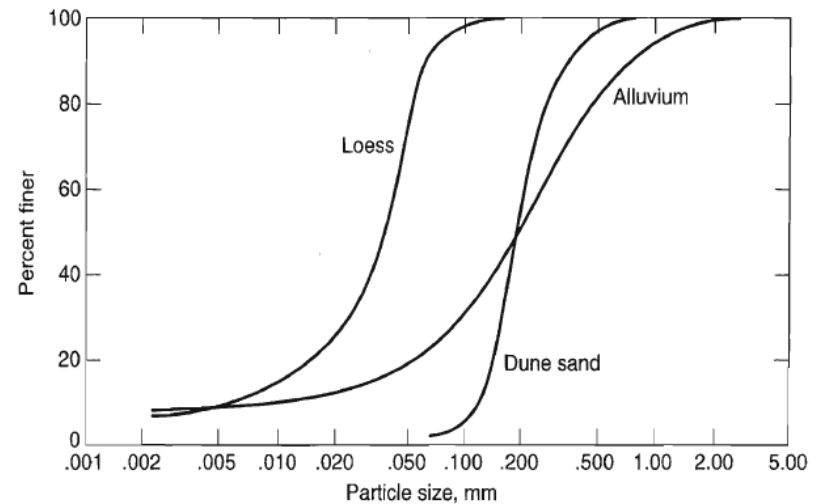


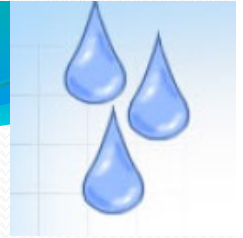
Environmental Engineering Department
Water Resources Management
(EENV 3352)

Ch2: Occurrence of Groundwater

Instructor:

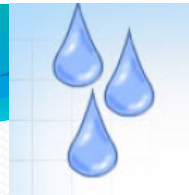
Dr. Yunes Mogheir





2. Occurrence of Groundwater

- Rock Properties Affecting Groundwater
- Vertical Distribution of Groundwater
- Zone of Aeration
- Zone of Saturation
- Geological Formation as Aquifers
- Types of Aquifers
- Storage Coefficient



Rock Properties Affecting Groundwater

Groundwater occurs in many types of geologic formations; those known as aquifers are of most importance. An *aquifer* may be defined as a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs.³⁵ This implies an ability to store and to transmit water; unconsolidated sands and gravels are a typical exam-

1. *Aquiclude*—A saturated but relatively impermeable material that does not yield appreciable quantities of water to wells; clay is an example.
2. *Aquifuge*—A relatively impermeable formation neither containing nor transmitting water; solid granite belongs in this category.
3. *Aquitard*—A saturated but poorly permeable stratum that impedes groundwater movement and does not yield water freely to wells, that may transmit appreciable water to or from adjacent aquifers and, where sufficiently thick, may constitute an important groundwater storage zone; sandy clay is an example.^{45*}



Porosity

The *porosity* of a rock or soil is a measure of the contained interstices or voids expressed as the ratio of the volume of interstices to the total volume. If α is the porosity, then

$$\alpha = \frac{V_v}{V} = \frac{V_t - V_s}{V_t} \quad (2.2.1)$$

where V_v is the volume of interstices (voids), V_s is the volume of solids, and V is the total volume (bulk volume). Porosity may also be expressed by

$$\alpha = \frac{\rho_m - \rho_d}{\rho_m} = 1 - \frac{\rho_d}{\rho_m} \quad (2.2.2)$$

where ρ_m is the density of mineral particles (grain density)[†] and ρ_d is the bulk density.

Porosity

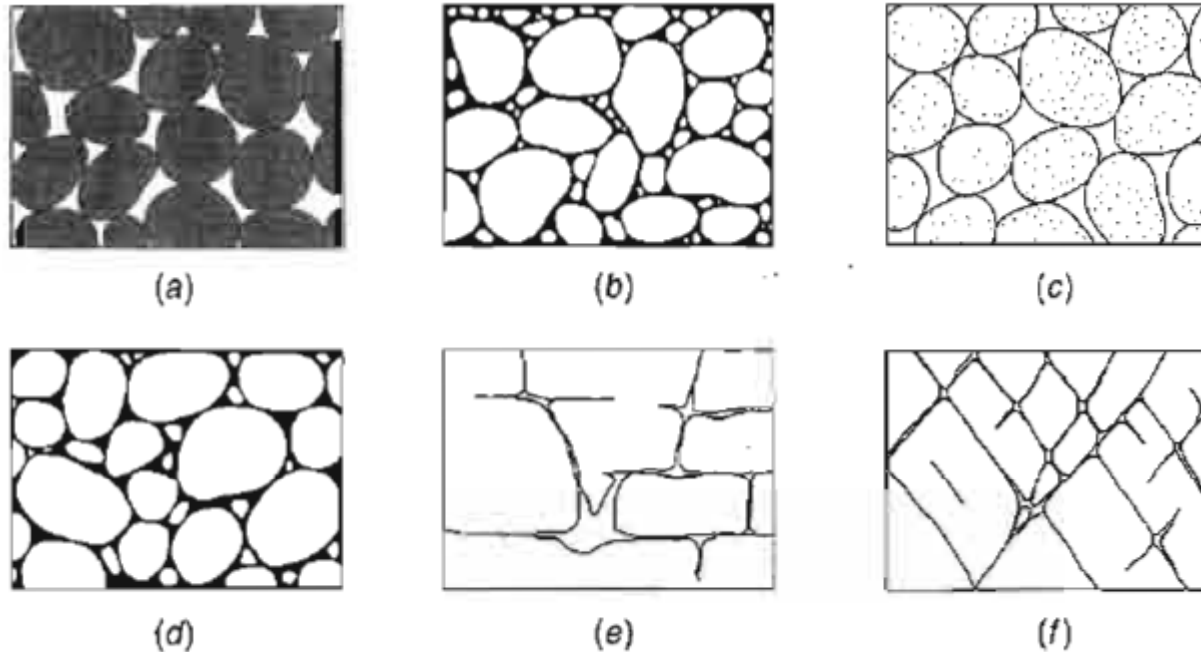


Figure 2.2.1. Examples of rock interstices and the relation of rock texture to porosity. (a) Well-sorted sedimentary deposit having **high porosity**. (b) Poorly sorted sedimentary deposit having **low porosity**. (c) Well-sorted sedimentary deposit consisting of pebbles that are themselves porous, so that the deposit as a whole has a very **high porosity**. (d) Well-sorted sedimentary deposit whose porosity has been diminished by the deposition of mineral matter in the interstices. (e) Rock rendered porous by solution. (f) Rock rendered porous by fracturing.⁴²

Porosity



In sedimentary rocks subject to compaction, measurements show that porosity decreases with depth of burial.³⁷ Thus, a typical relation has the form

$$\alpha_z = \alpha_o e^{-az} \quad (2.2.3)$$

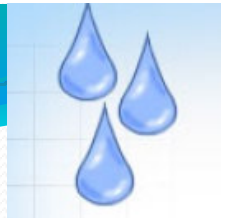
where α_z is the porosity at depth z , α_o is the porosity at the surface, a is a constant, and e is the base of Napierian logarithms.

Table 2.2.1 Representative Values of Porosity (after Morris and Johnson⁴⁵)

Material	Porosity, percent	Material	Porosity, percent
Gravel, coarse	28 ^a	Loess	49
Gravel, medium	32 ^a	Peat	92
Gravel, fine	34 ^a	Schist	38
Sand, coarse	39	Siltstone	35
Sand, medium	39	Claystone	43
Sand, fine	43	Shale	6
Silt	46	Till, predominantly silt	34
Clay	42	Till, predominantly sand	31
Sandstone, fine grained	33	Tuff	41
Sandstone, medium grained	37	Basalt	17
Limestone	30	Gabbro, weathered	43
Dolomite	26	Granite, weathered	45
Dune sand	45		

^aThese values are for repacked samples; all others are undisturbed.

EXAMPLE 2.2.2



The void ratio of an unconsolidated clay sample is 1.19. Determine the porosity of the sample.

Using the definition of the void ratio of an undisturbed sample, $e = \frac{V_v}{V_s}$, and substituting $V_v = V_t - V_s$, then the void ratio is $e = \frac{V_t - V_s}{V_s} = \frac{V_t}{V_s} - 1 \rightarrow \frac{V_t}{V_s} = 1 + e$.

Substituting this into the porosity equation, we obtain

$$\alpha = \frac{V_t - V_s}{V_t} \times 100 = \left[1 - \frac{V_s}{V_t} \right] \times 100 = \left[1 - \frac{1}{1 + e} \right] \times 100 = \frac{e}{1 + e} \times 100$$

Thus, the porosity of the sample is

$$\alpha = \frac{e}{1 + e} \times 100 = \frac{1.19}{1 + 1.19} \times 100 = 54.34\%$$



Soil Classification



Unconsolidated geologic materials are normally classified according to their size and distribution. A commonly employed system based on particle, or grain, size is listed in Table 2.2.2. Evaluation of the distribution of sizes is accomplished by mechanical analysis. This involves sieving particles coarser than 0.05 mm and measuring rates of settlement for smaller particles in suspension. Results are plotted on a particle-size distribution graph such as that shown in Figure 2.2.2. The percentage finer scale on the ordinate shows the percentage of material smaller than that of a given size particle on a dry-weight basis.

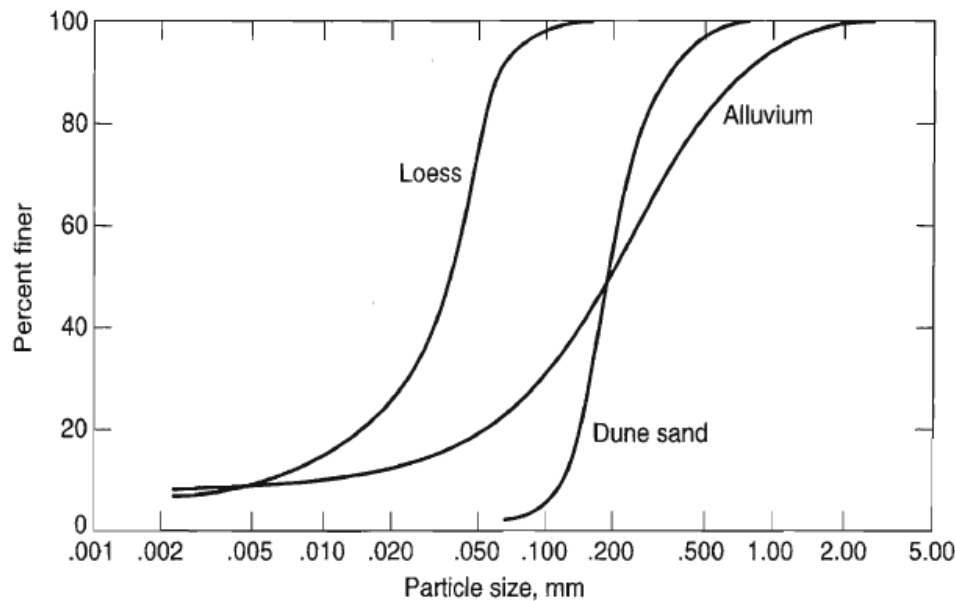
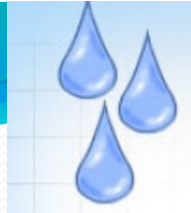


Table 2.2.2 Soil Classification Based on Particle Size (after Morris and Johnson⁴⁵)

Material	Particle size, mm
Clay	<0.004
Silt	0.004 – 0.062
Very fine sand	0.062 – 0.125
Fine sand	0.125 – 0.25
Medium sand	0.25 – 0.5
Coarse sand	0.5 – 1.0
Very coarse sand	1.0 – 2.0
Very fine gravel	2.0 – 4.0
Fine gravel	4.0 – 8.0
Medium gravel	8.0 – 16.0
Coarse gravel	16.0 – 32.0
Very coarse gravel	32.0 – 64.0

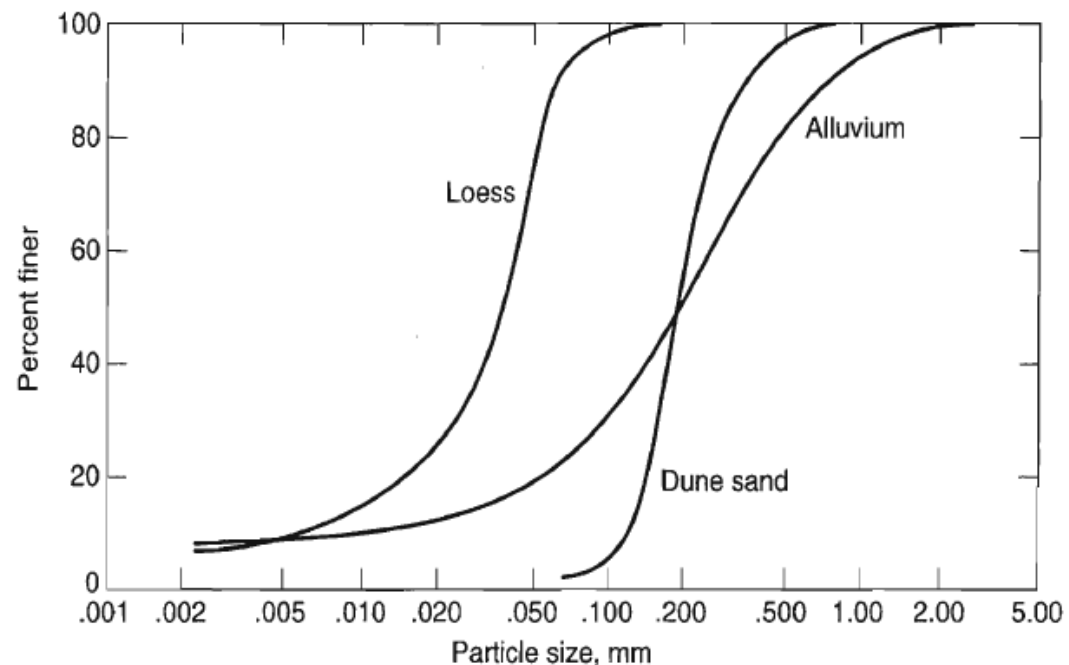
Soil Classification



The effective particle size is the 10 percent finer than value (d_{10}). The distribution of particles is characterized by the *uniformity coefficient* U_c as

$$U_c = d_{60}/d_{10} \quad (2.2.4)$$

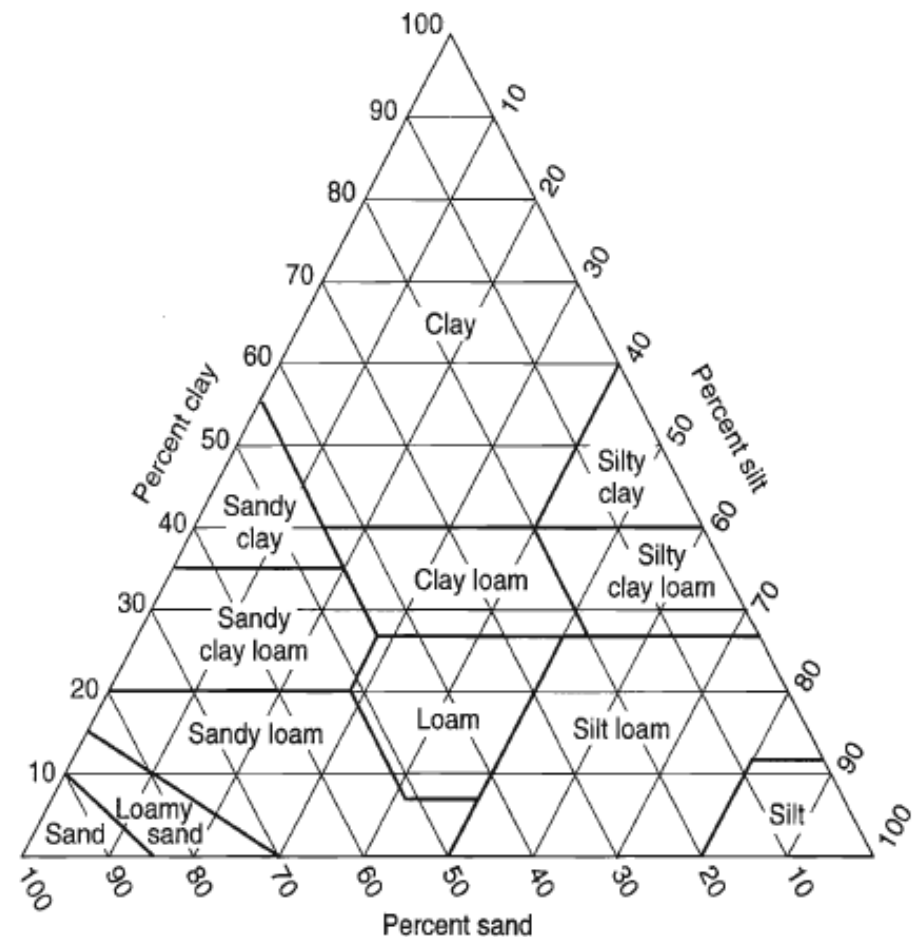
where d_{60} is the 60 percent finer than value. A *uniform material* has a low uniformity coefficient (the dune sand in Figure 2.2.2), while a *well-graded material* has a high uniformity coefficient (the alluvium).



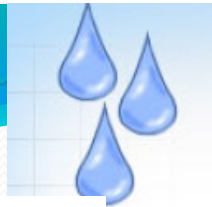
Soil Classification



The *texture* of a soil is defined by the relative proportions of sand, silt, and clay present in the particle-size analysis. This can be expressed by the soil-textural triangle in Figure 2.2.3. Note, for example, that a soil composed of 30 percent clay, 60 percent silt, and 10 percent sand constitutes a silty clay loam.



EXAMPLE 2.2.4

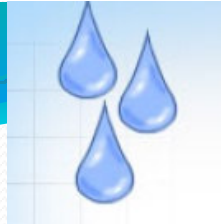


Using the tabulated results of a grain size distribution test on a field sample, perform the following tasks:

- (a) Prepare a grain size distribution curve for this sample.
- (b) Is this a well-graded or poorly graded sample?
- (c) Classify the sample using Table 2.2.2.
- (d) What would be reasonable porosity values for this sample?

<u>U.S. Standard Sieve Number</u>	<u>Mass retained (g)</u>
3/8	49.95
4	26.70
8	25.29
16	50.58
30	72.57
40	25.50
100	33.60
200	7.53
<u>Pan (passes through #200 sieve)</u>	<u>8.28</u>
Total sample weight	300.00

SOLUTION



- (a) The given data are analyzed as shown in the table below. Note that the particle size (sieve opening) corresponding to each U.S. Standard Sieve number is given in the table. The results yield the grain-size distribution curve shown in Figure 2.2.4.

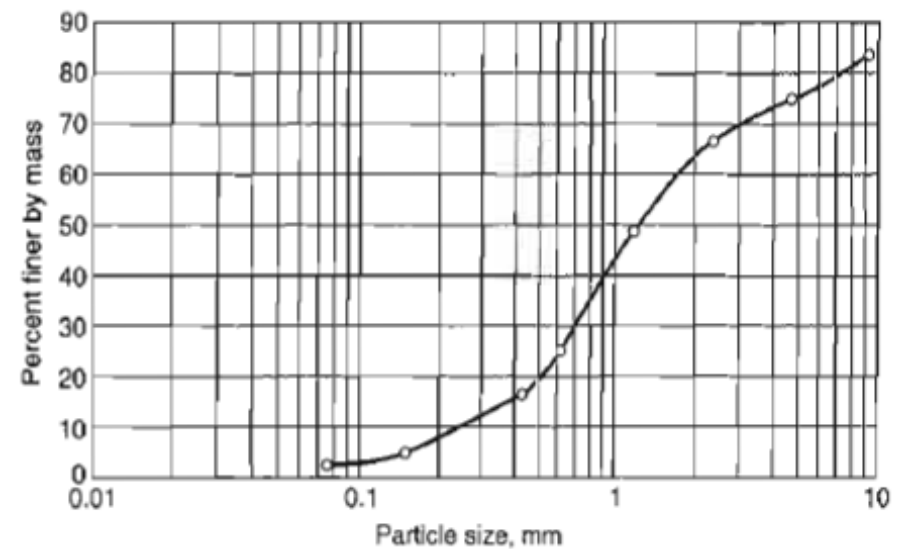
Sieve	Grain size (mm)	Mass retained (g)	Percent finer by mass
3/8	9.5	49.95	83.35
4	4.75	26.70	74.45
8	2.36	25.29	66.02
16	1.18	50.58	49.16
30	0.6	72.57	24.97
40	0.425	25.50	16.47
100	0.15	33.60	5.27
200	0.075	7.53	2.76
Pan	<0.075	8.28	
Total sample weight		300	

- (b) From the grain-size distribution curve:

$$d_{60} \cong 1.6 \text{ mm} \quad \text{and} \quad d_{10} \cong 0.23 \text{ mm}$$

From Equation 2.2.4, the uniformity coefficient is

$$U_c = \frac{d_{60}}{d_{10}} = \frac{1.6 \text{ mm}}{0.23 \text{ mm}} \approx 7$$



Vertical Distribution of Groundwater



The subsurface occurrence of groundwater may be divided into zones of aeration and saturation. The *zone of aeration* consists of interstices occupied partially by water and partially by air. In the *zone of saturation*, all interstices are filled with water under hydrostatic pressure. On most of the land masses of the earth, a single zone of aeration overlies a single zone of saturation and extends upward to the ground surface, as shown in Figure 2.3.1.

In the zone of aeration, *vadose water** occurs. This general zone may be further subdivided into the *soil water zone*, the *intermediate vadose zone*, and the *capillary zone* (Figure 2.3.1).¹⁴

The saturated zone extends from the upper surface of saturation down to underlying impermeable rock. In the absence of overlying impermeable strata, the *water table*, or *phreatic surface*,[†] forms the upper surface of the zone of saturation. This is defined as the surface of atmospheric pressure and appears as the level at which water stands in a well penetrating the aquifer. Actually, saturation extends slightly above the water table due to capillary attraction; however, water is held there at less than atmospheric pressure. Water occurring in the zone of saturation is commonly referred to simply as *groundwater*, but the term *phreatic water* is also employed.

Vertical Distribution of Groundwater

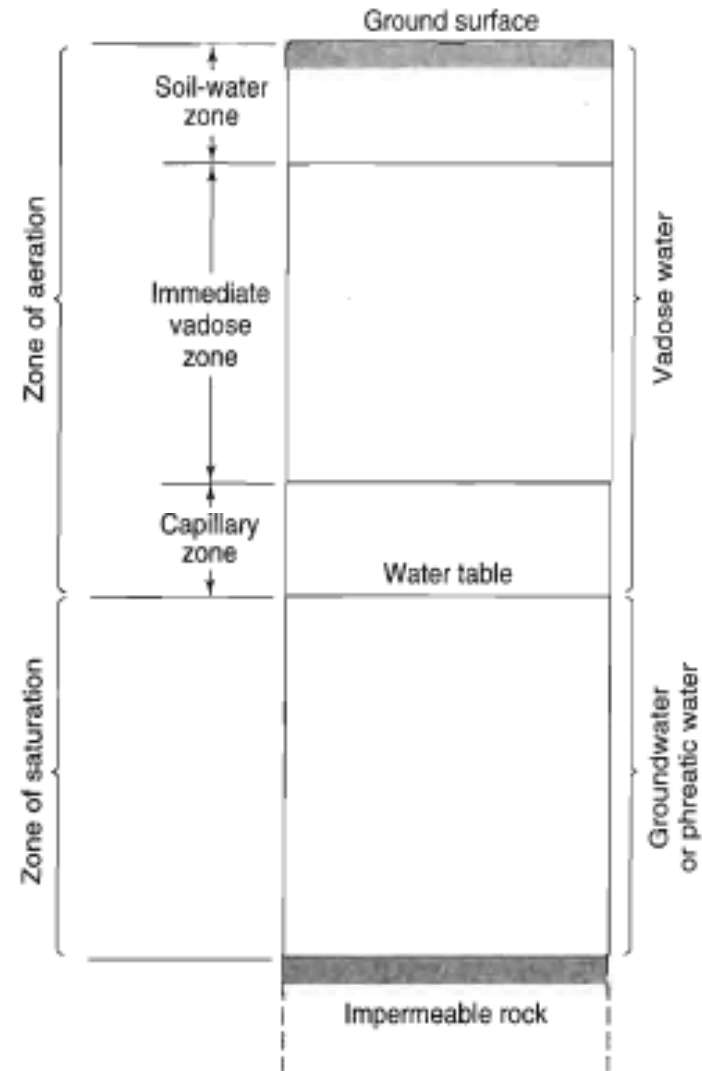
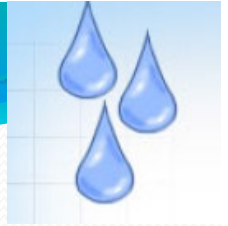
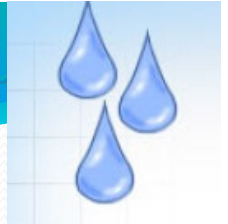


Figure 2.3.1. Divisions of subsurface water.

Zone of Aeration

1. Soil-water zone



Water in the soil–water zone exists at less than saturation except temporarily when excessive water reaches the ground surface as from rainfall or irrigation. The zone extends from the ground surface down through the major root zone. Its thickness varies with soil type and vegetation. Because of the agricultural importance of soil water in supplying moisture to roots, agriculturists and soil scientists have studied soil moisture distribution and movement extensively.

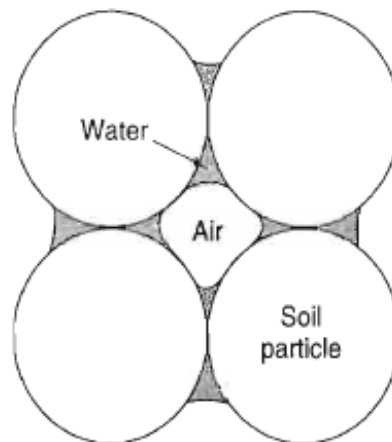
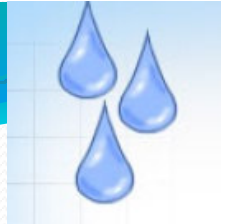


Figure 2.4.1. Illustration of vadose water held at contact points of particles in the unsaturated zone.

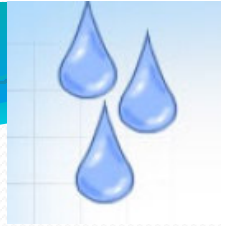
Zone of Aeration



2. Intermediate Vados zone

The intermediate vadose zone extends from the lower edge of the soil–water zone to the upper limit of the capillary zone (Figure 2.3.1). The thickness may vary from zero, where the bounding zones merge with a high water table approaching ground surface, to more than 100 m under deep water table conditions. The zone serves primarily as a region connecting the zone near ground surface with that near the water table through which water moving vertically downward must pass. Nonmoving vadose water is held in place by hygroscopic and capillary forces. Temporary excesses of water migrate downward as gravitational water.

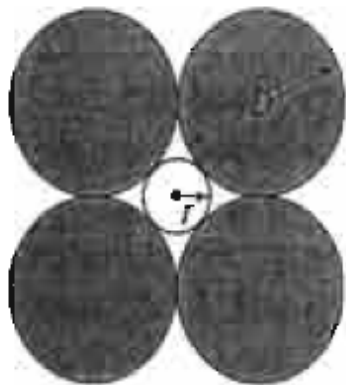
3. Capillary zone



The *capillary zone* (or *capillary fringe*) extends from the water table up to the limit of capillary rise of water. If a pore space could be idealized to represent a capillary tube, the *capillary rise* h_c (Figure 2.4.2) can be derived from an equilibrium between surface tension of water and the weight of water raised. Thus,

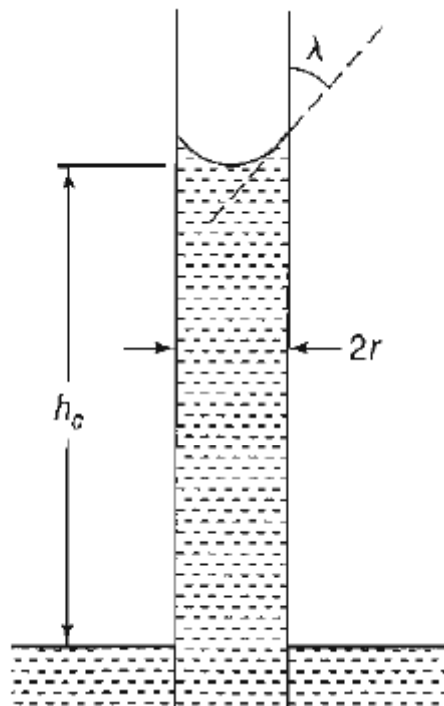
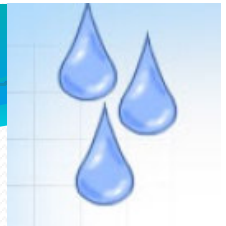
$$h_c = \frac{2\tau}{r\gamma} \cos \lambda \quad (2.4.1)$$

where τ is surface tension, γ is the specific weight of water, r is the tube radius, and λ is the angle of contact between the meniscus and the wall of the tube. For pure water in a clean glass, $\lambda = 0$, and at 20° C, $\tau = 0.074$ g/cm and $\gamma = 1$ g/cm³, so that for r in cm, the capillary rise (in cm) is



$$h_c = \frac{0.15}{r} \quad (2.4.2)$$

3. Capillary zone

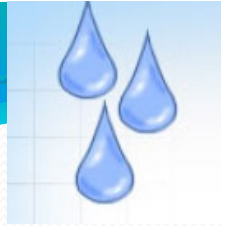


$$h_c = \frac{2\tau}{r\gamma} \cos \lambda$$

Table 2.4.1 Capillary Rise in Samples of Unconsolidated Materials (after Lohman³⁴)

Material	Grain size (mm)	Capillary rise (cm)
Fine gravel	5-2	2.5
Very coarse sand	2-1	6.5
Coarse sand	1-0.5	13.5
Medium sand	0.5-0.2	24.6
Fine sand	0.2-0.1	42.8
Silt	0.1-0.05	105.5
Silt	0.05-0.02	200 ^a

Zone of Saturation



In the zone of saturation, groundwater fills all of the interstices; hence, the (effective) porosity provides a direct measure of the water contained per unit volume. A portion of the water can be removed from subsurface strata by drainage or by pumping of a well; however, molecular and surface tension forces hold the remainder of the water in place.

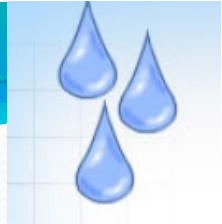
1. Specific Retention

The *specific retention* S_r of a soil or rock is the ratio of the volume of water it will retain after saturation against the force of gravity to its own volume. Thus,

$$S_r = \frac{w_r}{V_t} \quad (2.5.1)$$

where w_r is the volume occupied by retained water* and V_t is the bulk volume of the soil or rock.

2. Specific Yield



The *specific yield* S_y of a soil or rock is the ratio of the volume of water that, after saturation, can be drained by gravity to its own volume.¹⁷ Therefore,

$$S_y = \frac{w_y}{V_t} \quad (2.5.2)$$

where w_y is the volume of water drained. Values of S_r and S_y can also be expressed as percentages. Because w_r and w_u constitute the total water volume in a saturated material, it is apparent that

$$V_v = w_r + w_y \quad (2.5.3)$$

or

$$\alpha = S_r + S_y \quad (2.5.4)$$

2. Specific Yield

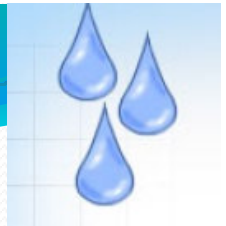


Table 2.5.1 Representative Values of Specific Yield (after Johnson²⁵)

Material	Specific yield (percent)
Gravel, coarse	23
Gravel, medium	24
Gravel, fine	25
Sand, coarse	27
Sand, medium	28
Sand, fine	23
Silt	8
Clay	3
Sandstone, fine grained	21
Sandstone, medium grained	27
Limestone	14
Dune sand	38
Loess	18
Peat	44
Schist	26
Siltstone	12
Till, predominantly silt	6
Till, predominantly sand	16
Till, predominantly gravel	16
Tuff	21

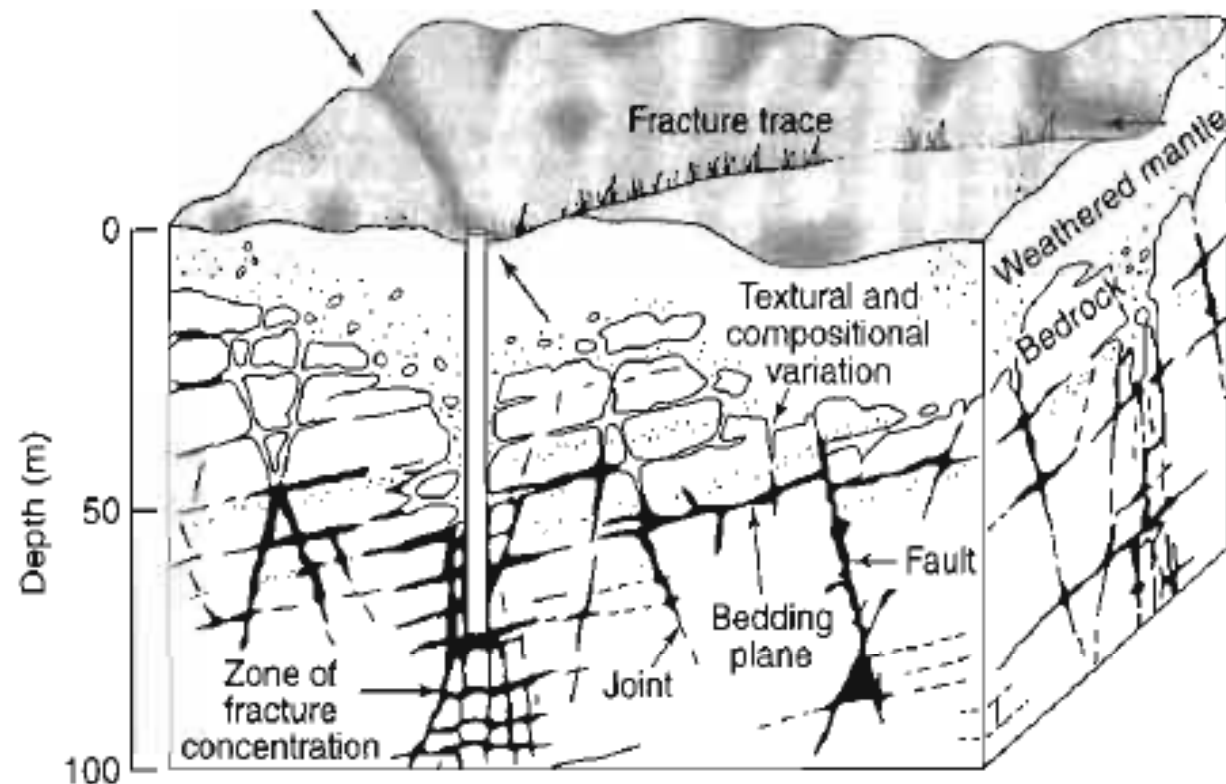
Geological Formation as Aquifers



Table 2.6.1 Geologic Origin of Aquifers Based on Type of Porosity and Rock Type (after Dept. of Economic and Social Affairs¹⁶)

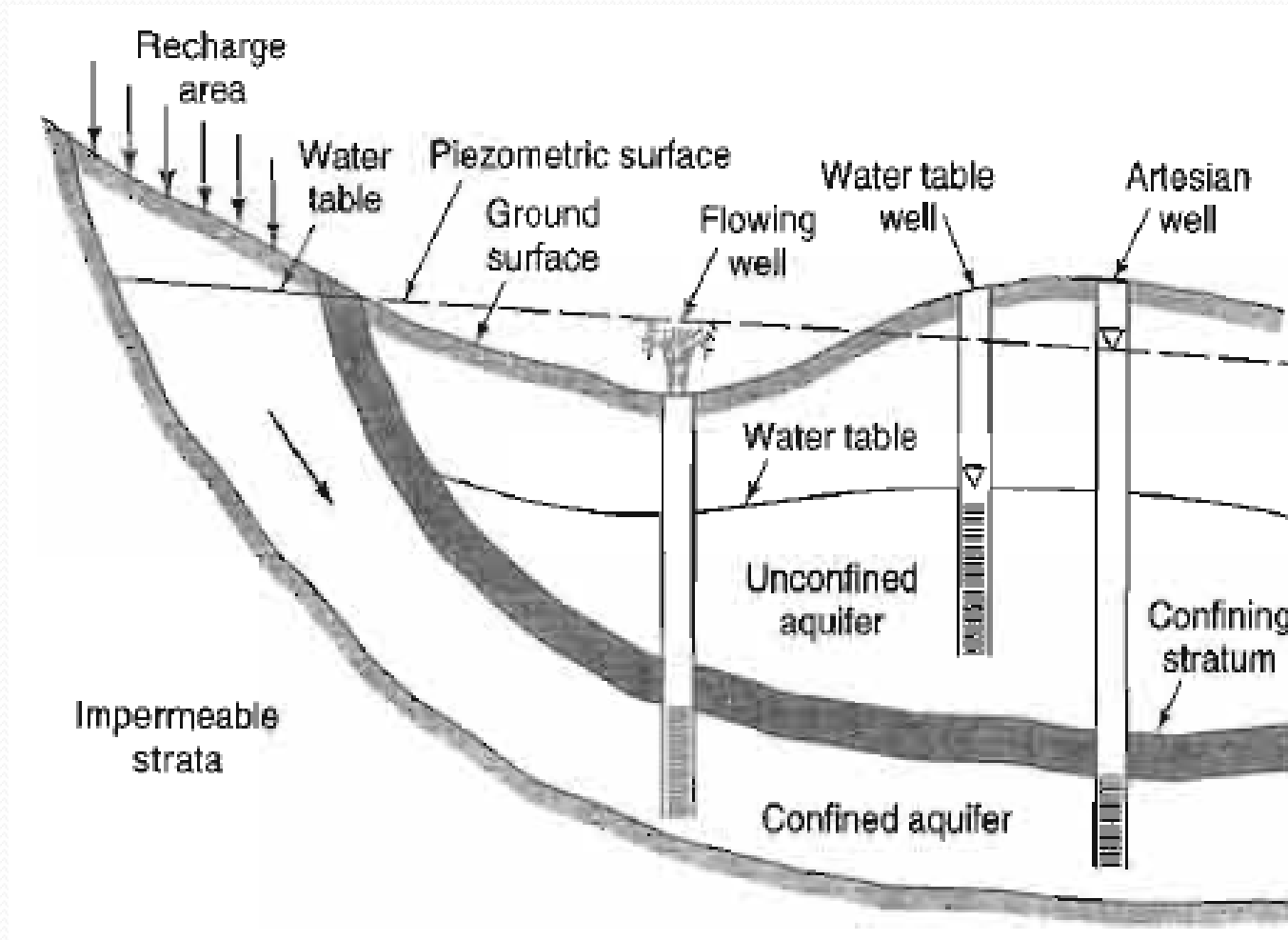
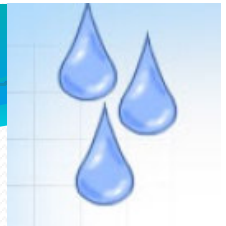
Type of porosity	Sedimentary			Igneous and metamorphic	Volcanic	
	<i>Consolidated</i>	<i>Unconsolidated</i>	<i>Carbonates</i>		<i>Consolidated</i>	<i>Unconsolidated</i>
Intergranular		Gravelly sand Clayey sand Sandy clay		Weathered zone of granite-gneiss	Weathered zone of basalt	Volcanic ejecta, blocks, and fragments Ash
Intergranular and fracture	Breccia Conglomerate Sandstone Slate		Zoogenic limestone Oolitic limestone Calcareous grit		Volcanic tuff Cinder Volcanic breccia Pumice	
Fracture			Limestone Dolomite Dolomitic limestone	Granite Gneiss Gabbro Quartzite Diorite Schist Mica schist	Basalt Andesite Rhyolite	

Limestone



Limestone varies widely in density, porosity, and permeability depending on degree of consolidation and development of permeable zones after deposition. Those most important as aquifers contain sizable proportions of the original rock that have been dissolved and removed.⁶⁴ Openings in limestone may range from microscopic original pores to large solution caverns forming subterranean channels sufficiently large to carry the entire flow of a stream.^{9, 28} The term *lost river* has been applied to a stream that disappears completely underground in a limestone terrain.* Large springs are frequently found in limestone areas.

Types of Aquifers



Types of Aquifers

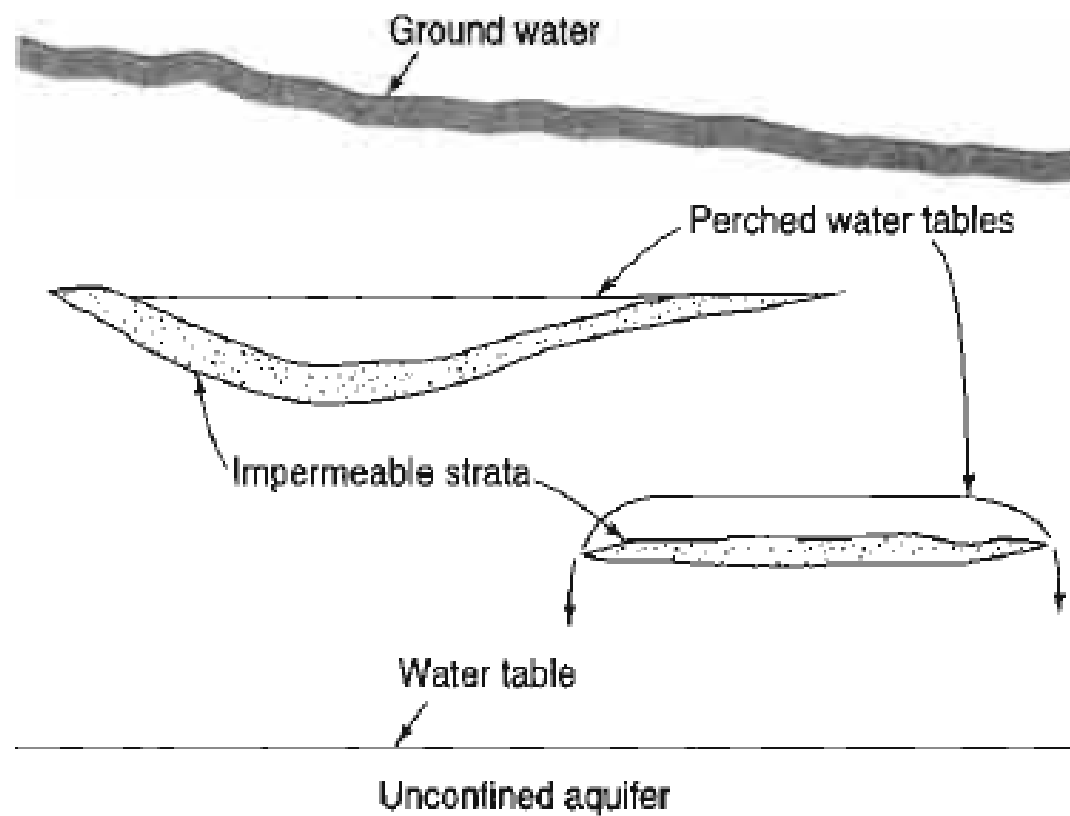
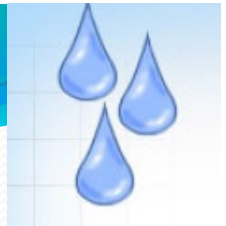


Figure 2.7.2. Sketch of perched water tables.

Types of Aquifers

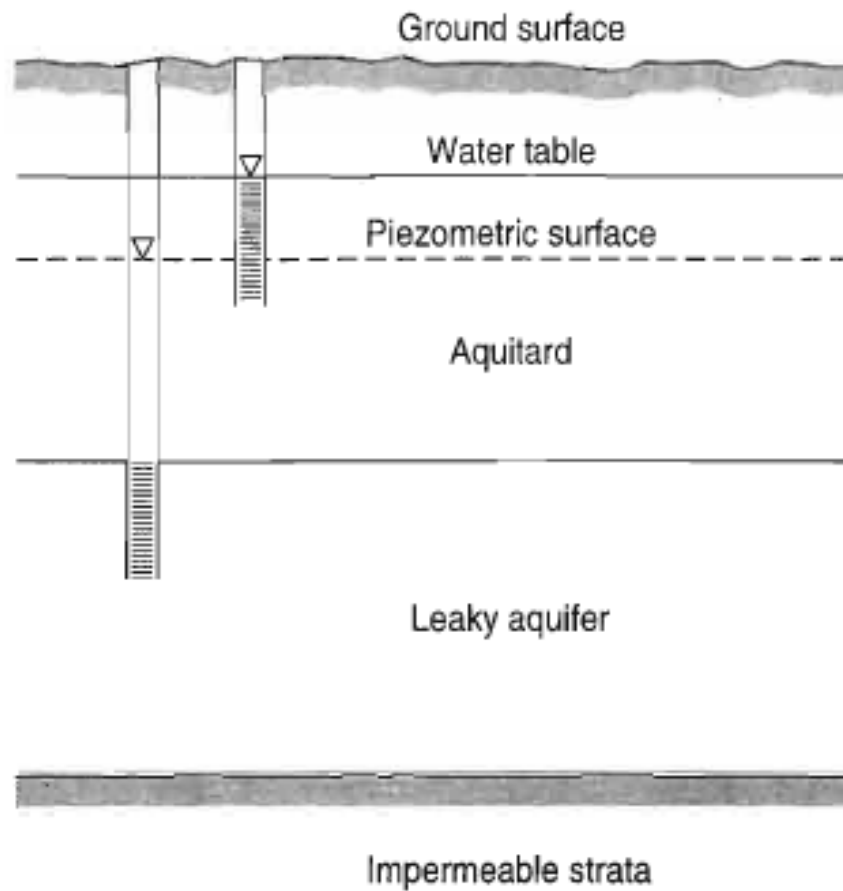
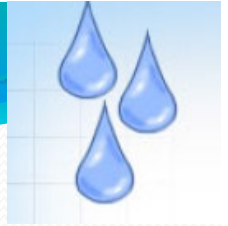
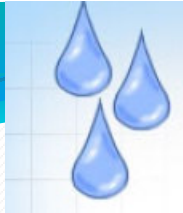


Figure 2.7.3. Sketch of a leaky, or semiconfined, aquifer.

Storage Coefficient



A *storage coefficient* (or *storativity*) is defined as 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 that surface. For a vertical column of unit area extending through a confined aquifer, as in Figure 2.8.1(a), the storage coefficient S equals the volume of water released from the aquifer when the piezometric surface declines a unit distance. The coefficient is a dimensionless quantity involving a volume of water per volume of aquifer. In most confined aquifers, values fall in the range $0.00005 < S < 0.005$, indicating that large pressure changes over extensive areas are required to produce substantial water yields. Storage coefficients can best be determined from pumping tests of wells (Chapter 4), or from groundwater fluctuations in response to atmospheric pressure or ocean tide variations (see Chapter 6).

The fact that S normally varies directly with aquifer thickness enables the rule-of-thumb relationship³⁴ for a confined aquifer

$$S = 3 \times 10^{-6}b \quad (2.8.1)$$

where b is the saturated aquifer thickness in meters to be applied for estimating purposes.

The storage coefficient for an unconfined aquifer corresponds to its specific yield, as shown in Figure 2.8.1(b).

Storage Coefficient

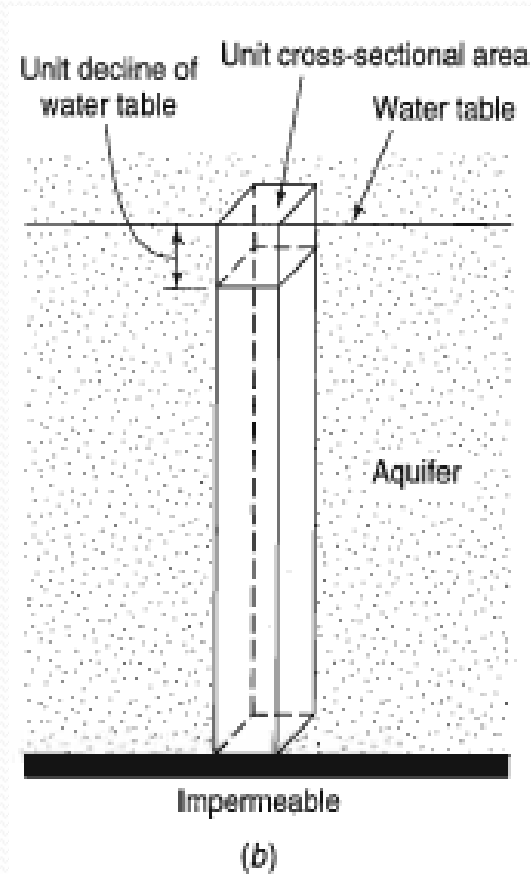
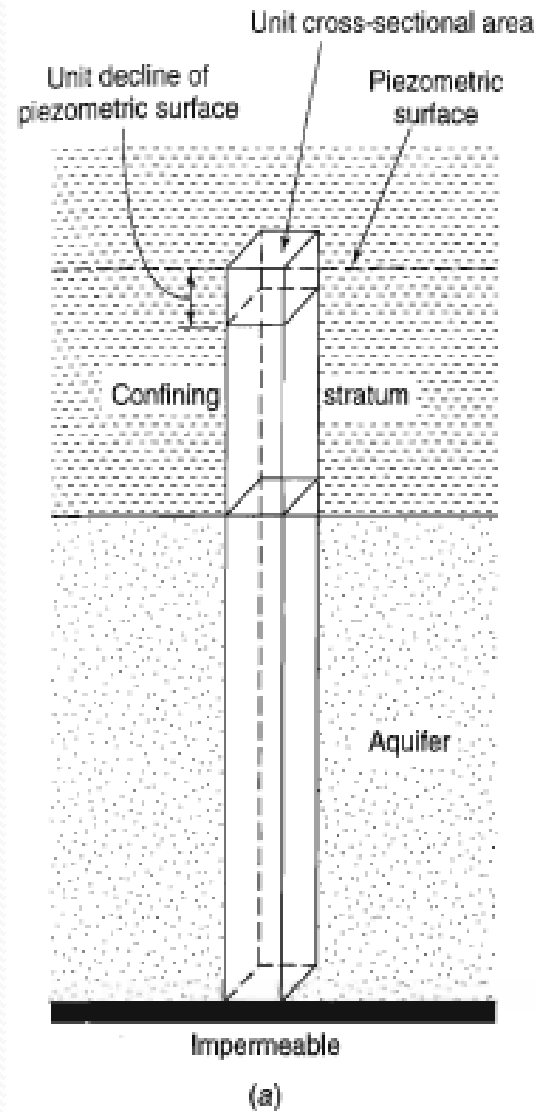
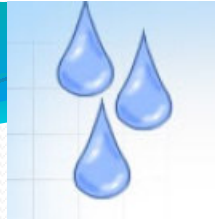
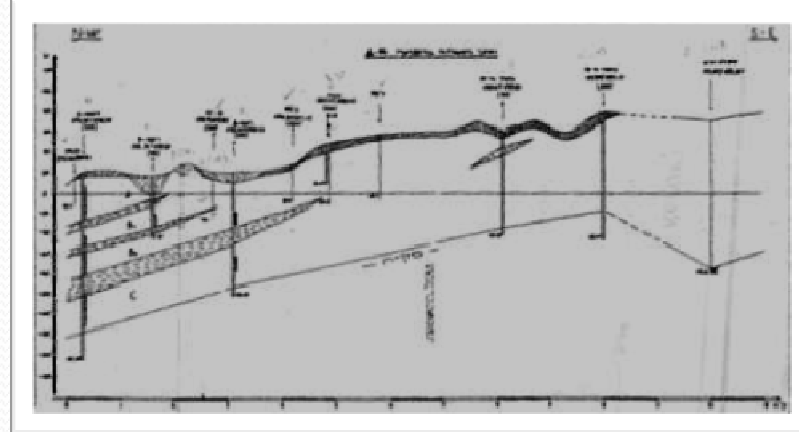
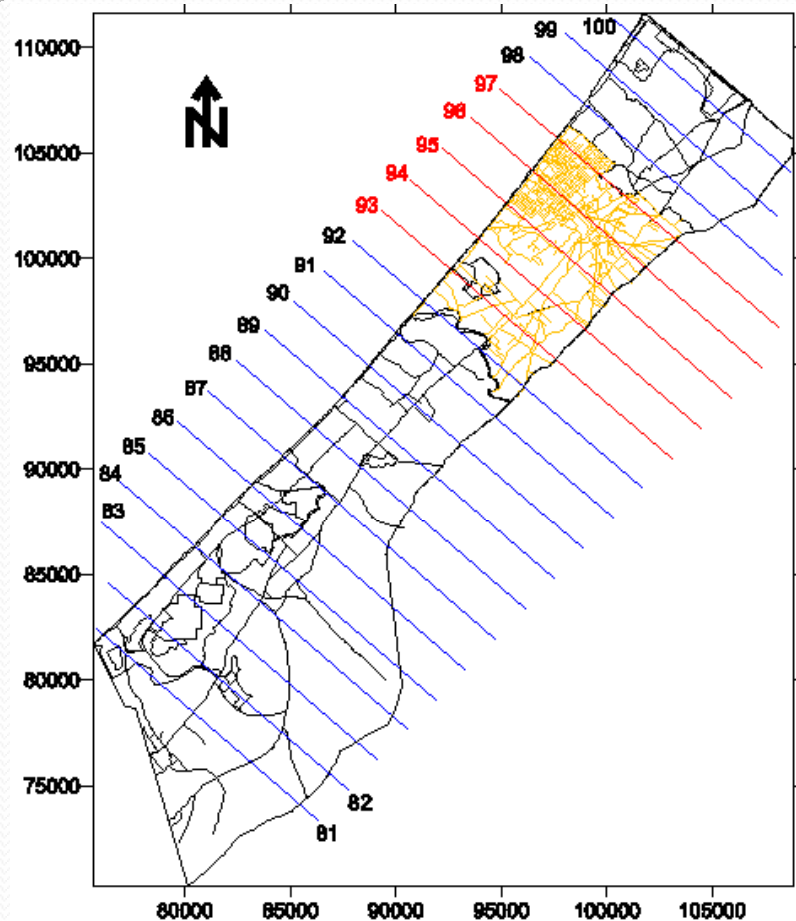
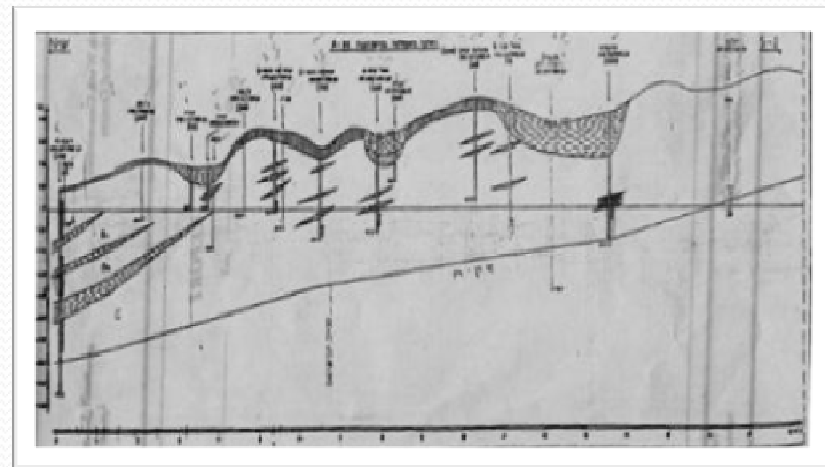


Figure 2.8.1. Illustrative sketches for defining the storage coefficient of (a) confined and (b) unconfined aquifers.

Gaza Aquifer



Geological cross section number 94



Geological cross section number 95