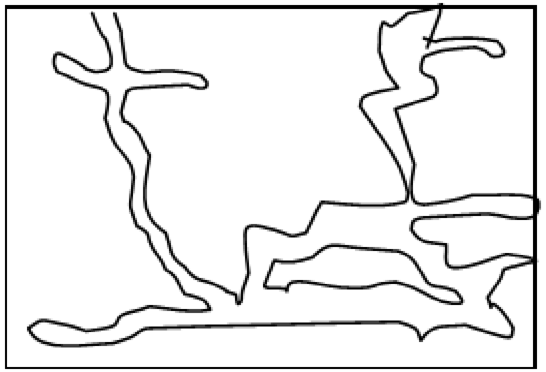
Porosity



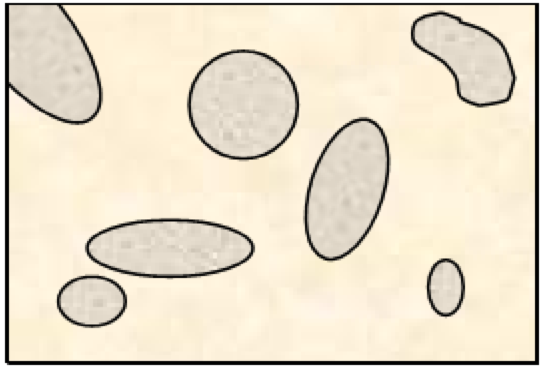
Well Sorted



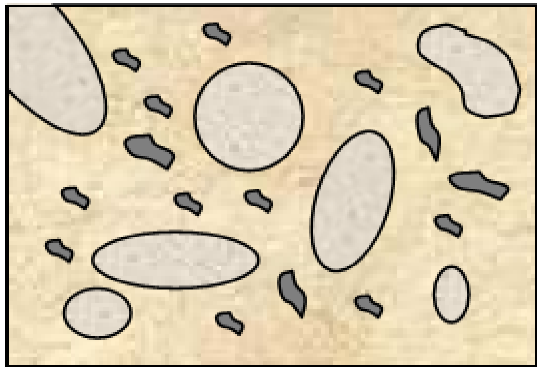
Intragranular



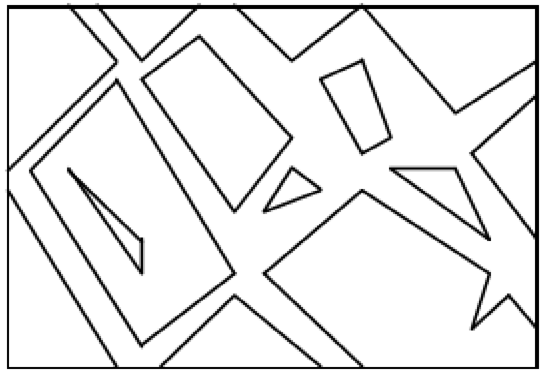
Dissolution



Poorly Sorted



Decreased Porosity
by Diogenesis



Fracture

Diogenesis – The formation of rock; pores fill up with precipitations of mineral and reduce porosity

- **Effective porosity** is that portion of the total void space of a porous material that is capable of transmitting fluid and it is almost similar to the specific yield. Porosity is the primary rock property that is used in all fluid (groundwater, oil, and gas)
- **Specific Yield and Retention** is the amount of water that can be extracted under the gravitation force, and specific retention cannot be separated from the grain surfaces because the fluid (water, oil) is attached to grain surfaces due to adhesion forces. The specific yield, Sy, is the storage term used directly for unconfined aquifers. It is defined as the drainable water volume, Vd, from storage per unit surface area of the aquifer per unit decline in the water table, which is shown diagrammatically in Figure 4. This definition implies that it is a dimensionless quantity (m3/m2m).

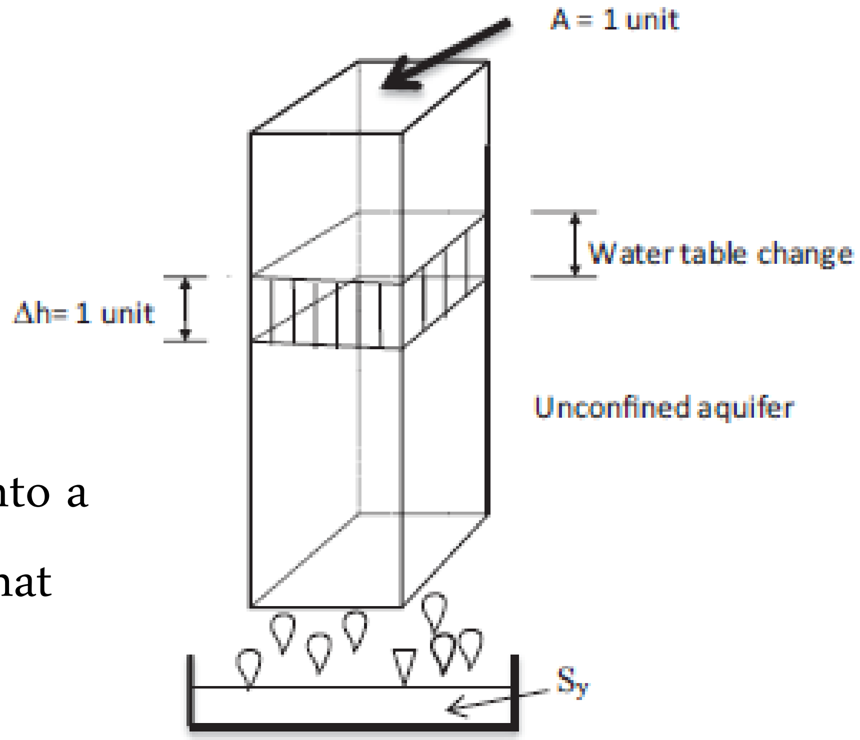
The porosity is the combination of specific yield and specific retention, Sr, and they complement each other,

$$n = Sy + Sr$$

Specific yield is useful to define part of porosity referring only to the movable (abstractable) water in the rock. It is also known as effective porosity in engineering.

$$Sy = Vw / VT$$

where Vw is the volume of drainable water due to gravitation.



Specific-yield definitions

EXAMPLE

A loose soil sample of 45 cm3 is collected from the field. It is poured into a graduated cylindrical cup and then filled with water. It is determined that 25.2 cm3 of water is in the voids. What is the porosity of this soil?

Solution

The definition of porosity equation leads after the substitution of the relevant numerical parameters into the following expression as,

$n = VT – Vv / VT$

$= 45.0 - 25.2 / 45.0$

$= 0.44$

Permeability is the ease with which fluids flow through a rock or sediment.

Permeability depends on:

Grain size

Coarser-grained sediments are more permeable than fine-grained sediments because the pores between the grains are larger.

Sorting

Grain shape

Packing (controls pore size)

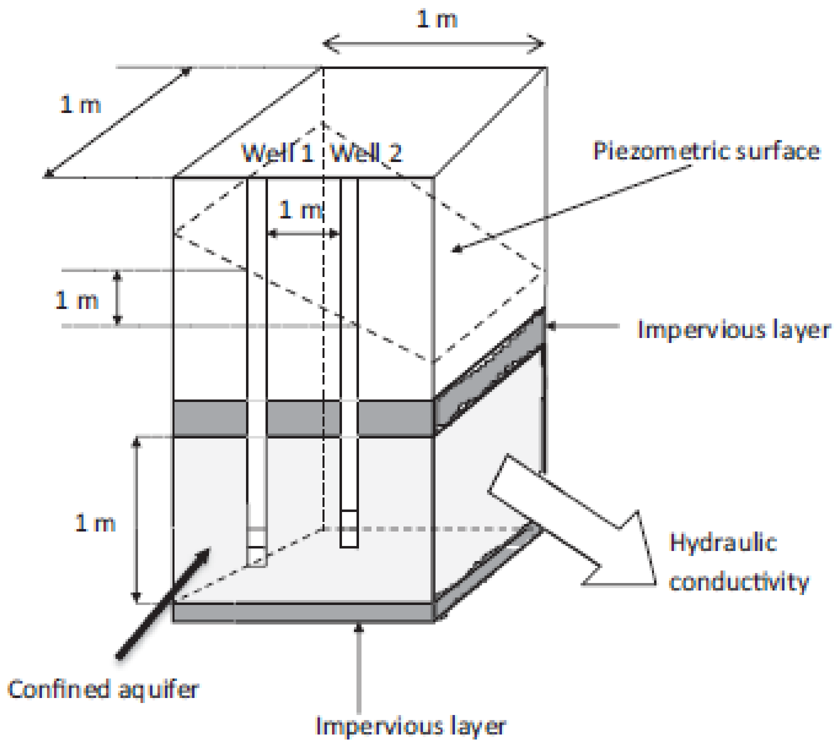
permeability measure the transmission property of the media and the interconnection of the pores. Related to hydraulic conductivity and transmissivity.

Two types of Porosity

- Intergranular
  - Between grains, mostly part of the effect of porosity, but also dead-end pores
- Intragranular
  - Within grains
  - Usually not considered part of the effective porosity
  - Incredible wide range of widths and length scales
- Simple dichotomous model - dual porosity

Hydraulic Conductivity

Hydraulic conductivity is one of the parameters, which tells about the transmission properties of an aquifer. It depends upon the specific (effective porosity) of the aquifer, which means the degree of interconnection of the pores. It can be defined as the volume of water per unit time passing through per unit cross-sectional area of the aquifer under the effect of unit hydraulic gradient as shown in Figure 6



Definition of hydraulic conductivity.

Under the light of this definition, one can write notationally the hydraulic conductivity, K, as,

$$K = \frac{Q}{Ai}$$

where Q is the discharge, A is the cross-sectional area, and i is the hydraulic gradient. Hydrauli conductivity is a property that describes the ease with which water can move through the interconnected void spaces.

Material	Hydraulic Conductivity (m/s)
UNCONSOLIDATED SEDIMENTARY MATERIALS	
Gravel	3×10^{-4}–3×10^{-2}
Coarse sand	9×10^{-7}–6×10^{-3}
Medium sand	9×10^{-7}–5×10^{-4}
Fine sand	2×10^{-7}–2×10^{-4}
Silt, loess	1×10^{-9}–2×10^{-5}
Till	1×10^{-12}–2×10^{-6}
Clay	1×10^{-11}–4.7×10^{-9}
Unweathered marine clay	8×10^{-13}–2×10^{-9}
SEDIMENTARY ROCKS	
Karst and reef limestone	1×10^{-6}–2×10^{-2}
Limestone, dolomite	1×10^{-9}–6×10^{-6}
Sandstone	3×10^{-10}–6×10^{-6}
Siltstone	1×10^{-11}–1.4×10^{-8}
Salt	1×10^{-12}–1×10^{-10}
Anhydrite	4×10^{-13}–2×10^{-8}
Shale	1×10^{-13}–2×10^{-9}

Hydraulic Conductivity Classifications

K (cm/s)	10^{2}	10^{1}	10^{0}	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}	10^{-8}	10^{-9}	10^{-10}
Relative permeability	Pervious				Semi-pervious				Impervious				
Aquifer	Good					Poor					None		
Unconsolidated	Well		Well sorted			Very fine sand, silt							
Sand and gravel	Sorted gravel		Sand or sand and gravel			Loess, loam							
Unconsolidated Clay and organic					Peat		Layered clay				Fat/unweathered clay		
Consolidated rock	Highly fractured				Oil reservoir rock			Fresh sandstone			Fresh limestone, dolomite		Fresh granite

- Transmissivity: is the product of the average hydraulic conductivity and the thickness of the aquifer. Consequently, transmissivity is the rate of flow under unit hydraulic gradient through a cross-section of unit width over the whole saturated thickness of the aquifer (Kruseman and de Ridder, 1990), One can write transmissivity, T, in terms of aquifer thickness and hydraulic conductivity by

- $T=Kb$

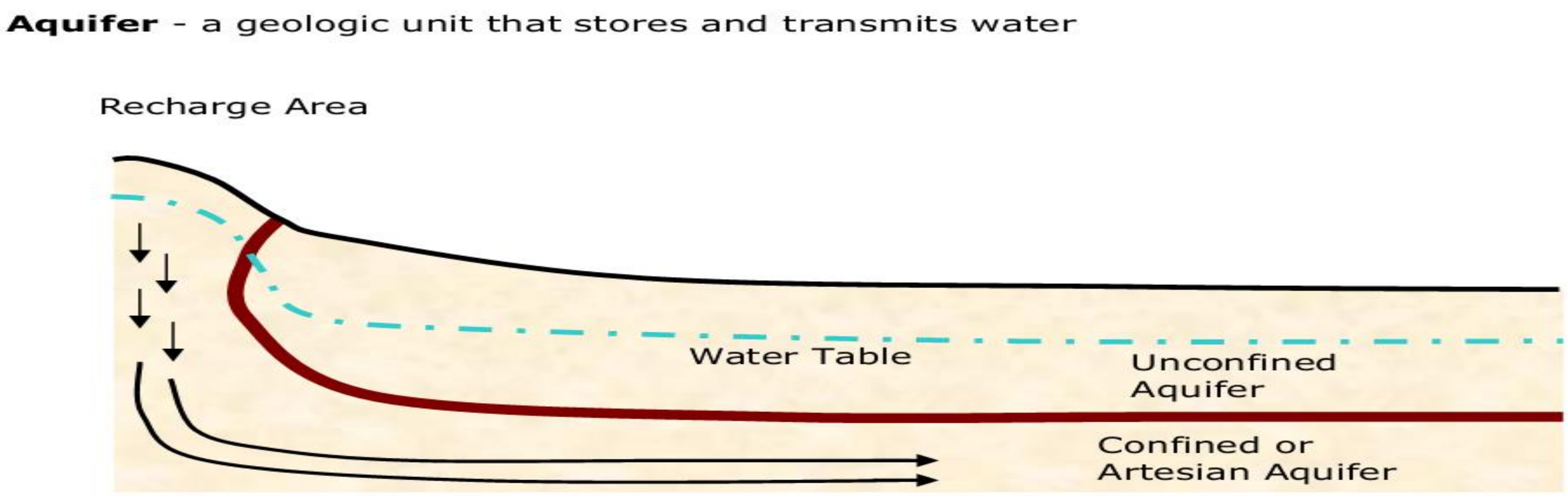
- Where:
- T is transmissivity (L^2/T; ft^2/d ; m^2/d
- b is saturated thickness of the aquifer (L; ft or m)
- k is hydraulic conductivity (L/T; ft/d or m/d)

Physical hydrogeology

- The occurrence of groundwater within the Earth's crust and the emergence of springs at the ground surface are determined by
- the lithology of geological materials
- regional geological structure
- geomorphology of landforms
- and the availability of recharge sources.

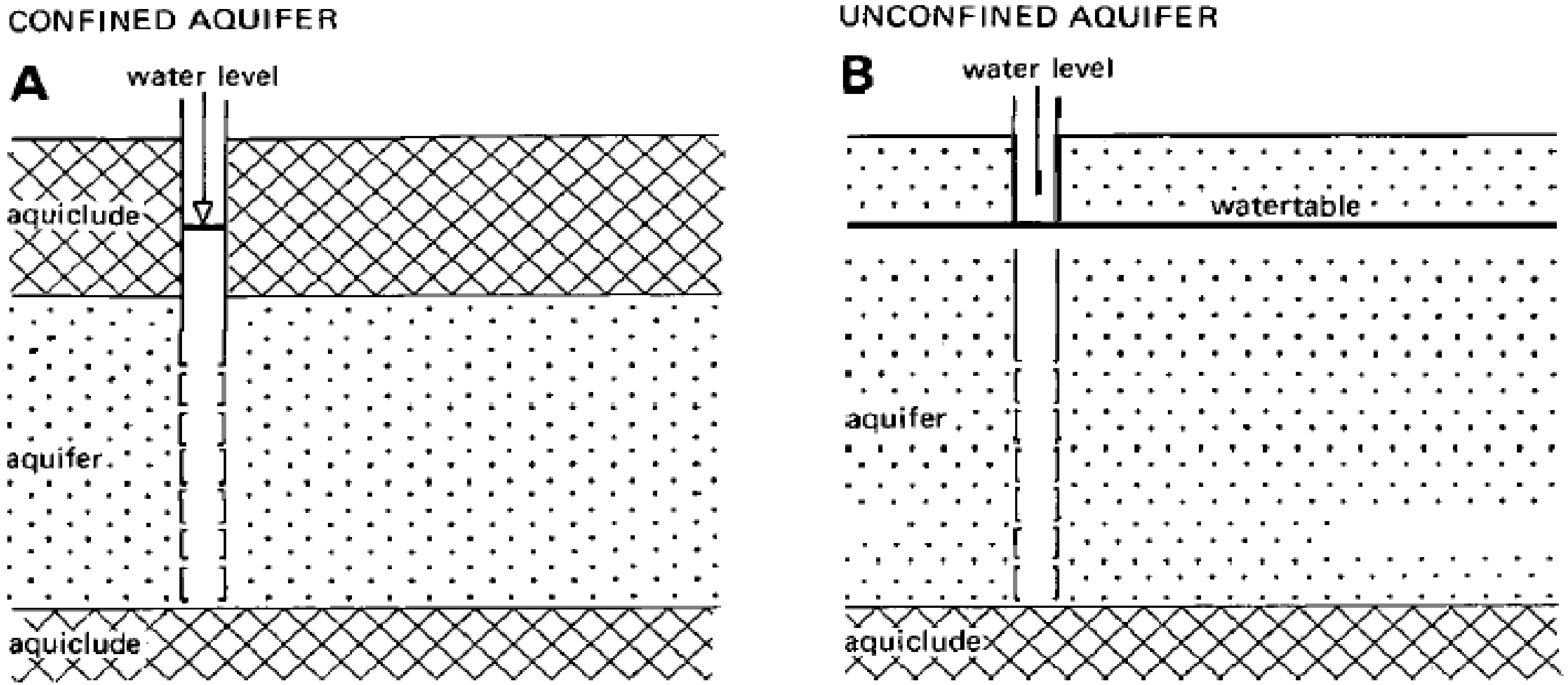
The infiltration of rainfall to the water table and the flow of groundwater in an aquifer towards a discharge area are governed by physical laws that describe changes in energy of the groundwater

Aquifer types



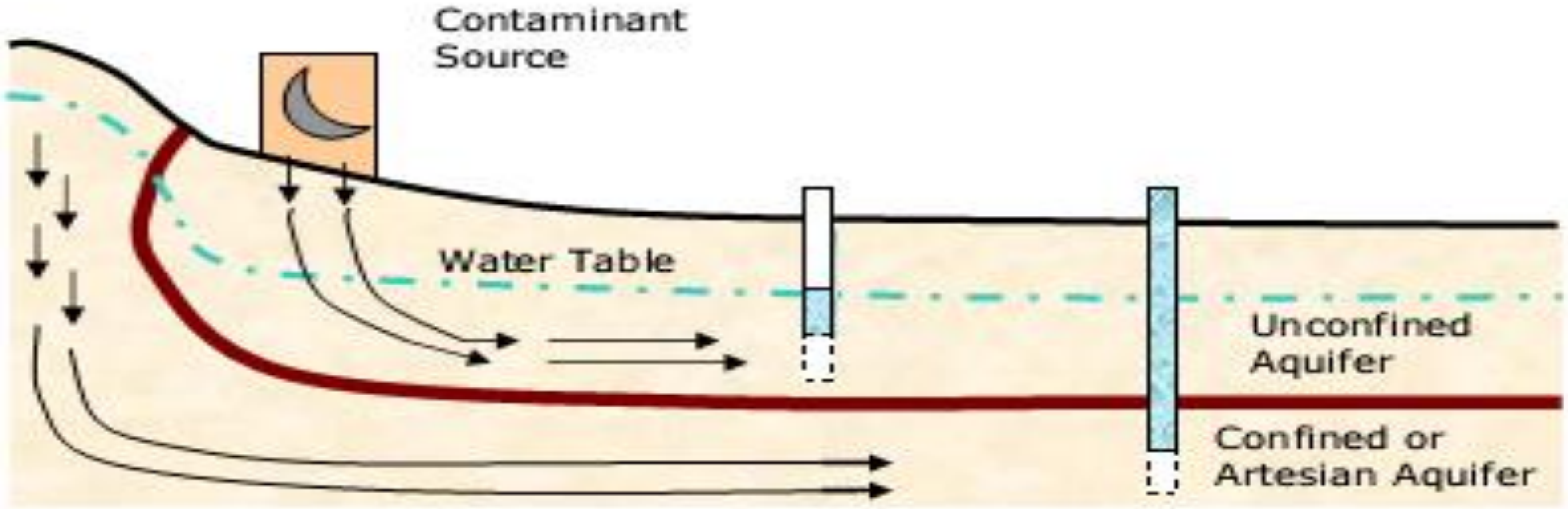
- Unconfined aquifer : An unconfined aquifer (Figure 7), also known as a water table aquifer, is bounded below by an aquiclude, but is not restricted by any confining layer above it. Its upper boundary is the water table, which is free to rise and fall. Water in a well penetrating an unconfined aquifer is at atmospheric pressure and does not rise above the water table.

- Confined aquifer : A confined aquifer (Figure 8) is bounded above and below by an aquiclude. In a confined aquifer, the pressure of the water is usually higher than that of the atmosphere, so that if a well taps the aquifer, the water in it stands above the top of the aquifer, or even above the ground surface. We then speak of a free-flowing or artesian well.



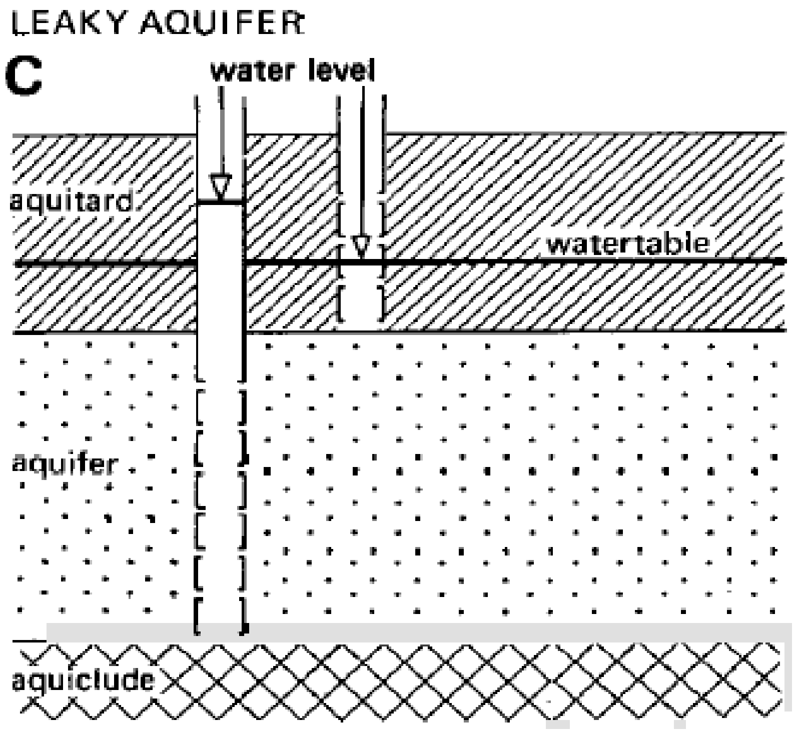
In confined vs. unconfined aquifers

- Although unconfined aquifers are used for water supply, they are often contaminated by wastes and chemicals at the surface.
- Confined aquifers are less likely to be contaminated and thereby provide supplies of good quality.
- Mechanisms of transport are advection and dispersion.
- There can be chemical interactions in aqueous phase or between the water and solid media
- Aquifer contamination

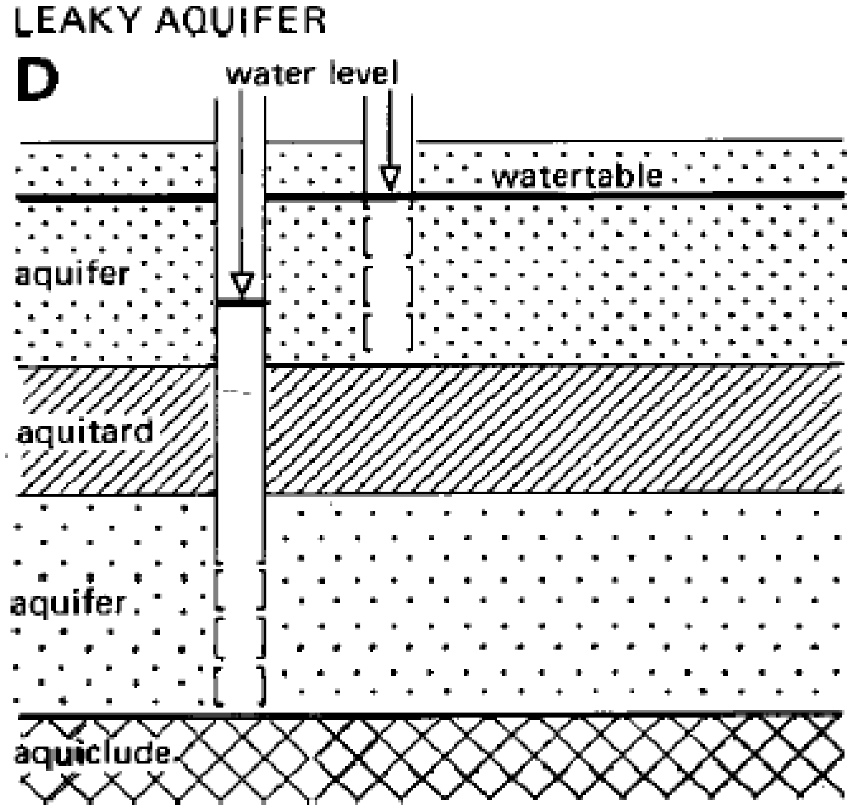


• Semi- confined aquifer

Semi- confined aquifer or leaky aquifer is a completely saturated aquifer that is bounded above by a semi- pervious layer and below by a layer that is either impervious. A semi- pervious layer is defined as a layer which has a low permeability. Lowering of the piezometric head in a leaky aquifer, for example by pumping, will generate a vertical flow of water from the semi-pervious layer into the pumped aquifer. For the detection of water movement in this type of aquifer, piezometers should be installed not only in the aquifer itself, but also in the upper semi-pervious layer and in the lower semi-pervious layer.



- **Semi- unconfined aquifer**
- If the hydraulic conductivity of the fine grained layer in a semi-confined aquifer is to great that the horizontal flow component in the covering layer cannot be ignored, then such an aquifer is intermediate between the traditional semi-confined aquifer and the unconfined aquifer and may be called a semi-unconfined aquifer.



Storage coefficient and specific yield

- Storage coefficient and specific yield are both defined as the volume of water released or stored per unit surface area of the aquifer per unit change in the component of head normal to that surface. Both are designated by the symbol S and are dimensionless. The storage coefficient refers only to the confined parts of an aquifer and depends on the elasticity of the aquifer material and the fluid. It has order of magnitude of 0.0001- 0.000001.
- The specific yield refers to the unconfined parts of an aquifer. In practice, it may be considered to equal the effective porosity or drainable pore space because in unconfined aquifer the effects of the elasticity of aquifer material and fluid are generally negligible. The specific yield may be in the order of 0.01-0.1.

Hydraulic resistance

The hydraulic resistance, also called reciprocal leakage coefficient or resistance against vertical flow, is a property of semi- confined aquifer. It is the ratio of the saturated thickness of the semi-pervious layer D' and the hydraulic conductivity of the semi-pervious layer for vertical flow k', hence D'/ k'. It characterizes the resistance of the semi-pervious layer to upward or downward leakage. It is designated by the symbol c and has the reduced dimension of time (expressed in day)

Leakage factor

The leakage factor $L = \sqrt{kDc}$ determines the distribution of the leakage into the semi- confined aquifer. In other words, it determines the origin of the water withdrawn from a well tapping the aquifer. High values of L indicate a great resistance of the semi-pervious strata to flow, as compared with the resistance of the aquifer itself. In that case the influence of leakage will be small. The factor L has the dimension of length and it is expressed in meters.

- **Drainage factor**

The drainage factor $B = \sqrt{(kD/\alpha Sy})$, which is encountered in unconfined aquifers with delayed yield can be compared with the leakage factor in semi-confined aquifers although it is defined in a different way. Large values of B indicate a fast drainage. The drainage factor has the dimension of length and is, expressed in meters.

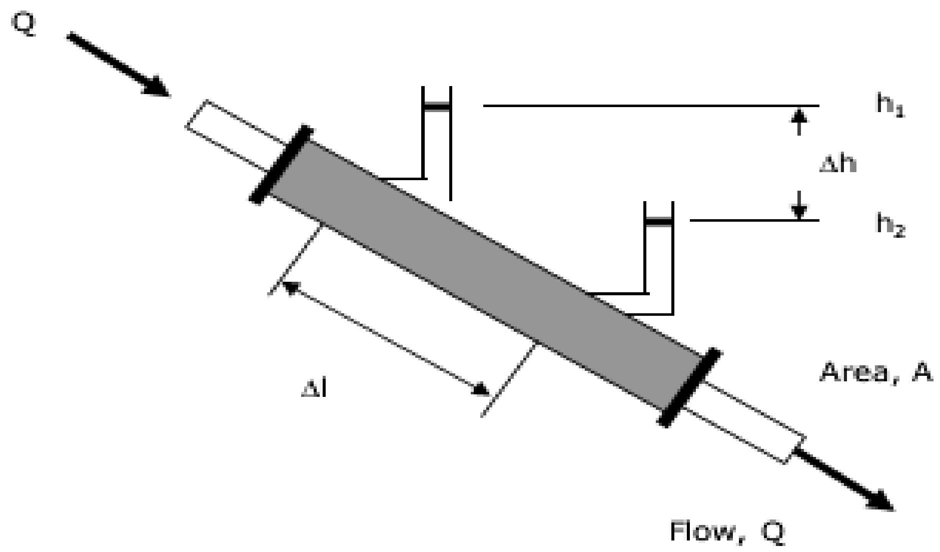
Darcy's law and hydraulic conductivity

Water contained within the interconnected voids of soils and rocks is capable of moving, and the ability of a rock to store and transmit water constitutes its hydraulic properties. At the Centre of the laws that govern the behavior of groundwater flow in saturated material is that formulated empirically by the French municipal engineer for Dijon, Henry Darcy, in 1856. Using the type of experimental apparatus shown in Fig. below, Darcy studied the flow of water through porous material contained in a column and found that the total flow, Q, is proportional to both the difference in water level, h1–h2 , measured in manometer tubes at either end of the column and the cross-sectional area of flow, A, and inversely proportional to the column length, L. When combined with the constant of proportionality, K, Darcy obtained:

$$Q = KA\frac{(h_1 - h_2)}{L}$$

In general terms, Darcy's law, as it is known, can be written as:

$$Q = -KA\frac{dh}{dl}$$



groundwater flow

Principles of groundwater flow

- The flow of groundwater is controlled by the laws of physics and thermodynamics
- There are three outside acting on groundwater
- Gravity which pulls water downward
- External pressure which represent the combination of atmospheric pressure and the weigh of overlying, water creates pressure in the zone of saturation
- Third molecular attraction

adhere to solid surface

These two lead to phenomenon of capillarity

surface tension when the water exposed to air

- Darcy low
- The flow through a pipe filled with sand is proportional to the decrease in hydraulic head divided by the length of the pipe.
- The hydraulic head is the sum of the pressure head and the elevation head. Expressed in terms of hydraulic head, Darcy's law is

$$Q= - KA\frac{dh}{dl}$$

- Darcy law is in one dimensional form

GROUNDWATER VELOCITY AND FLOW

- The velocity of groundwater flow (v), as defined by Darcy's law, is the product of the hydraulic conductivity (K) and the hydraulic gradient (i):

$$v= k^*i$$

- the volumetric flow rate in Darcy's law (Q) is the product of Darcy's velocity and the total cross-sectional area of flow (A):

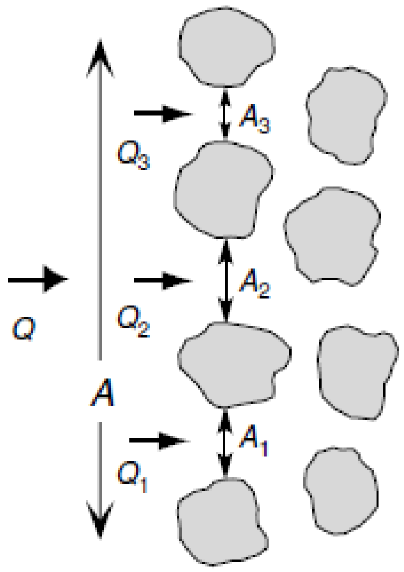
$$Q = V * A$$

Since the flow takes place only through voids, the actual cross-sectional area of flow is the sum of the individual cross-sectional areas of voids:

$$Av = A1 + A2 + A3$$

- The total volumetric flow is the sum of the individual flows:

$$Q = Q1 + Q2 + Q3$$



Schematic presentation of volumetric flow rates and the cross-sectional areas of groundwater flow through intergranular porous media.

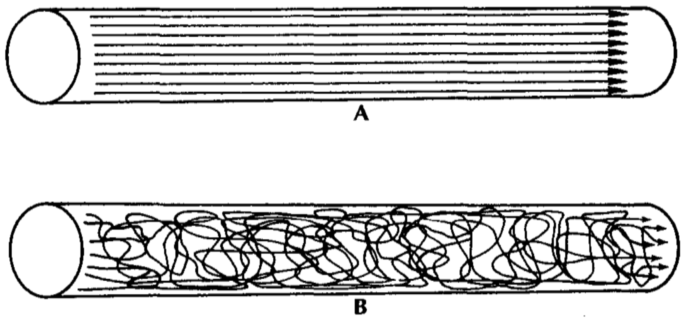
The applicability of Darcy's law

- When fluid at rest starts to move, it must overcome resistance to flow due to the viscosity of the fluid.
- Laminar flow because of low energy level, water flow in smooth lines
- When velocity increase

The moving fluid gains

Kinetic energy resist the viscous forces, the fluid particle begin to rush fast in an erratic fashion the result is turbulent flow

Darcy's law is valid for laminar flow, which appears at very low velocities where water molecules move along almost smooth and linear paths



- Darcy's law is not valid for turbulent flow. The flow regime is expressed through the Reynolds number, Re, which is given as,

$$Re = \frac{\rho v d}{\mu} \quad \text{..........5}$$

- where v is the fluid (groundwater) velocity;
- d is the dimension of the water conduit;
- ρ is the density of fluid;
- μ is the viscosity of fluid (g/sm-s);
- and finally, μ/ρ is the kinematic viscosity of the fluid. The following criteria is valid for deciding whether the flow is laminar or turbulent

turbulence in ground water flow is difficult to detect.

Darcy's law is valid when the resistivity forces of viscosity predominate. Reynolds number is less than 1 to 10

Under most natural groundwater conditions, the velocity is sufficiently low for Darcy's law to be valid. Exceptions might be areas of rock with large openings such as solution openings and basalt flows.

- Example

a sand aquifer has a median grain diameter of 0.05 cm. for pure water at 15 °C, what is the greatest velocity for which Darcy's law is valid?

$$\rho = 0.999 * 10^3 \text{ kg}/m^3$$

$$\mu = 1.14 * 10^{-2} \text{ g/s.cm}$$

Convert units to kg, m, s

d= 0,05cm*0.01m/cm = 0.0005m

$\mu = 1.14 * 10^{-2}$ g/s.cm *0.001kg/g*100 cm/m

= $\mu = 1.14 * 10^{-3}$ kg/s.m

- By rearrange eq 5 for velocity

$$Re = \frac{\rho v d}{\mu}$$

$$v = \frac{R\mu}{\rho d}$$ if R cannot exceed 1, the max velocity :

$$v = \frac{1 \times 1.14 \times 10^{-3} kg/s.m}{0.999 \times 10^{3} kg/m^{3} \times 0.0005 m}$$

= 0.0023 m/s

Darcy's law will be valid for discharge velocities equal to or less than 0.0023 m/s

- Example
- A sand aquifer has a median pore diameter of 0.232 mm. the density is

And the fluid viscosity is

$$1.003 * 10^3 \text{ kg}/m^3$$

$$1.15 * 10^{-3} \text{ N.s}/m^2$$

If the flow rate is 0.0067 m/s, is Darcy's law valid ? What is the reason for your answer ?