Groundwater Flow

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Important Terminology

Well yield: is a measure how much water can be withdrawn from the well over a period of time and measured in m^3/hr or m^3/day.

Static water level: is the level of water in the well when no water is being taken out.

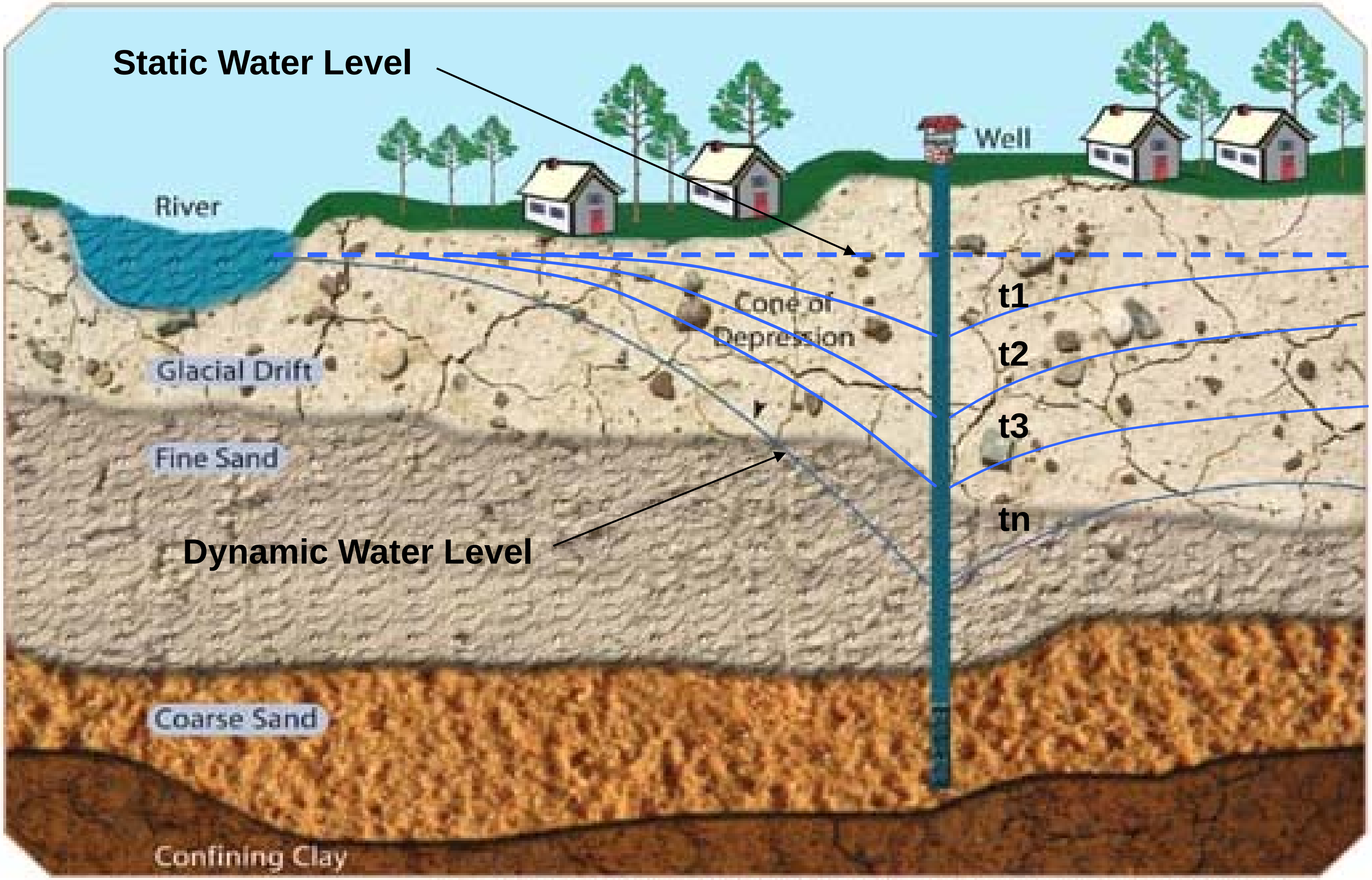
Dynamic Water level: is the level when water is being drawn from the well. The cone of depression occurs during pumping when water flows from all directions toward the pump.

Aquifer Terminology:

Aquiclude:
A water-bearing layer of rock or sediment that is incapable of transmitting water.

Aquifer:
A water-bearing layer of rock or sediment capable of transmitting significant quantities of water.

Aquitard:
A water-bearing layer of rock or sediment that transmits small quantities of water in relation to Aquifer.



Adapted from *Groundwater and Wells, Second Edition* by Fletcher G. Driscoll, Ph.D.

A cone of depression expanding beneath a riverbed creates a hydraulic gradient between the aquifer and river. This can result in induced recharge to the aquifer from the river.

Terminology….Con't

Confined Aquifer:
An aquifer whose upper and lower boundaries are defined by aquicludes.

Drawdown:
the amount of water level decline in a well due to pumping. Usually measured relative to static (non-pumping) conditions.

Unconfined Aquifer:
An aquifer in which the water table forms the upper boundary.

Potentiometric Surface: an imaginary surface to which water would rise in wells from a given point in confined aquifer. The **water table** is a particular potentiometric surface for unconfine aquifers.

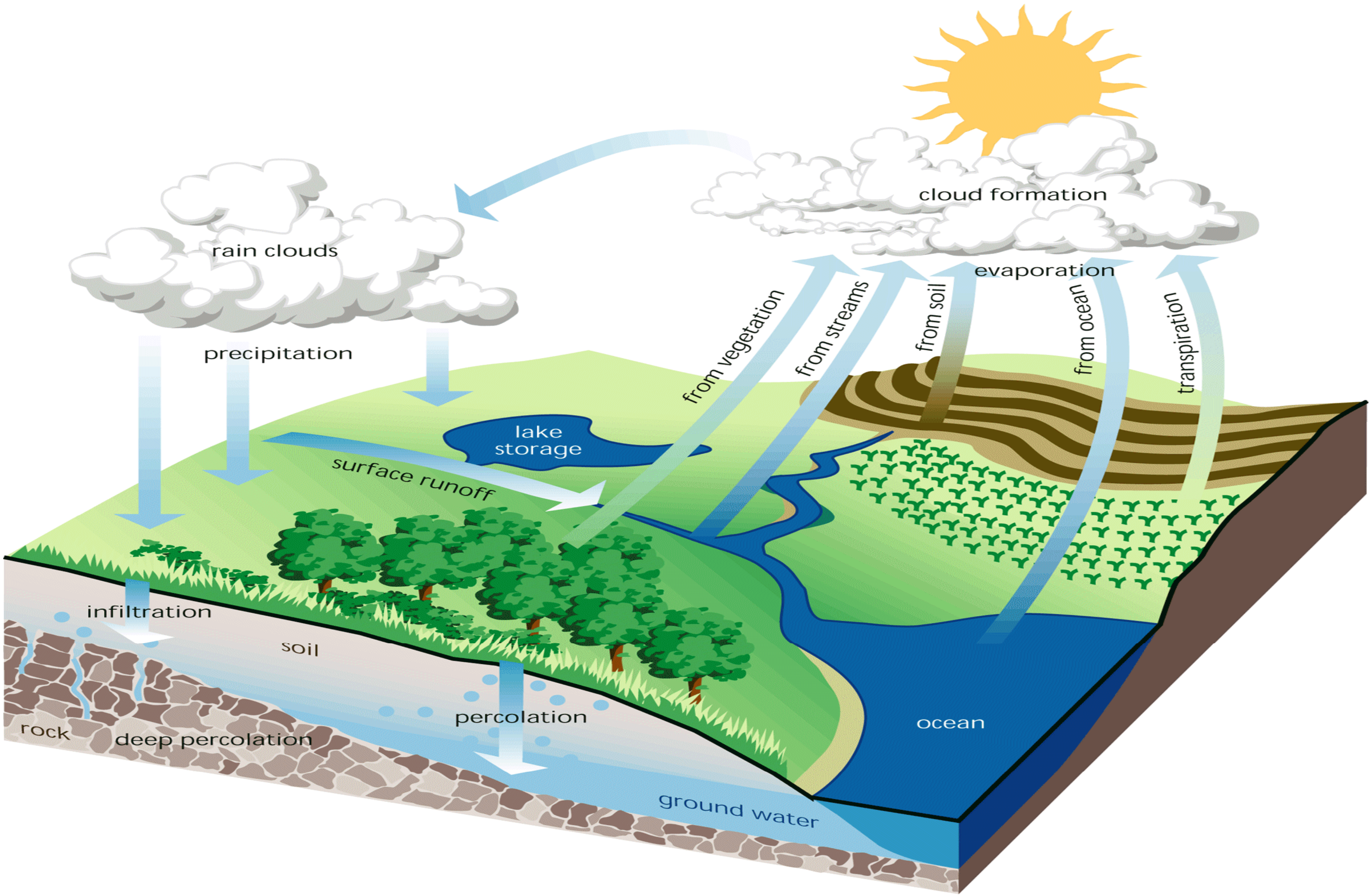


Figure 1 Schematic representation of the hydrologic cycle

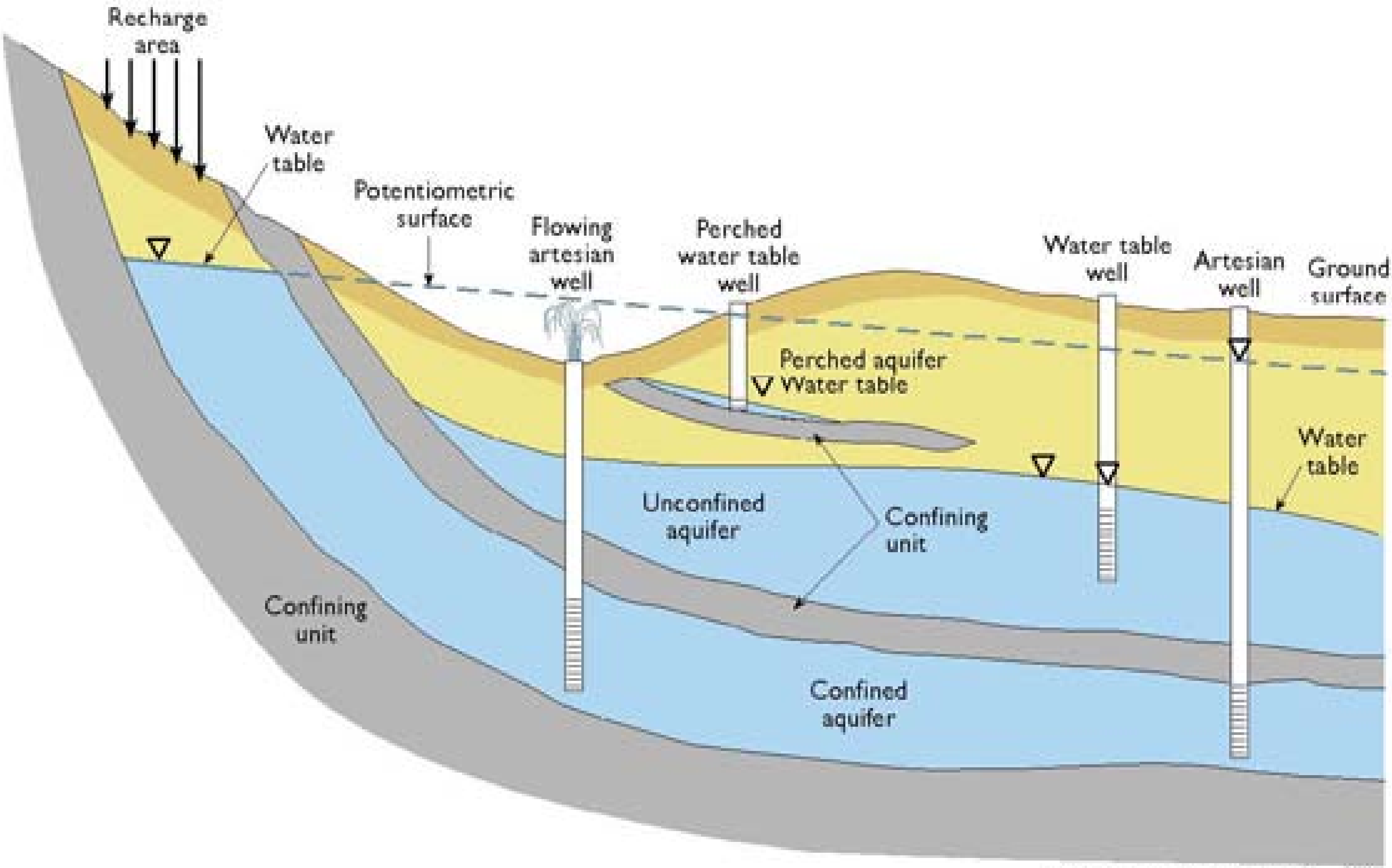


Figure 2 Schematic cross-section of aquifer types

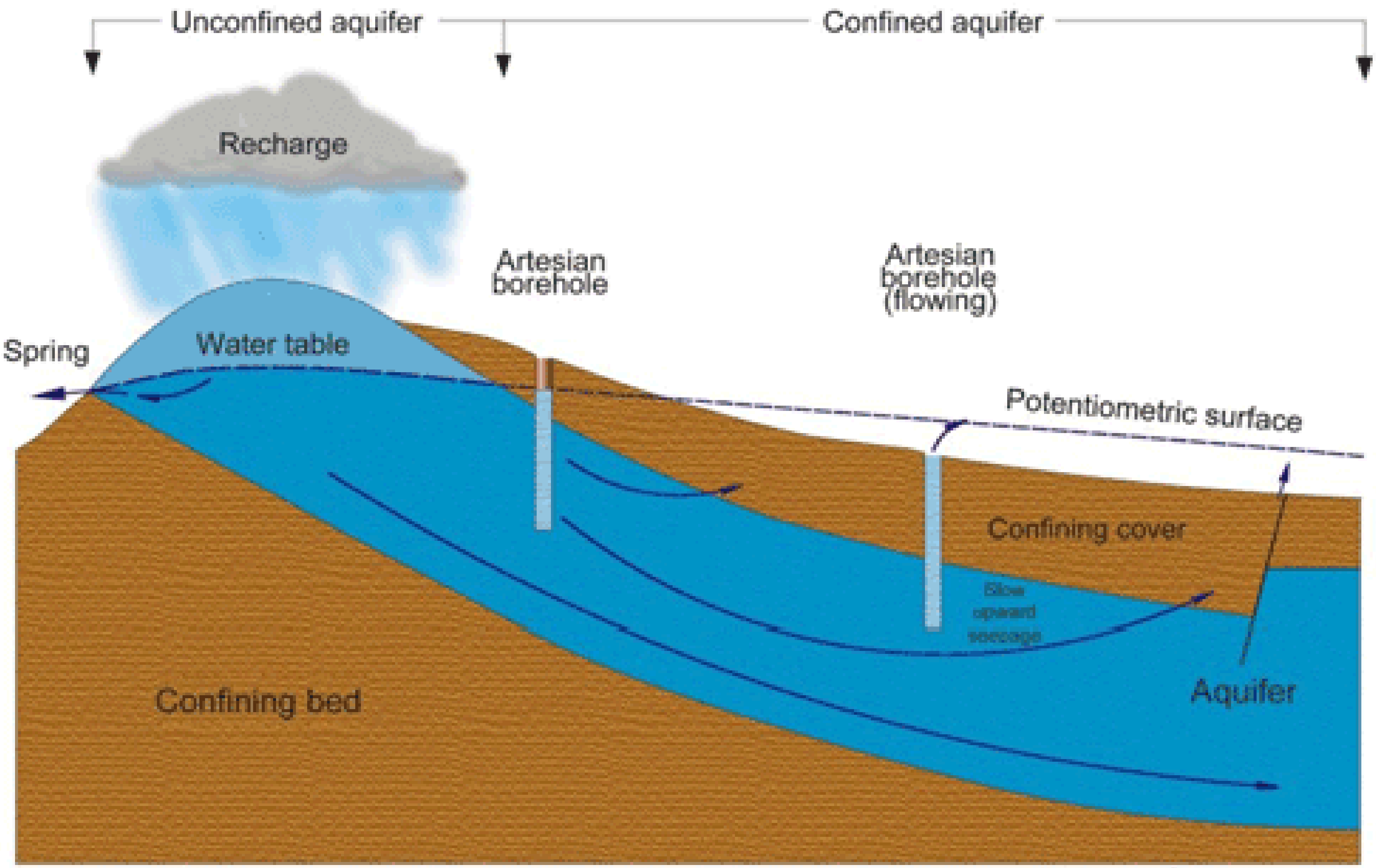


Figure 3 Water table and Piezometric Surface

Aquifer Properties

1. **Porosity**

Porosity (n) is the percentage of rock or soil that is void of material. The larger the pore space or the greater their number, the higher the porosity and the larger the water-holding capacity. It is defined mathematically by the equation:

$$n = \frac{V_v}{V} x\, 100$$

where,

n **is the porosity (percentage)**

Vv is the volume of void space in a unit volume of earth materials (L3, cm3 or m3)

V is the unit volume of earth material, including both voids and solids (L3, cm3 or m3)

- **In sediments or sedimentary rocks the porosity depends on *grain size, the shape of the grains, the degree of sorting and the degree of cementation*. In rocks, the porosity depends upon the *extent, spacing and pattern of cracks and fractures*.**

- **Well-rounded coarse-grained sediments *usually have higher porosity* than fine-grained sediments, because the grain don’t fit together well (see Figure 4)**

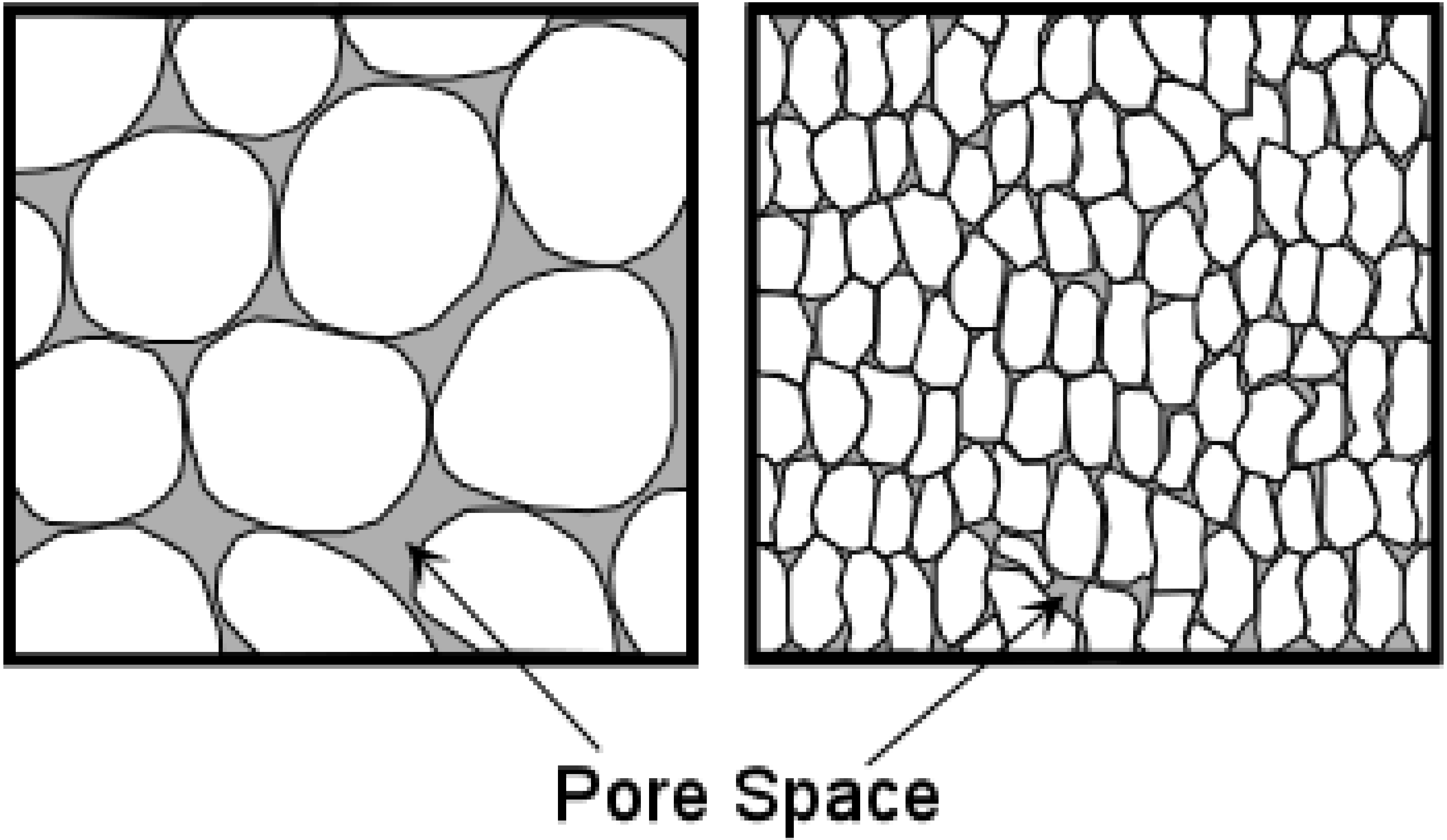


Figure 4 Porosity of well-rounded coarse sediments vs. fine grained sediments

- Poorly sorted sediments (sediments contains a mixture of grain sizes) ***usually have lower porosity*** because the fine-grained fragments tend to fill the open spaces (see Figure 5).

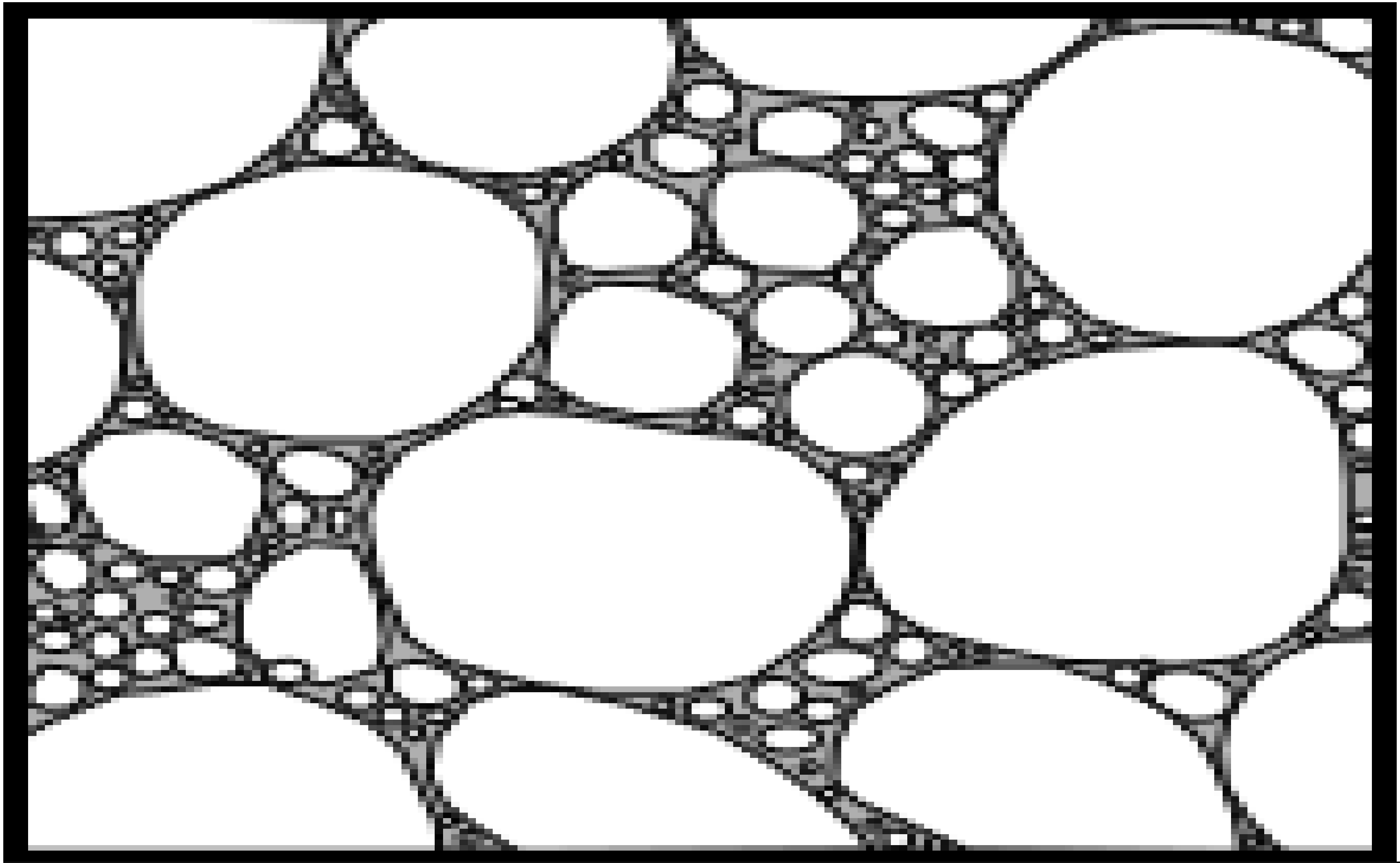


Figure 5 Poorly sorted sediments

- **Since cements tend to fill in the pore space, *highly cemented sedimentary rocks have lower porosity* (see Figure 6).**

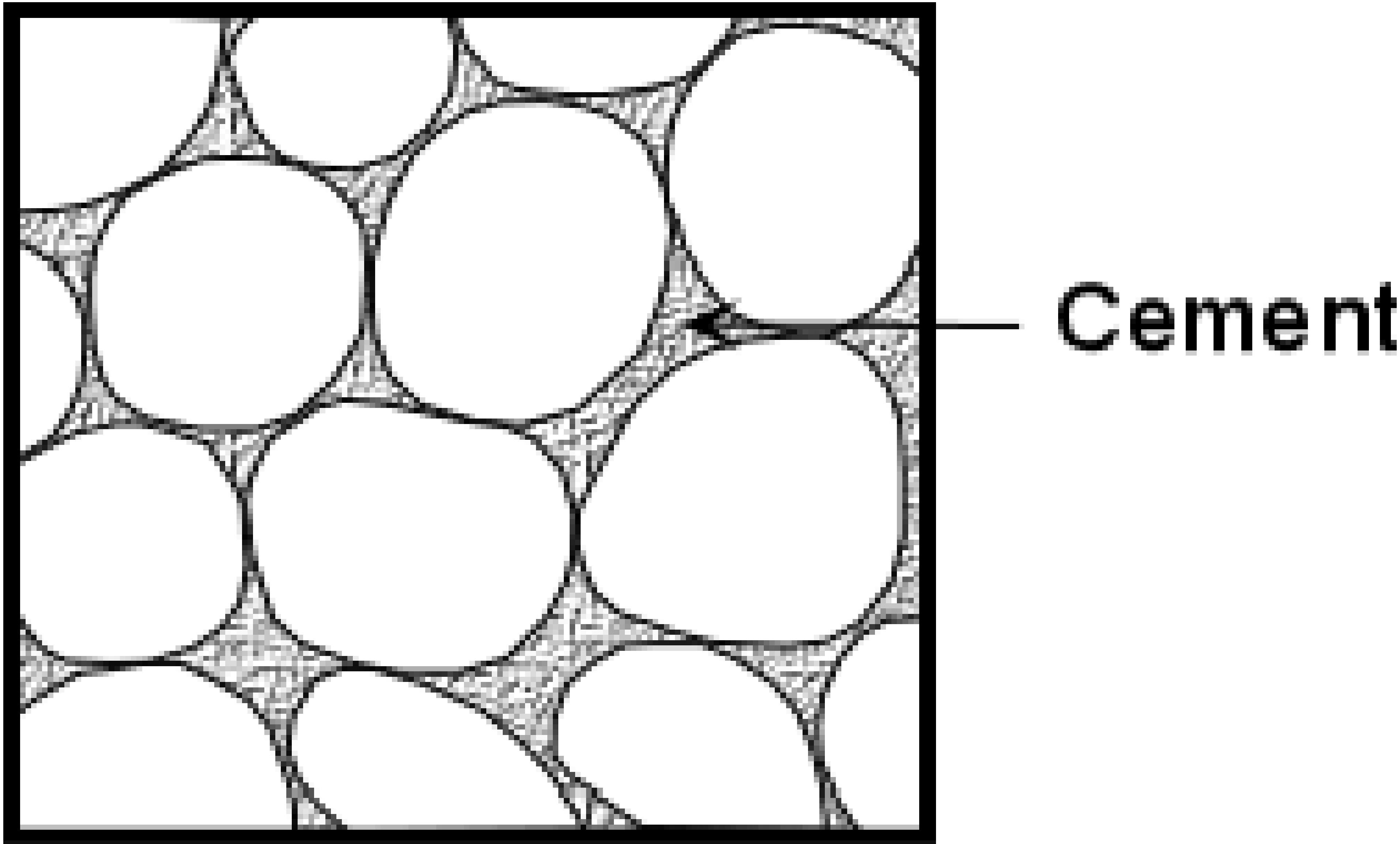


Figure 6 Highly cemented sedimentary rocks

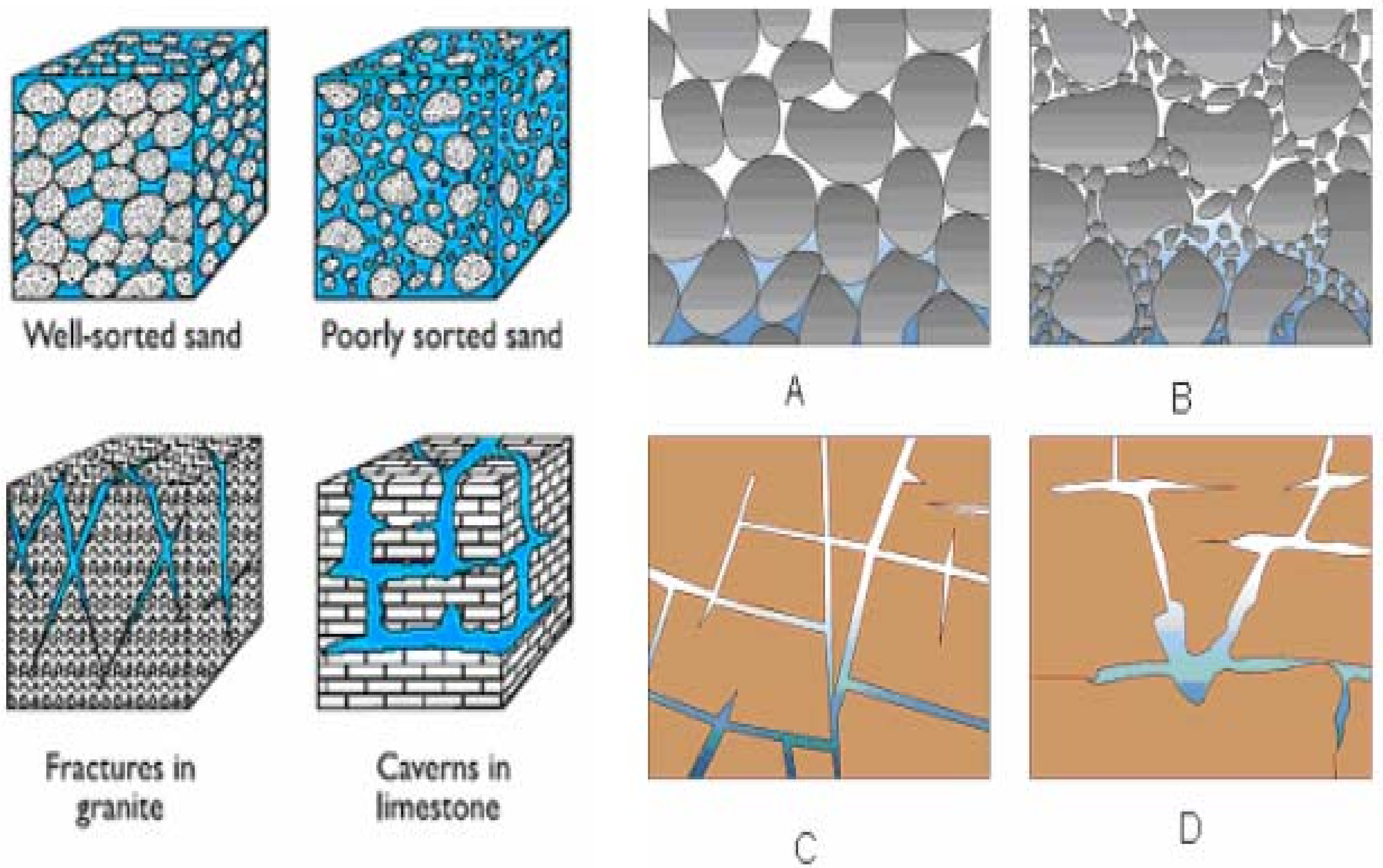


Figure 8 Relation between texture and porosity **A.** Well –sorted sand having high porosity; **B.** Poorly- sorted sand having low porosity; **C.** Fractured crystalline rocks (granite); **D.** Soluble rock-forming material (limestone).

- **Porosity can range from *zero to more than 60%.***
- **Recently deposited sediments *have higher porosity*.**
- **Dense crystalline rock or highly compacted soft rocks such as shale *have lower porosity.***

- It is worth distinguishing between ***Intergranular or matrix or primary porosity*** is the porosity provided by small spaces between adjacent grains of the rock, and ***secondary porosity or Fracture porosity*** is the porosity provided by discrete rock mass discontinuities (faults, joints and fractures)
- Table 1 lists representative porosity ranges from various geologic materials

Table 1 Range of values of porosity

Formation	n (%)
Unconsolidated deposits	
✓ Gravel	25 - 40
✓ Sand	25 - 50
✓ Silt	35 - 50
✓ Clay	
Rocks	
	40 - 70
✓ Fractured basalt	5 - 50
✓ Karst limestone	5 - 50
✓ Sandstone	5 - 30
✓ Limestone, dolomite	0 - 20
✓ Shale	0 – 10
✓ Fractured crystalline rock	0 - 10
✓ Dense crystalline rock	0 – 5

2. Specific Yield (Sy)

Specific yield (Sy) is the ratio of the volume of water that drains from a saturated rock owing to the attraction of gravity (or by pumping from wells) to the total volume of the saturated aquifer. It is defined mathematically by the equation:

$$S_y = \frac{Vw}{V} * 100$$

Where,

- ***Sy*** **is the Specific yield (percentage)**
- **Vw is the volume of water in a unit volume of earth materials (L3, cm3 or m3)**
- **V is the unit volume of earth material, including both voids and solids (L3, cm3 or m3)**

All the water stored in a water bearing stratum cannot be drained out by gravity or by pumping, because a portion of the water is rigidly held in the voids of the aquifer by molecular and surface tension forces (see table 2).

Table 2 Specific yield in percent

Formation	S_y (range)	S_y (average)
✓ Clay	0 - 5	2
✓ Sandy clay	3 - 12	7
✓ Silt	3 - 19	18
✓ Fine sand	10 - 28	21
✓ Medium sand	15 - 32	26
✓ Coarse sand	20 - 35	27
✓ Gravelly sand	20 - 35	25
✓ Fine gravel	21 - 35	25
✓ Medium gravel	13 - 26	23
✓ Coarse gravel	12 - 26	22

3. Coefficient of permeability (Hydraulic conductivity) (K)

Permeability is the ease with which water can flow in a soil mass or a rock. The coefficient of permeability (K) is equal to the discharge per unit area of soil mass under unit hydraulic gradient. Because the discharge per unit area is equal to the velocity, the coefficient of permeability has the dimension of the velocity [L/T]. it is usually expressed as cm/s, m/s, m/day, etc. The coefficient of permeability is also called hydraulic conductivity.

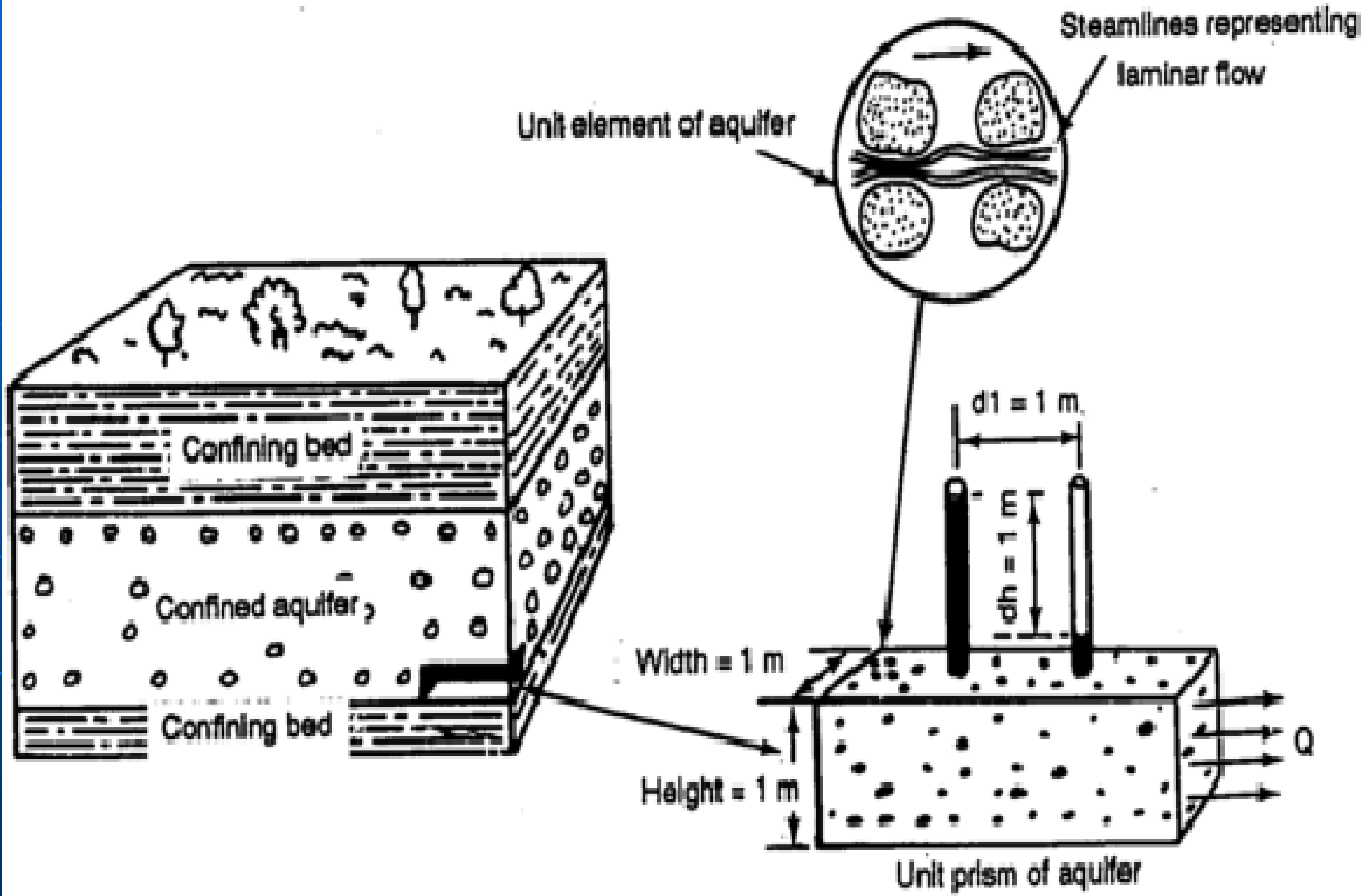


Figure 10 Hydraulic conductivity

- **The rate of groundwater flow is controlled by the two properties of the rock, *porosity and permeability.***

- ***Low porosity usually results in low permeability*, but *high porosity does not necessarily imply high permeability*. It is possible to have a highly porous rock with little or no interconnections between pores. A good example of a rock with high porosity and low permeability is a vesicular volcanic rock, where the bubbles that once contained gas give the rock a high porosity, but since these holes are not connected to one another the rock has low permeability.**

- **Typical values of hydraulic conductivity for unconsolidated and hard rocks are given in Table 3 respectively which are taken from Marsily [1986].**

Table 3 Hydraulic conductivity for unconsolidated and hard rocks

Medium	K (ms^{-1})
Unconsolidated deposits	
✓ Coarse gravel	$10^{-2} – 10^{-1}$
✓ Sands and gravels	$10^{-5} – 10^{-2}$
✓ Fine sands, silts	$10^{-9} – 10^{-5}$
✓ Clay, shale, glacial	$10^{-13} – 10^{-9}$
Hard Rocks	
✓ Dolomitic limestone	$10^{-5} – 10^{-3}$
✓ Weathered chalk	$10^{-5} – 10^{-3}$
✓ Unweathered chalk	$10^{-9} – 10^{-6}$
✓ Limestone	$10^{-9} – 10^{-5}$
✓ Sandstone	$10^{-10} – 10^{-4}$
✓ Granite, gneiss, compact basalt	$10^{-13} – 10^{-9}$

4. **Transmissivity (T)**

Transmissibility (T) is equal to the discharge rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient. Thus

$$T = Kb$$

where, *b* is the saturated thickness of the aquifer. b is equal to the *depth of a confined aquifer*. It is equal to the *average thickness* of the saturated zone of *an unconfined aquifer*.

- **Transmissibility is usually expressed as m2/s, or m3/day/m or litter/day/m.**

5. **Storage coefficient (S)**

- **Storage coefficient (S) is the volume of water released from storage, or taken into storage, per unit of aquifer storage area per unit change in head.**

- **The storage coefficient is also called *Storativity*.**

- **The storage coefficient is *a dimensionless* as it is the ratio of the volume of water released from original unit volume.**

- **The value of the storage coefficient usually lies between *1*10-5 – 1*10-3*, with an average value of 1*10-4.**

- **In *unconfined aquifers*, *Storativity is the same as the specific yield* of the aquifer.**

- **In confined aquifer, *Storativity is the result of compression of the aquifer and expansion of the confined water* when the head (pressure) is reduced during pumping.**

6. Specific Storage (Ss)

Specific Storage (Ss) is the storage coefficient per unit saturated thickness of the aquifer. Thus,

$$S_s = \frac{S}{b}$$

Where, **b** is the thickness of aquifer.

The specific storage is usually expressed as cm-1 or m-1.
For most aquifers, the specific storage is about 3*10-7 m-1.

Table 4 shows the values of specific storage for given values of aquifer compressibility assuming porosity equals to 15 %.

Table 4 Values of specific storage for given values of aquifer compressibility assuming porosity equal to 15 % (After Younger, 1993)

Typical Lithologies	Aquifer Compressibility (ms^2/kg)	Specific Storage (m^{-1})
Clay	10^{-6}	9.81×10^{-3}
Silt, fine sand	10^{-7}	9.82×10^{-4}
Medium sand, fine gravel	10^{-8}	9.87×10^{-5}
Coarse sand, medium gravel, highly fissured rock	10^{-9}	1.05×10^{-5}
Coarse gravel, moderately fissured rock	10^{-10}	1.63×10^{-6}
Unfissured rock	10^{-11}	7.46×10^{-7}

Heterogeneity and Anisotropy of Hydraulic Conductivity

- <u>Heterogeneity</u> is the change of a property in space.
- <u>Anisotropy</u> is the change of a property with the direction of measurement.
- If (K) is independent of position within a geological formation, then the formation is <u>homogenous</u>.
- If (K) is dependent on position within a geological formation, then the formation is <u>heterogeneous</u>.

- If (K) is independent of the direction of measurement, then the formation is **isotropic**.

- If (K) is dependent on the direction of measurement, then the formation is **anisotropic**.

- Note: Statistical distributions are used to provide a quantitative description of the degree of heterogeneity in a geological formation.

Process Governing Flow in Porous Media

The steady state flow of fluid through a porous media is governed by physical processes which are expressed mathematically by Darcy's Law, which expresses the relationship between the motive force applied to the fluid and the resulting discharge of fluid through the medium.

Darcy's Law for flow porous media

- The classic work on the flow of water through a porous medium was conducted by ***Henri Darcy in France in 1856***. Darcy's result is of fundamental importance and remains at the heart of almost all groundwater flow calculations.

- Darcy discovered that the ***discharge Q of water through a column of sand is proportional to the cross sectional area A of the sand column***, and to the ***difference in piezometric head between the ends of the column***, h1– h2, and ***inversely proportional to the length of the column L***. That is:

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

Thank You