SESSION # ONE

BASIC PRINCIPLES OF GROUNDWATER HYDROLOGY I

Dr. Amjad Aliewi
House of Water and Environment (HWE)

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1 Groundwater

- Groundwater is water that exists in the pore spaces and fractures in rock and sediment beneath the Earth's surface. It originates as a rainfall or snow, and then moves through the soil into the groundwater system, where it eventually makes its way back to the surface streams, lakes, or oceans.
  - Groundwater makes up about 1% of the water on the Earth (most water is in oceans)
  - But, groundwater makes up to 35 times the amount of water in lakes and streams.

- **Groundwater occurs everywhere beneath the Earth's surface, but is usually restricted to depth less than about 750 meters.**
- **The volume of groundwater is equivalent to a 55-meter thick layer spread out over the entire surface of the Earth.**
- **Ground water is our most important source of freshwater in the West Bank**

2 Origin of Groundwater

- Practically groundwater originates as surface water which will enter the ground surface as natural or artificial recharge.

- ***Connate Groundwater*** is a water in marine sediments at the time of deposition of sedimentary rocks.

- ***Magmatic Water*** (in or from Magma)

- ***Metamorphic Water*** (is or has been with rocks during their metamorphism)

- ***Meteoric Water*** (is or recently from the atmosphere)

3 Occurrence of Groundwater

- To understand the ways in which groundwater occurs, it is needed to think about the ground and the water properties.
- ***Porosity***, which is the property of a rock of possessing pores or voids.

  Saturated and unsaturated zones.
- ***Permeability***, which is the ease with which water can flow through the rock.
- ***Aquifer***, which is a geologic formation sufficiently porous to store water and permeable enough to allow water to flow through them in economic quantities.
- ***Storage coefficient***, which is the volume of water that an aquifer releases from or takes into storage per unit surface area of aquifer per unit change in the component of head normal to surface

4 Groundwater and Hydrological Cycle

- **The hydrological cycle is the most fundamental principle of hydrology.**

- **The driving force of the circulation is derived from the radiant energy received from the sun.**

- **Water *evaporates*. it travels into the air and becomes part of a cloud. It falls down to earth as *precipitation*. Then it evaporates again.**

- **Precipitation creates *runoff* that travels over the ground surface and helps to fill lakes and rivers.**

- It also *infiltrates* or *percolates* or moves downward through openings in the soil to replenish aquifers under the ground.
- Some places receive more precipitation than others, these areas are usually close to oceans or large bodies of water that allow more water to evaporate and form clouds. Other areas receive less. Often these areas are far from water or near mountains.
- As clouds move up and over mountains, the water vapor condenses to form precipitation and freezes.
- Figure 1 shows a schematic representation of the hydrologic cycle

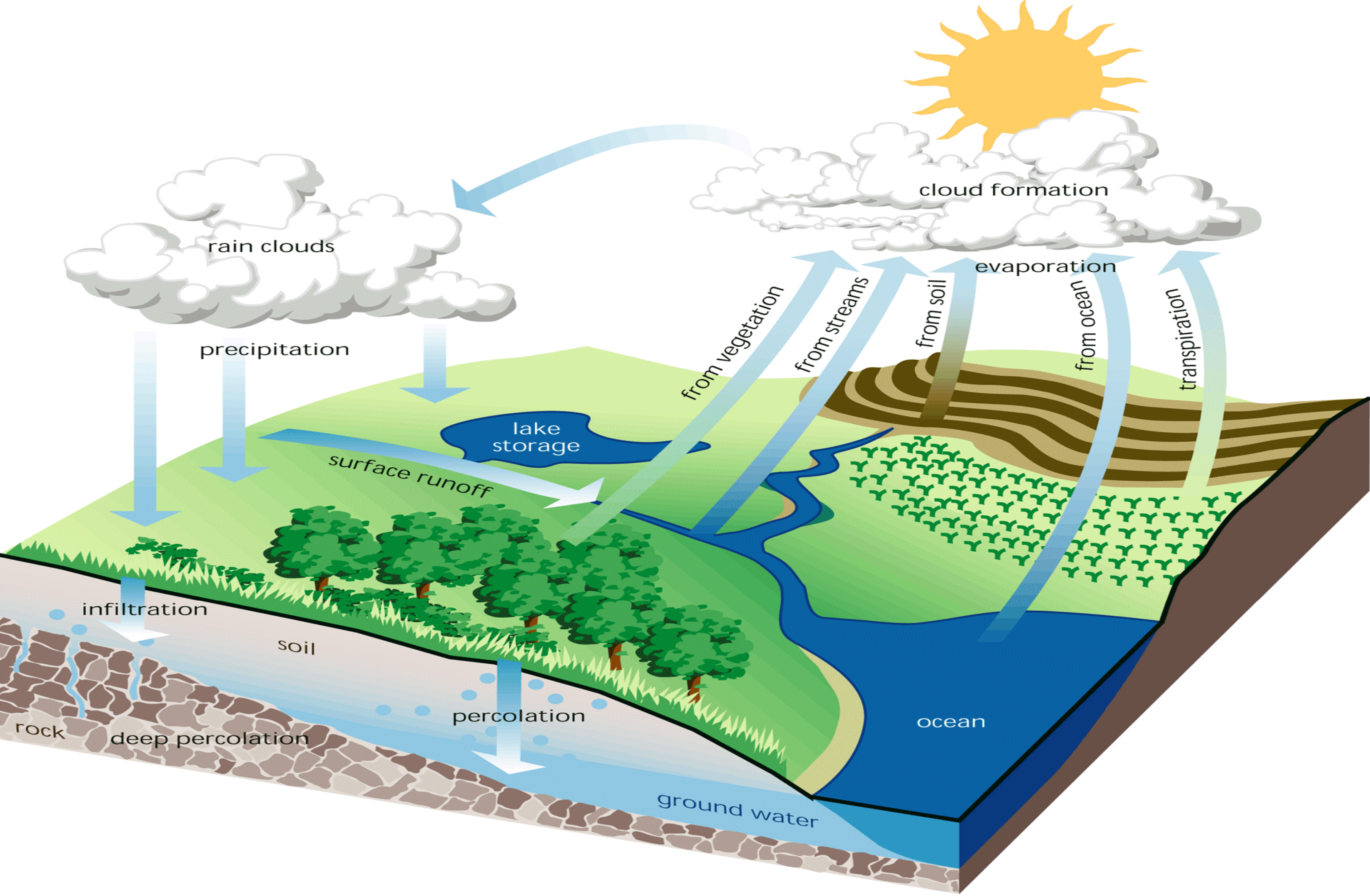


Figure 1 Schematic representation of the hydrologic cycle

5 Types of Geologic Formations and Aquifers

1. **Aquifer**

An aquifer is a layer of rock beneath the earth's surface which contains water which can be drawn off for human consumption. The rock can be non-consolidated materials such as sand or gravel. It can also be consolidated materials such as fractured limestone or sandstone. There are also aquifers of oil, natural gas and saltwater. There are three types of aquifers: *confined*, *unconfined*, or *perched*.

- ***Confined Aquifer (Artesian Aquifer)***

  A confined aquifer is one in which the water is being held under pressure which is greater than the atmospheric pressure. The water is between two *confining layers*. This forces the water to rise.

- ***Unconfined Aquifer (water table aquifer)***

  An unconfined aquifer is one in which the water is under atmospheric pressure and only partially filled. Here the only confining layer is on the bottom.

- ***Perched Aquifer***

  A perched aquifer is one where a small body of groundwater is separated from the main aquifer by a confining layer Notes:

- ***Confining layer*** **is a geological unit with low permeability.**

- ***Potentiometric surface*** **is a surface representative of the level to which water will rise in a well cased to the aquifer. If it is above the land surface a flowing artesian well will flow.**

Figure 2 illustrates aquifer types.

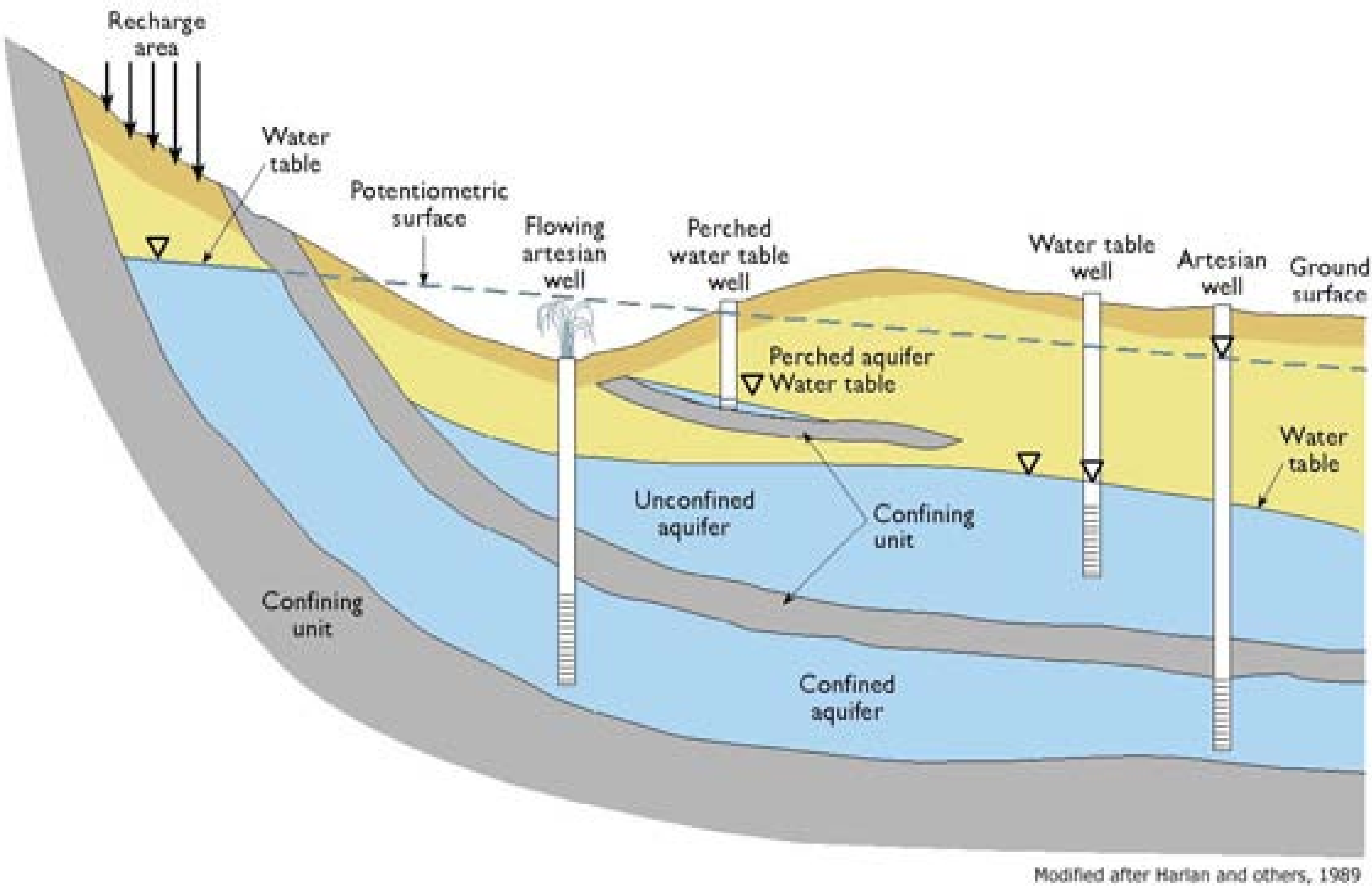


Figure 2 Schematic cross-section of aquifer types

2. **Aquitard**

An aquitard is a partly permeable geologic formation. ***It transmits water at such a slow rate that the yield is insufficient***. Pumping by wells is not possible. For example, sand lenses in a clay formation will form an aquitard

3. **Aquiclude**

An aquiclude is composed of rock or sediment that acts as a barrier to groundwater flow. Aquicludes are made up of ***low porosity and low permeability*** rock/sediment such as shale or clay.

4. **Aquifuge**

An aquifuge is a geologic formation which doesn't have interconnected pores. It is neither porous nor permeable. Thus ***it can neither store water nor transmit it***. Examples of aquifuge are rocks like basalt, granite, etc. without fissures.

6 Water Table and Piezometric Surface

1. **Water Table**

- Water table is the surface of water level in an unconfined aquifer at which the pressure is atmospheric.
- It is the level at which the water will stand in a well drilled in an unconfined aquifer.
- The water table fluctuates whenever there is a recharge or an outflow from the aquifer.
- In fact, the water table is constantly in motion adjusting its surface to achieve a balance between the recharge and the out flow.
- Generally, the water table follows the topographic features and is high below ridges and low below valleys.

2. **Perched Water Table**

- It occurs when a small water body is separated from the main groundwater body by a relatively small impermeable stratum.
- Wells drilled below the perched water table upto the small impervious stratum yield very small quantity of water and soon go dry.

3. Piezometric Surface

- The water in a confined aquifer is under pressure.
- When a well is drilled in a confined aquifer, the water level in it is above the top of aquifer.
- The piezometric surface is an imaginary surface to which the water level would rise if piezometers were inserted in the aquifer.
- Thus, it indicates the pressure of the water in the aquifer.
- Hence, a piezometric surface is the water table equivalent of the confined aquifer.

Figure 3 illustrates the concepts of water table and piezometric surface

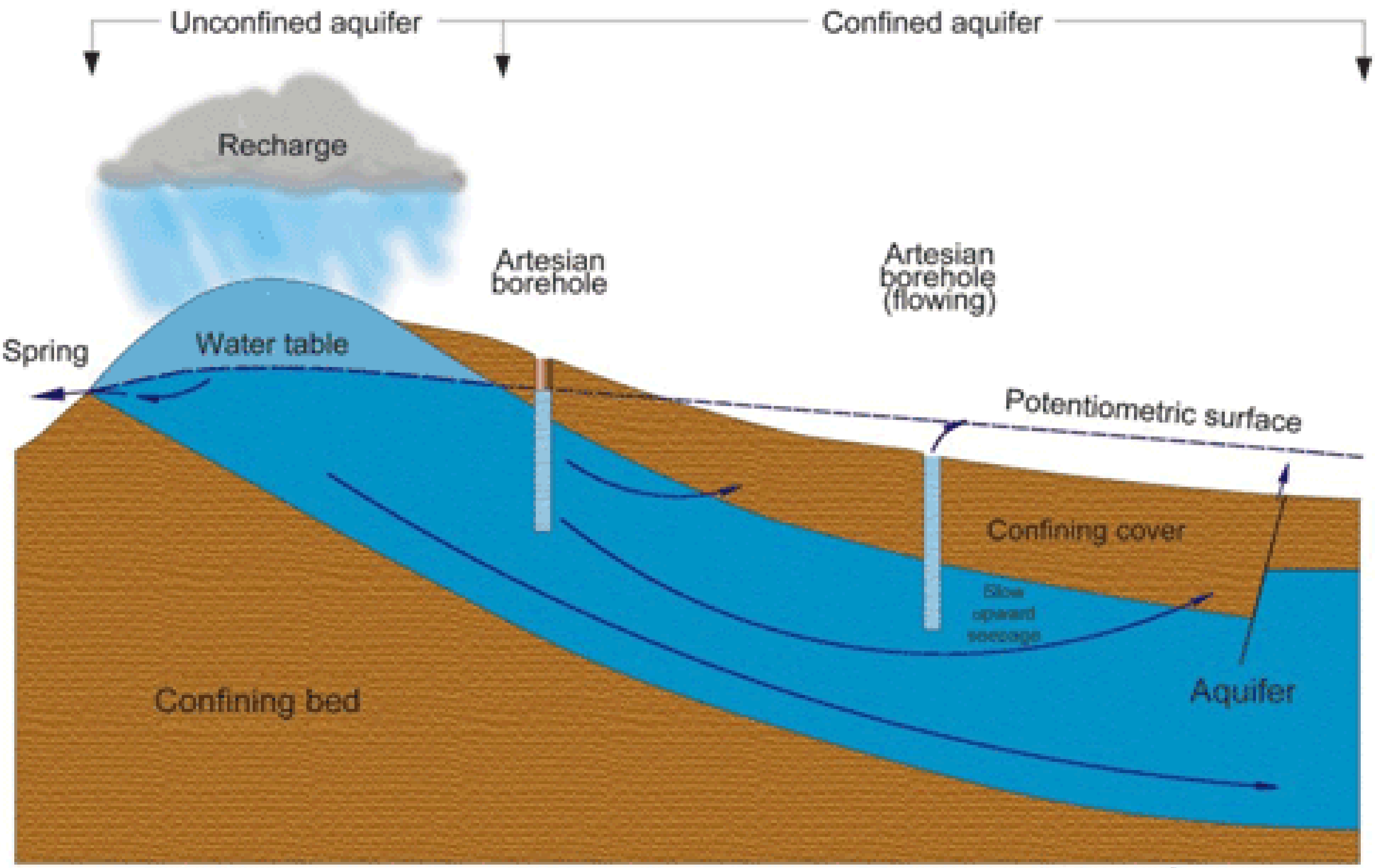


Figure 3 Water table and Piezometric Surface

7 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 *<u>grain size, the shape of the grains, the degree of sorting and the degree of cementation</u>*. In rocks, the porosity depends upon the *<u>extent, spacing and pattern of cracks and fractures</u>*.**

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

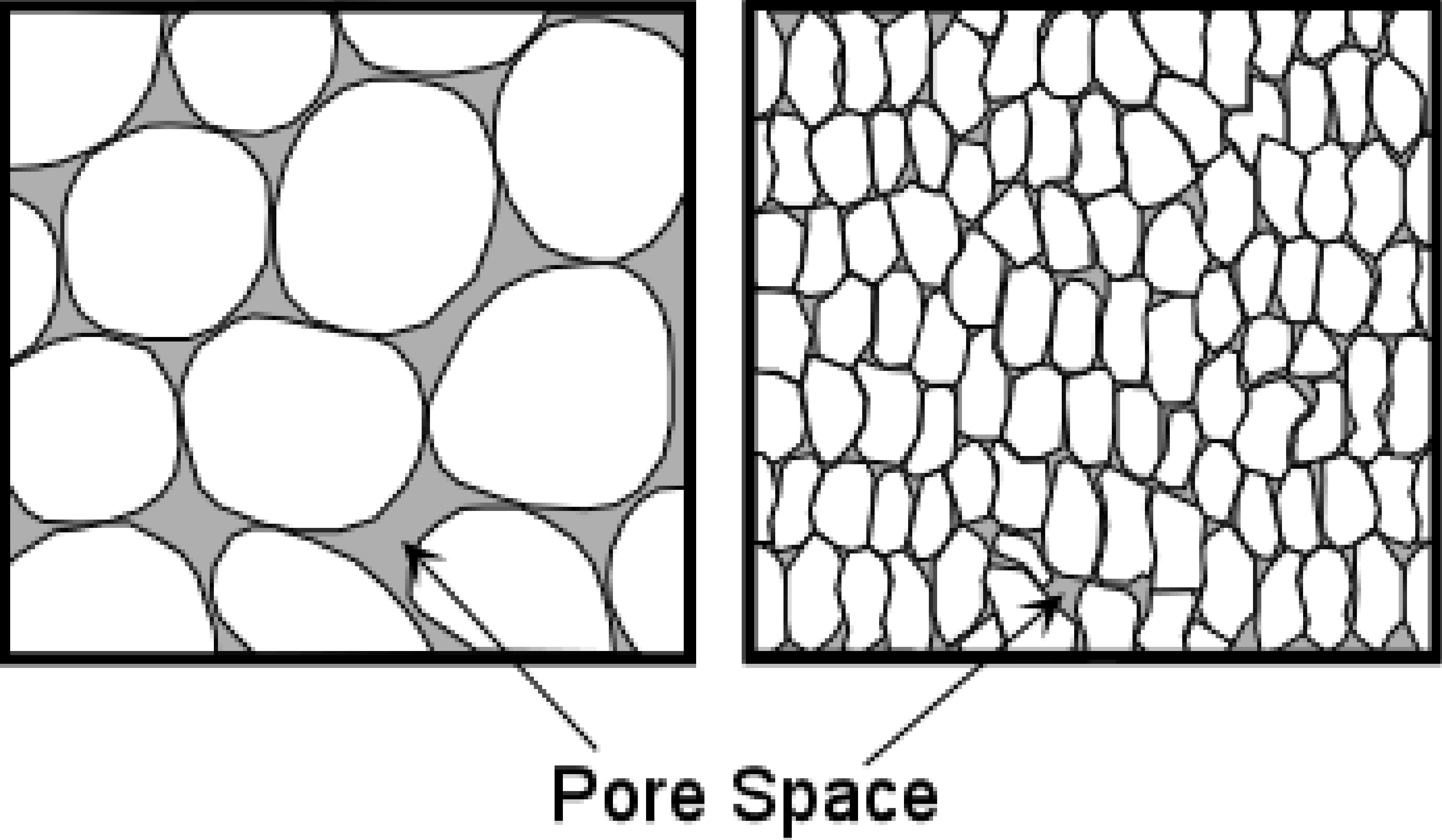


Figure 4 Porosity of well-rounded coarse sediments vs. fine grained sediments

- **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).**

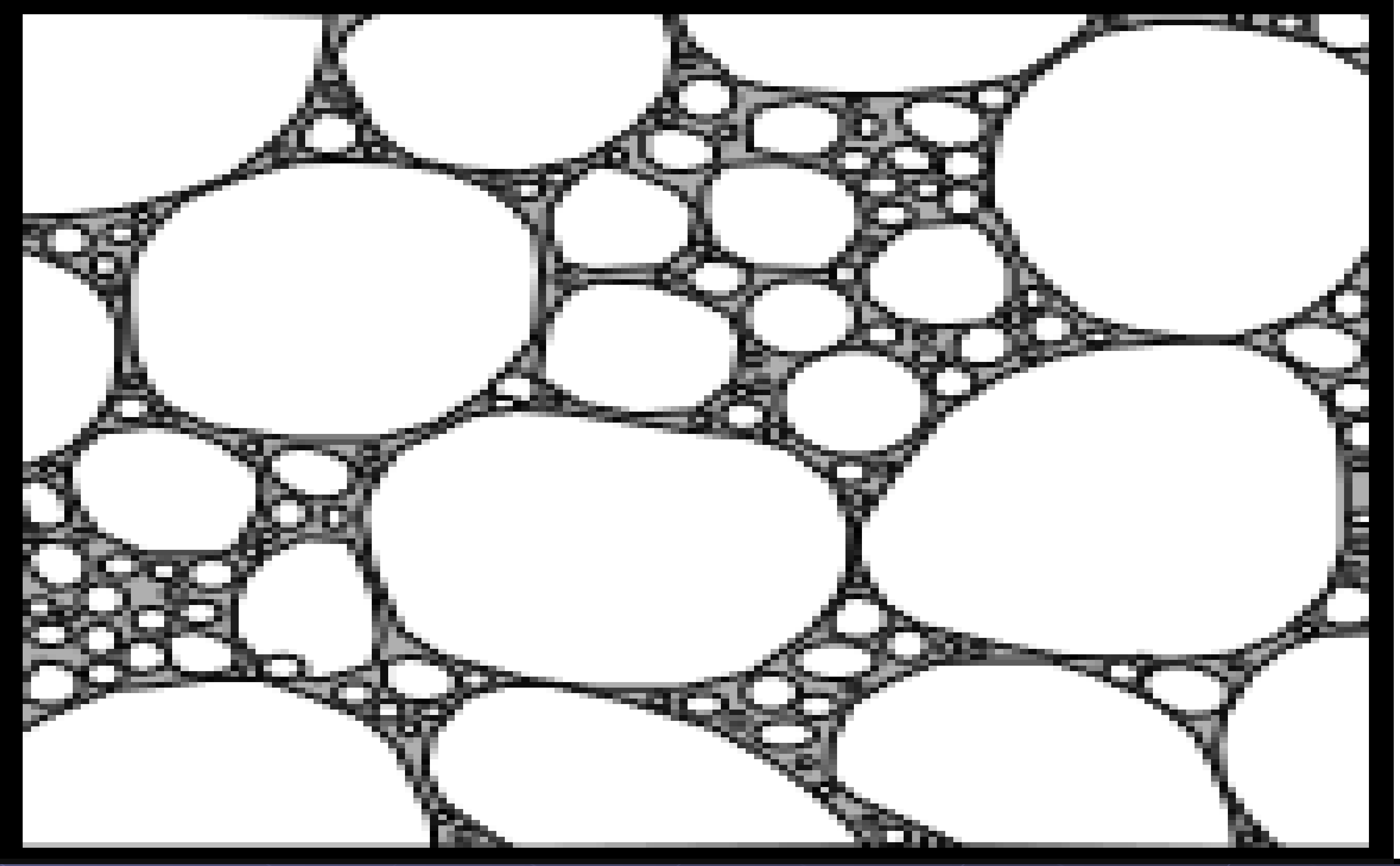


Figure 5 Poorly sorted sediments

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

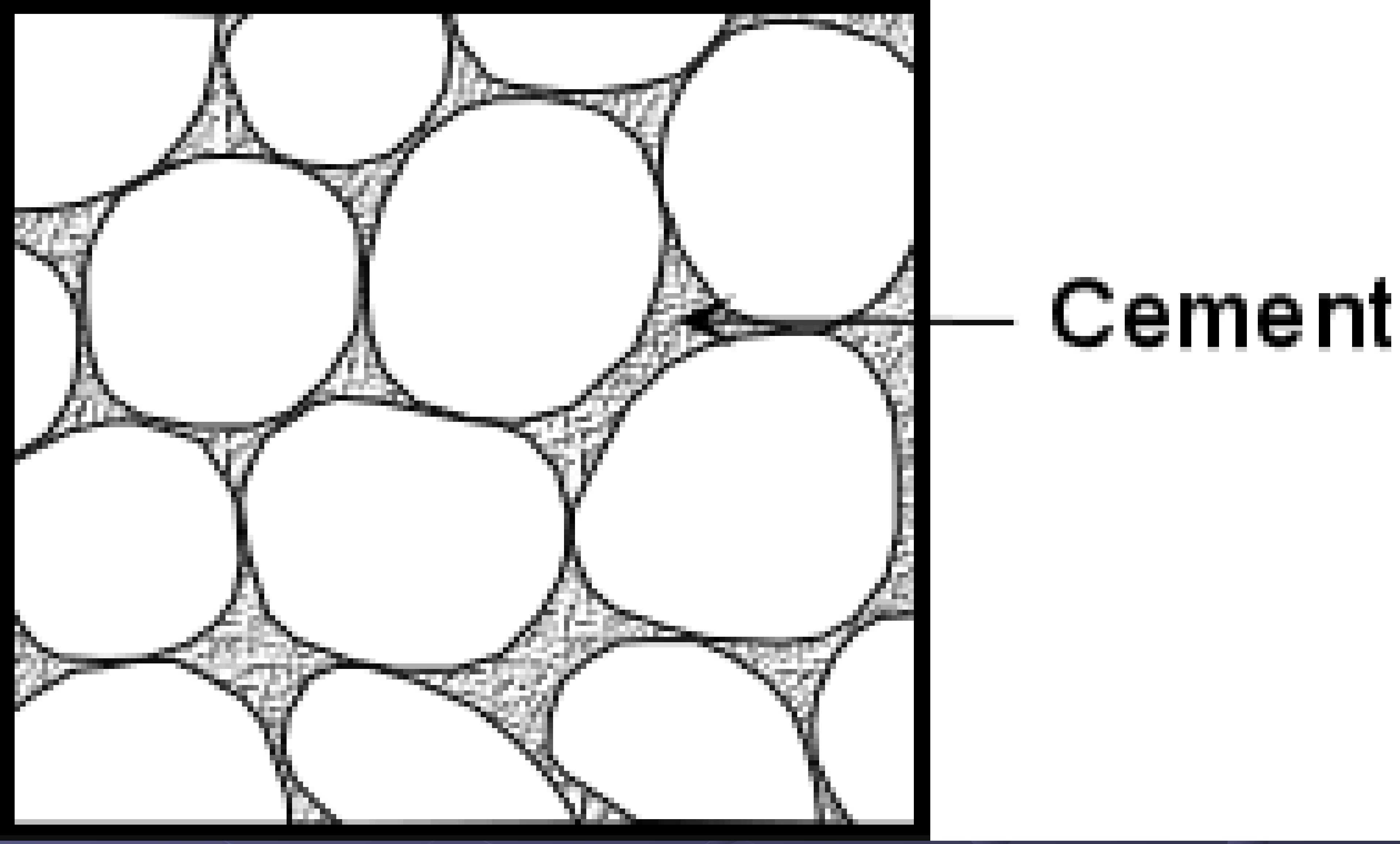


Figure 6 Highly cemented sedimentary rocks

- **In igneous and metamorphic rocks porosity *__is usually low__* because the minerals tend to be intergrown, leaving little free space. Higher fractured igneous and metamorphic rocks, however, could have high porosity (see Figure 7).**

- **The porosity of sediments is affected by the shape of the grains. Well-rounded grains may be almost perfect spheres, but many grains are very irregular. They can be shaped like rods, disks, or books. Sphere-shaped grains will pack more tightly and have less porosity than particles of other shapes. The fabric or orientation of the particles, if they are not spheres, also influences porosity (see Figure 8).**

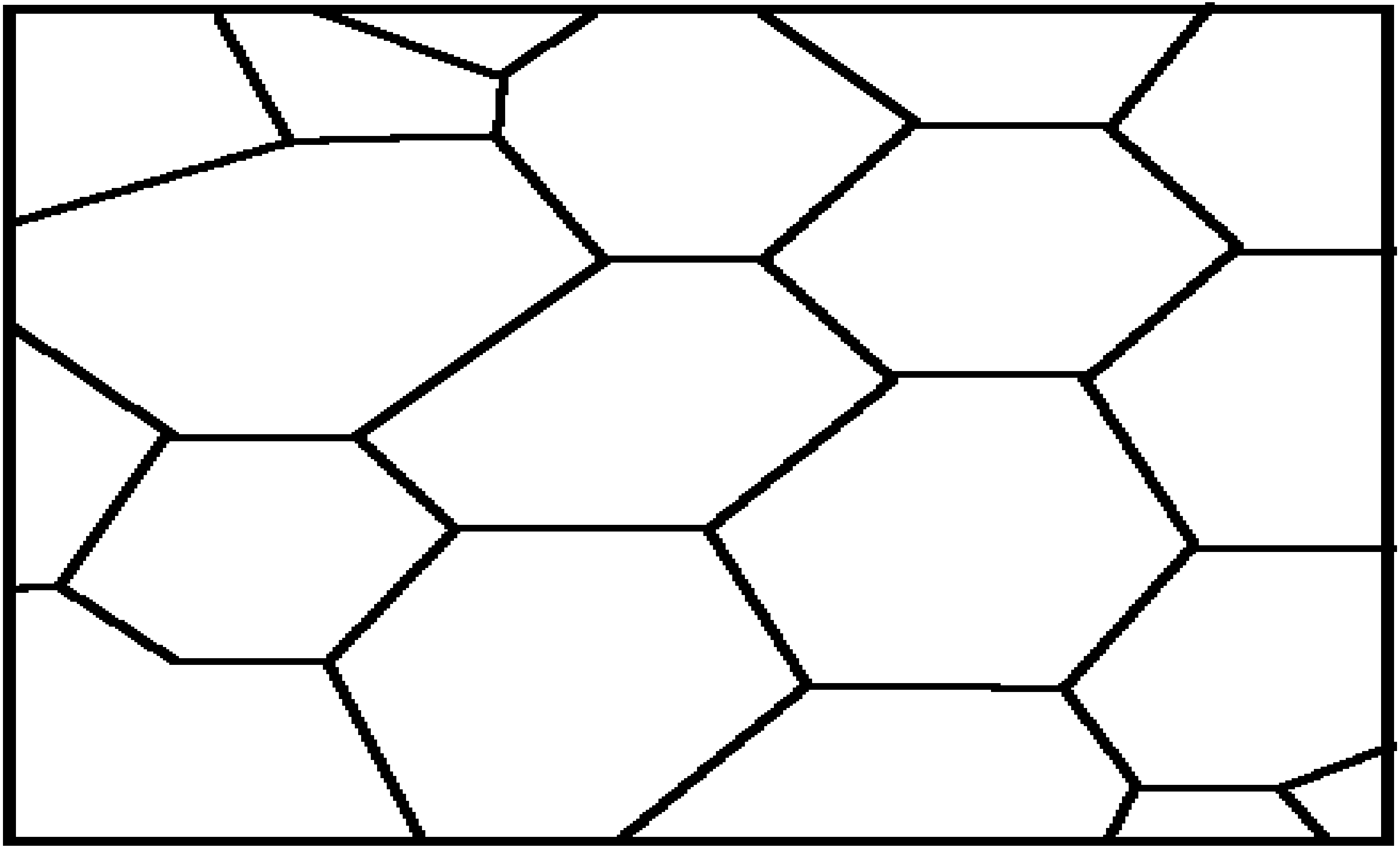


Figure 7 Igneous and metamorphic rocks textures

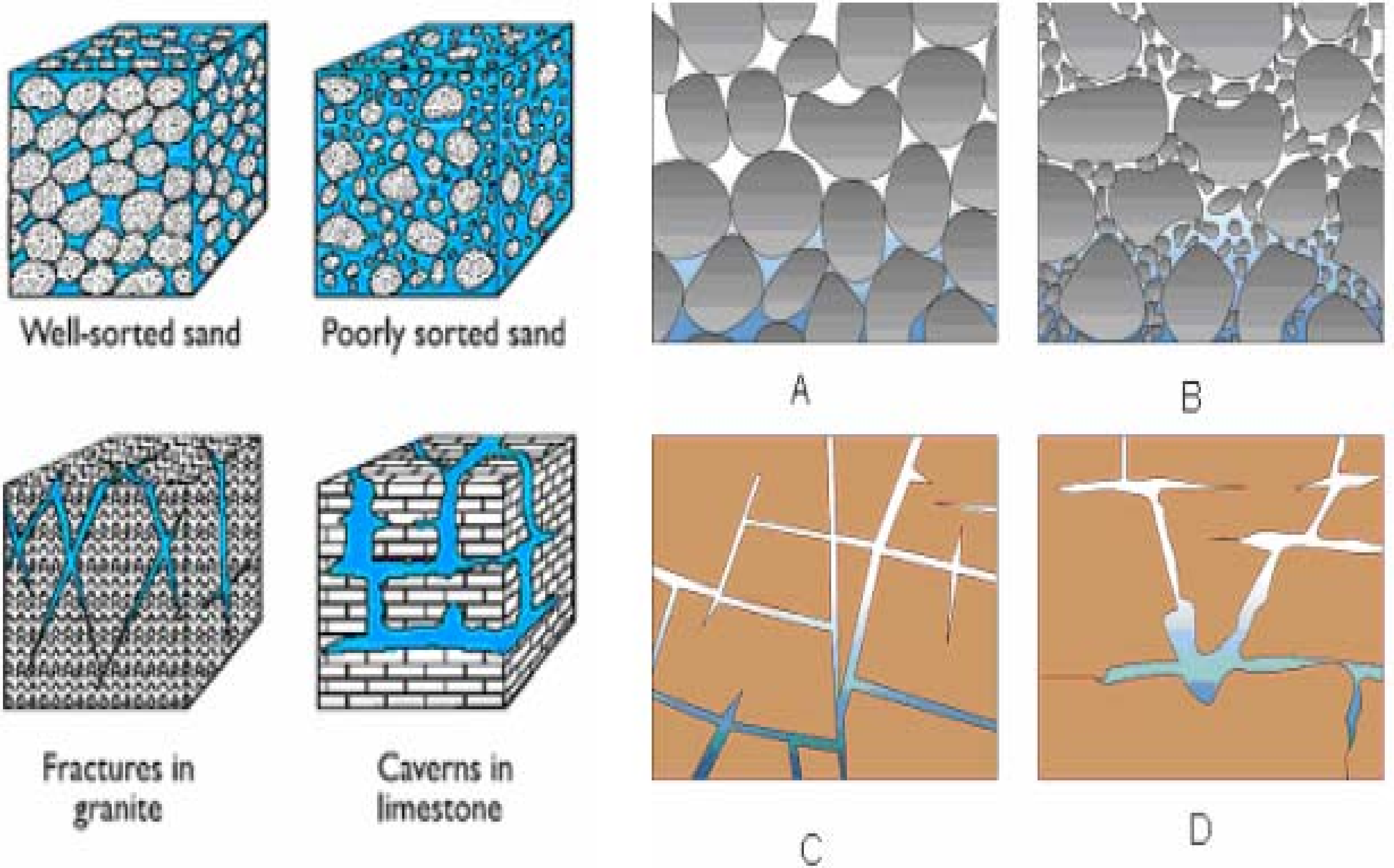


Figure 8 Relation between texture and porosity **A.** Well –sorted sand having high porosity; **B.** Poorly- sorted sand having low porosity; **C.** Fractured crystalline rocks (granite); **D.** Soluble rock-forming material (limestone).

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

- **In porous rock, there may be small pores known as dead end pores which have only one entrance, and so water molecules can diffuse in and out of them, but there can be no hydraulic gradient across them to cause bulk flow of groundwater. In extreme cases, there may be pores containing water that are completely closed so that the water in them is trapped. This may occur during digenetic transformations of the rock. Since we are frequently interested in the movement of groundwater, it is useful to define a porosity that refers only to the movable water in the rock. This is called *<u>the kinematic or effective porosity ne [dimensionless]</u>***

- **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,

- ***n*** **is the porosity (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

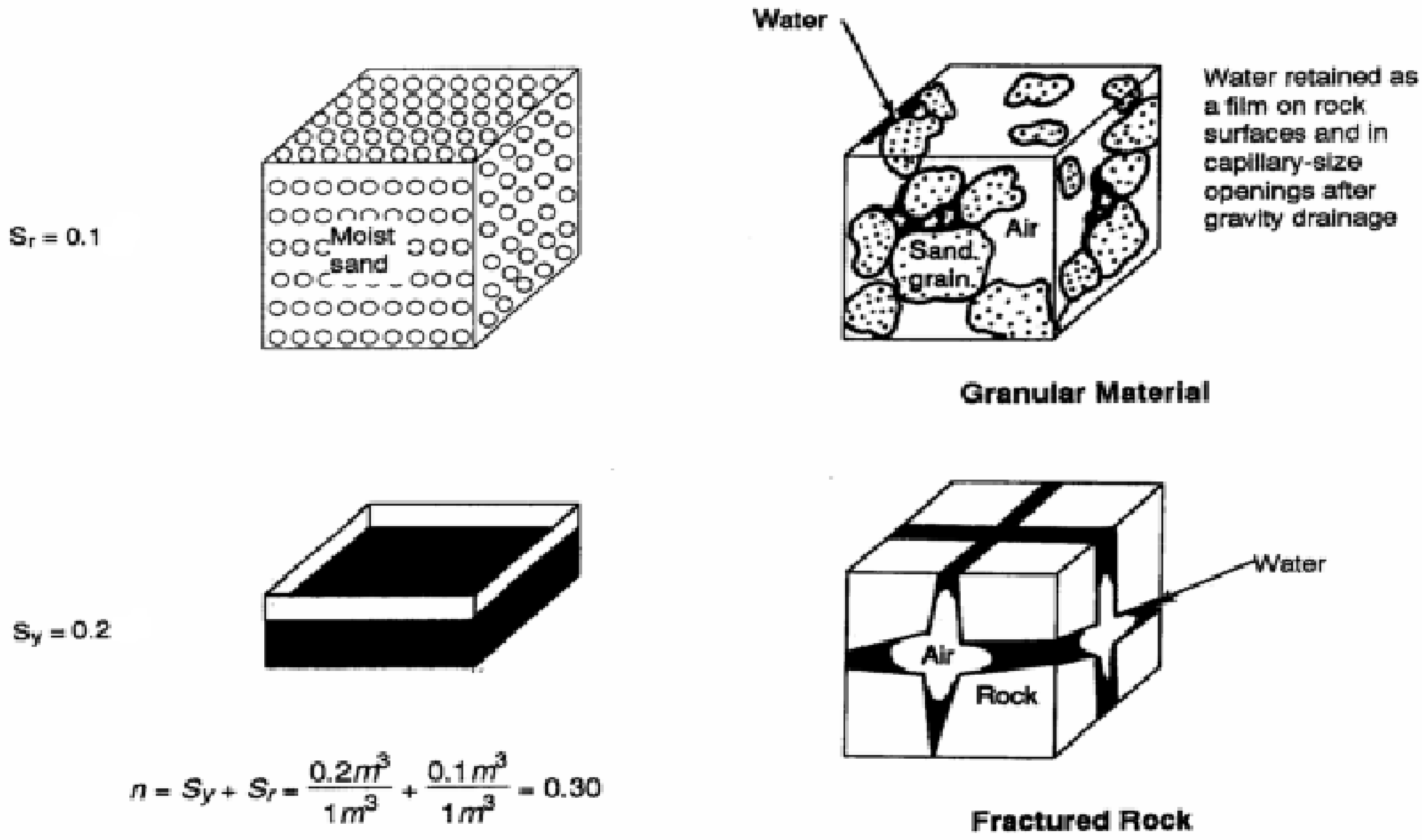
Formation	S_y (range)	S_y (average)
✓ Clay	0 - 5	2
✓ Sandy clay	3 - 12	7
✓ Silt	3 - 19	18
✓ Fine sand	10 - 28	21
✓ Medium sand	15 - 32	26
✓ Coarse sand	20 - 35	27
✓ Gravelly sand	20 - 35	25
✓ Fine gravel	21 - 35	25
✓ Medium gravel	13 - 26	23
✓ Coarse gravel	12 - 26	22

3. Specific Retention (Sr)

Specific retention (Sr) is the ratio of the volume of water that cannot be drained out to the total volume of the saturated aquifer. Since the specific yield represents the volume of water that a rock will yield by gravity drainage, with specific retention the remainder, the sum of the two is equal to porosity (see Figure 9).

$$n = S_r + S_y$$

- **The specific yield and specific retention depend upon the shape and size of particle, distribution of pores (voids), and compaction of the formation.**
- **The specific retention increases with decreasing grain size.**
- **It should be noted that it is not necessary that a soil with a high porosity will have a high specific yield because that soil may have low permeability and the water may not easily drain out. For example, clay has a high porosity but low specific yield because its permeability is low.**



$$n = S_y + S_r = \frac{0.2m^3}{1m^3} + \frac{0.1m^3}{1m^3} = 0.30$$

Figure 9 Specific retention

4. 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.

The coefficient of permeability (K) depends on the properties of both porous medium and fluid. It can be expressed as (see Figure 10),

$$K = \frac{C d_m^2 \rho g}{\mu}$$

- where,

  C is the shape factor which depends upon the shape, particle size and packing of the porous media

  dm is the mean particle size (d50)

  ρ is the mass density

  g is the acceleration due to gravity

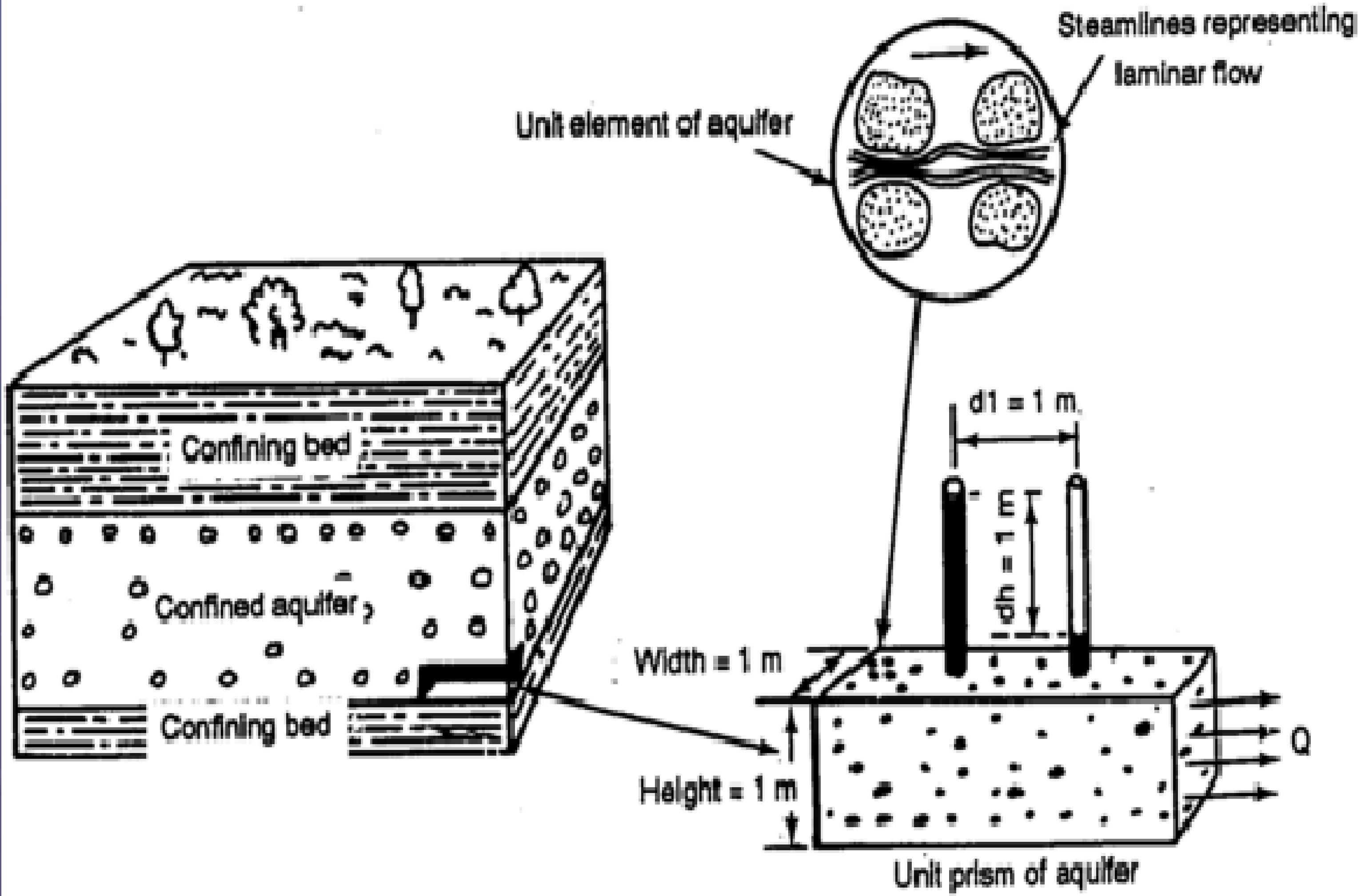


Figure 10 **Hydraulic conductivity**

- Another coefficient of permeability, called ***intrinsic permeability (k)***, is sometimes used. The intrinsic permeability depends upon the porous medium and is independent of the properties of the fluid. It is usually expressed as,

$$k = Cd_m^2$$

- The intrinsic permeability k has the dimensions of [L2] and is usually expressed in cm2 or Darcy, where 1 Darcy = 0.987 * 10-8 cm2.

- The intrinsic permeability is ***rarely used in groundwater hydrology***, but this term is very popular in the petroleum and natural gas industries.

- The intrinsic permeability is also called the ***absolute permeability***.

- **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	$10^{-13} – 10^{-9}$

5. **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.**

- **Transmissibility of most formations lies between 1*104 -1*106 L/d/m, with an average value of 1*105 l/d/m.**
- **Figure 11 illustrates the difference between hydraulic conductivity and transmissivity.**

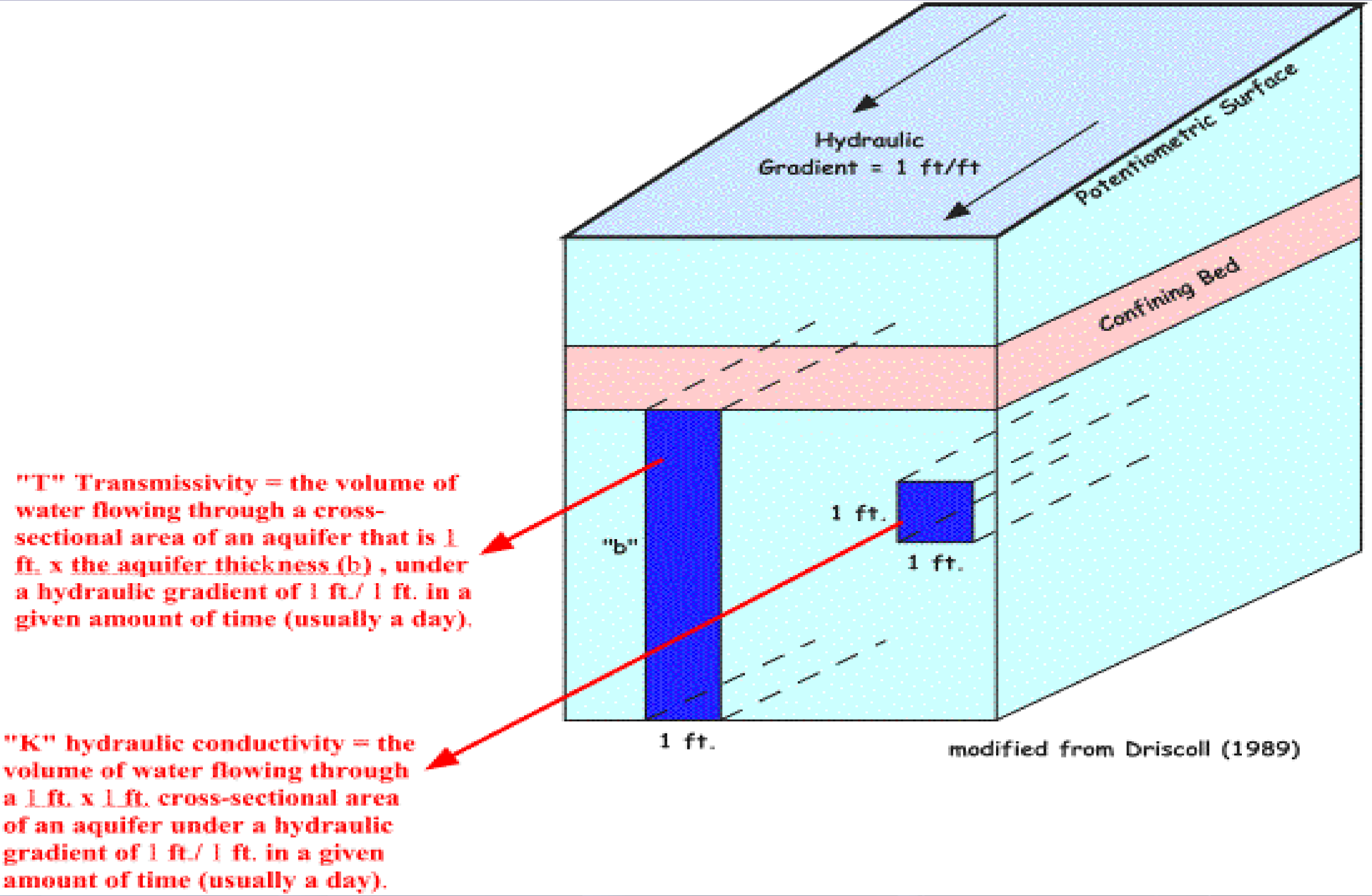


Figure 11 Illustration of the coefficients of hydraulic conductivity and transmissivity

6. 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.

- **The transmissivity and storage coefficients are especially important because they *define the hydraulic characteristics of a water-bearing formation*. The coefficient of transmissivity indicates how much water will move through the formation, and the coefficient of storage indicates how much can be removed by pumping or draining. If these two coefficients can be determined for a particular aquifer, predictions of great significance can usually be made. Some of these are:**
  - **Drawdown in the aquifer at various distances from a pumped well.**
  - **Drawdown in a well at any time after pumping starts.**
  - **How multiple wells in a small area will affect one another.**
  - **Efficiency of the intake portion of the well.**
  - **Drawdown in the aquifer at various pumping rates.**

7. 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}

THANK YOU