Chapter 2: Occurrence of Groundwater

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Origin and age of groundwater using Hydrogen-3 (tritium) and Carbon-14

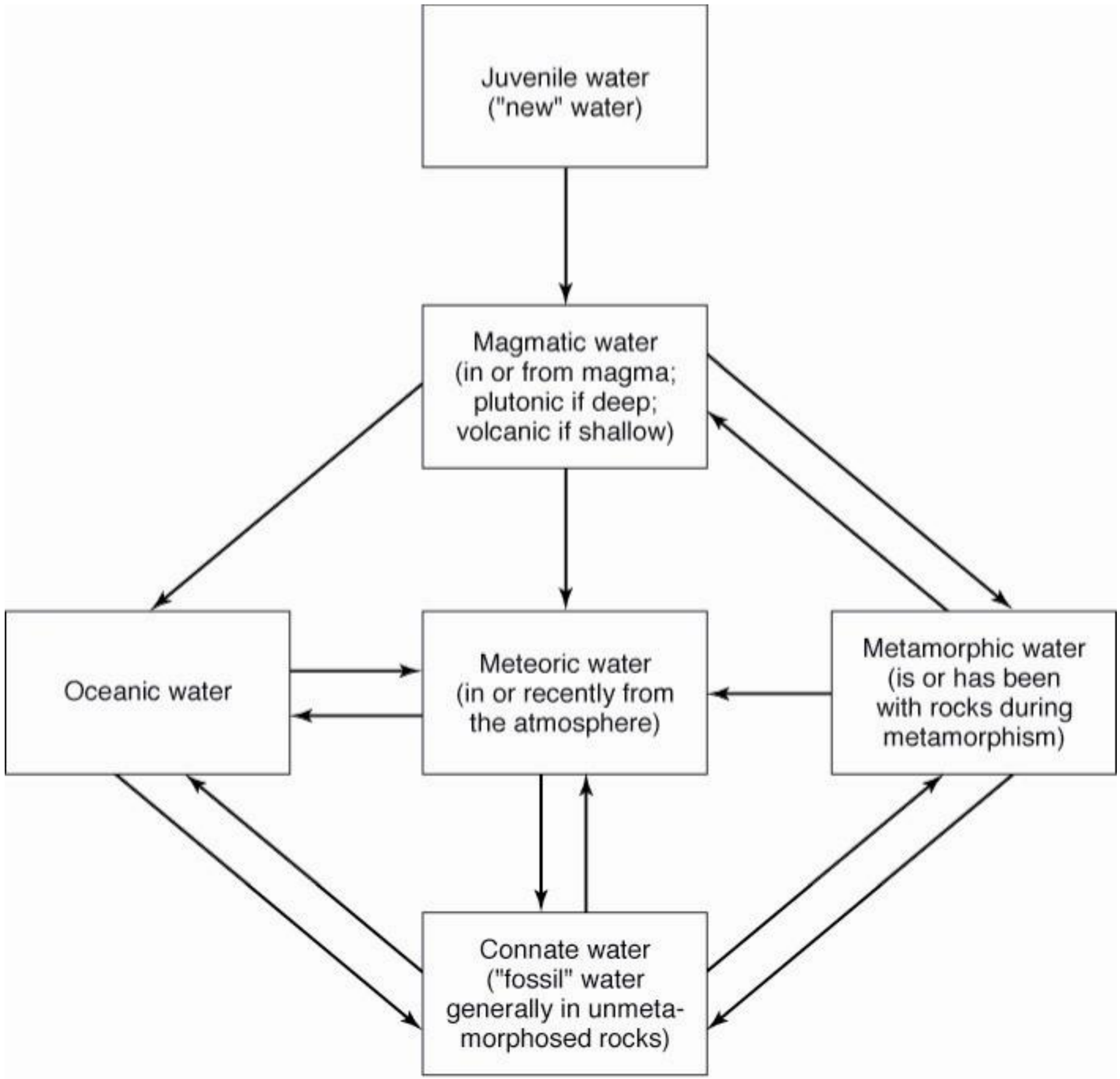
$$A = A_0 e^{-\lambda t}$$

$A = \text{Observed radioactivity}$

$A_0 = \text{Radioactivity at the time water entered into aquifer}$

$\lambda = \text{Decay constant}$

$t = \text{age of water}$


Juvenile water
("new" water)
Magmatic water
(in or from magma;
plutonic if deep;
volcanic if shallow)
Oceanic water
Meteoric water
(in or recently from
the atmosphere)
Metamorphic water
(is or has been
with rocks during
metamorphism)
Connate water
("fossil" water
generally in unmeta-
morphosed rocks)

Rock properties affecting groundwater

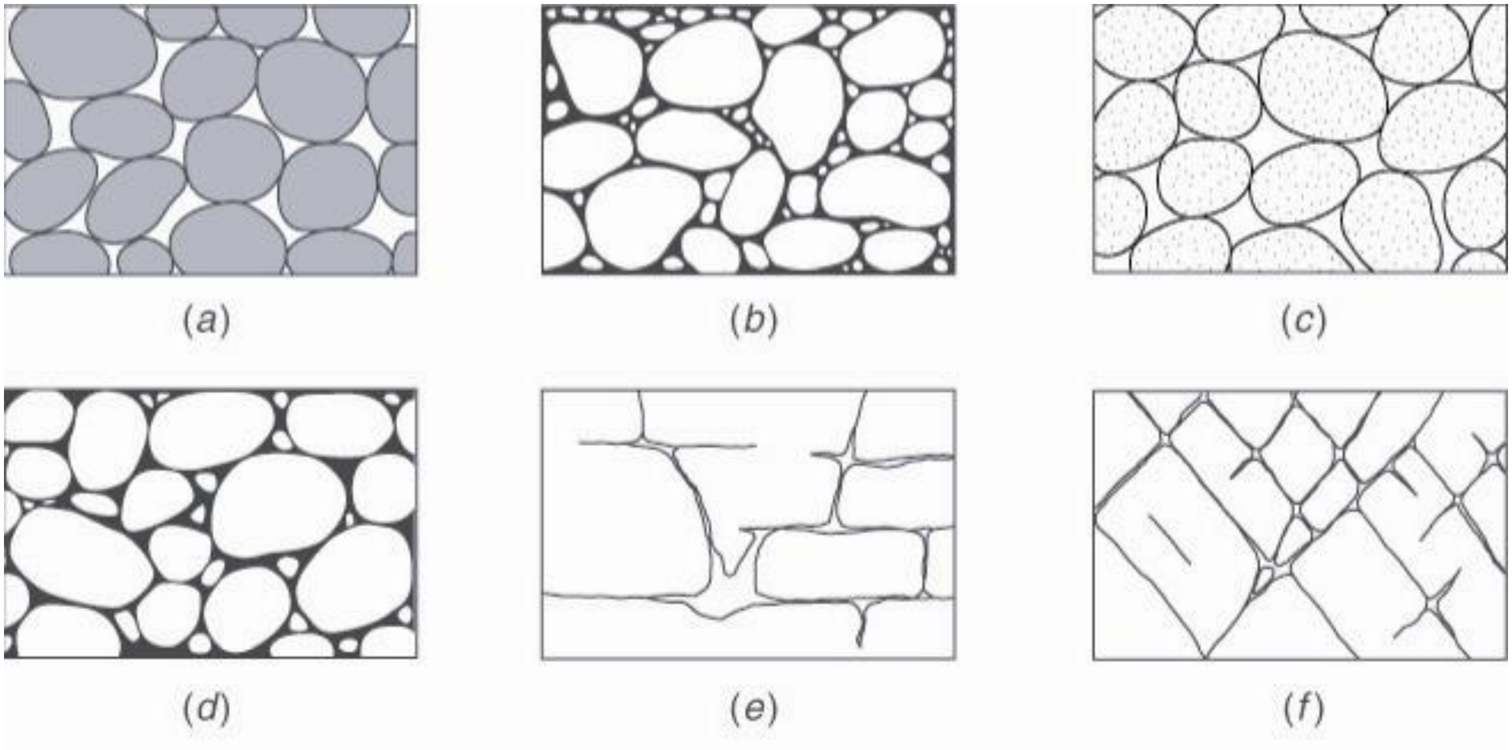
Aquifers

An ***aquifer*** may be defined as a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs. Aquifers are generally aerially extensive and may be overlain or underlain by a confining bed, which may be defined as a relatively impermeable material stratigraphically.

Types of confining beds

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

Porosity $$\alpha = \frac{V_v}{V_t} = \frac{V_t - V_s}{V_t} = \frac{\rho_m - \rho_d}{\rho_m} = 1 - \frac{\rho_d}{\rho_m}$$



(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

In sedimentary rocks subject to compaction:

$$\alpha_z = \alpha_0 e^{-az}$$

$$\alpha_z = \text{porosity at depth z}$$

$$\alpha_0 = \text{porosity at the surface}$$

$$a = \text{constant}$$

Table 2.2.1 Representative Values of Porosity (after Morris and Johnson[45])

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		

[a]These values are for repacked samples; all others are undisturbed.

Example 2.2.1

An undisturbed sample of a medium sand weighs 484.68 g. The core of the undisturbed sample is 6 cm in diameter and 10.61 cm high. The sample is oven-dried for 24 hr at 110°C to remove the water content. At the end of the 24 hr, the core sample weighs 447.32 g. Determine the bulk density, void ratio, water content, porosity, and saturation percentage of the sample.

The dry weight of the sample is $W_d = 447.32$ g and the total weight is $W_T = 484.68$ g. The total volume of the undisturbed sample is

$$V_t = \pi r^2 h = \pi(3\text{ cm})^2(10.61\text{ cm}) = 300\text{ cm}^3$$

The *bulk density* is defined as the density of solids and voids together, after drying. Thus,

$$\rho_d = \frac{W_d}{V_t} = \frac{447.32\text{ g}}{300\text{ cm}^3} = 1.491\text{ g/cm}^3$$

Assuming quartz is the predominant mineral in the sample, then $\rho_m = 2.65$ g/cm^3

Thus, the volume V_s of the solid phase of the sample is

$$V_s = \frac{W_d}{\rho_m} = \frac{447.32\text{ g}}{2.65\text{ g/cm}^3} = 168.8\text{ cm}^3$$

Thus, the *total volume of voids* in the sample is

$$V_v = V_t - V_s = 300\text{ cm}^3 - 168.8\text{ cm}^3 = 131.2\text{ cm}^3$$

With this information, we can calculate the *void ratio e* of the sample is

$$e = \frac{V_v}{V_s} = \frac{131.2\ \text{cm}^3}{168.8\ \text{cm}^3} = 0.777$$

The *volumetric water content* of a sample is the volume of the water divided by the volume of the sample

$$\theta_v = \frac{V_{\text{water}}}{V_t} = \frac{(W_T - W_d)/\rho_{\text{water}}}{V_t} = \frac{484.68\ \text{g} - 447.32\ \text{g}}{300\ \text{cm}^3} / 1\text{g}/\text{cm}^3 = 0.1245\ \text{g/cm}^3 = 0.125$$

where W_w is the total weight of the undisturbed sample before drying.
The *gravimetric water content* of the sample is

$$\theta_w = \frac{\text{W}_T - \text{W}_d}{\text{W}_d} \times 100 = \frac{484.68\ \text{g} - 447.32\ \text{g}}{447.32\ \text{g}} \times 100 = 8.35\%$$

The porosity of the sample is

$$\alpha = \frac{V_t - V_s}{V_t} \times 100 = \frac{300\ \text{cm}^3 - 168.8\ \text{cm}^3}{300\ \text{cm}^3} \times 100 = 43.73\%$$

Finally, the *saturation percentage of a sample* is defined as the percentage of the pore space that is filled by water,

$$\frac{\theta_v}{\alpha} \times 100 = \frac{(0.1245)}{(0.4373)} \times 100 = 28.47\%$$

■

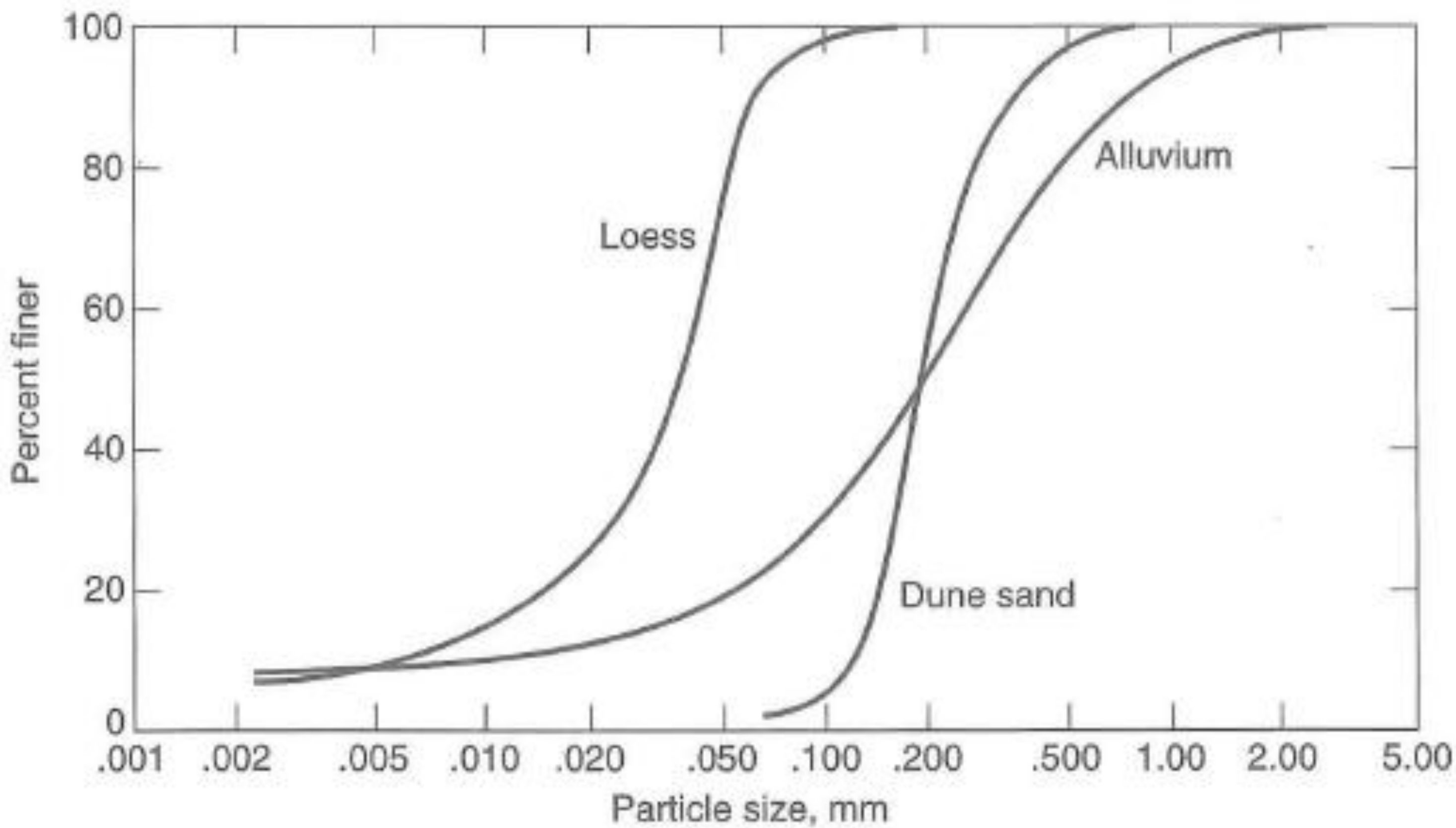
Soil classification

$$U_c = \frac{d_{60}}{d_{10}}$$

U_c = uniformity coefficient

d_{60} = 60% finer than the value

d_{10} = 10% finer than the value



Soil classification

Table 2.2.2 Soil Classification Based on Particle Size (after Morris and Johnson[45])

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

Group Symbols	Typical Names		Classification Criteria	
GW	Well-graded gravels and gravel-sand mixtures, little or no fines	Classification on basis of percentage of fines Less than 5% Pass No. 200 sieve: *GW*, *GP*, *SW*, *SP* More than 12% Pass No. 200 sieve: *GM*, *GC*, *SM*, *SC* 5% to 12% Pass No. 200 sieve: Borderline classification requiring use of dual symbols	$C_u = D_{60}/D_{10}$ Greater than 4 $C_z = \dfrac{(D_{30})^2}{D_{10} \times D_{60}}$ Between 1 and 3	
GP	Poorly graded gravels and gravel-sand mixtures, little or no fines		Not meeting both criteria for *GW*	
GM	Silty gravels, gravel-sand-silt mixtures		Atterberg limits plot below "*A*" line or plasticity index less than 4	Atterberg limits plotting in hatched area are borderline classifications requiring use of dual symbols
GC	Clayey gravels, gravel-sand-clay mixtures		Atterberg limits plot above "*A*" line and plasticity index greater than 7	
SW	Well-graded sands and gravelly sands, little or no fines		$C_u = D_{60}/D_{10}$ Greater than 6 $C_z = \dfrac{(D_{30})^2}{D_{10} \times D_{60}}$ Between 1 and 3	
SP	Poorly graded sands and gravelly sands, little or no fines		Not meeting both criteria for *SW*	
SM	Silty sands, sand-silt mixtures		Atterberg limits plot below "*A*" line or plasticity index less than 4	Atterberg limits plotting in hatched area are borderline classifications requiring use of dual symbols
SC	Clayey sands, sand-clay mixtures		Atterberg limits plot above "*A*" line and plasticity index greater than 7	

Ref: Peck Hanson & Thornburn 2nd Ed.

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?

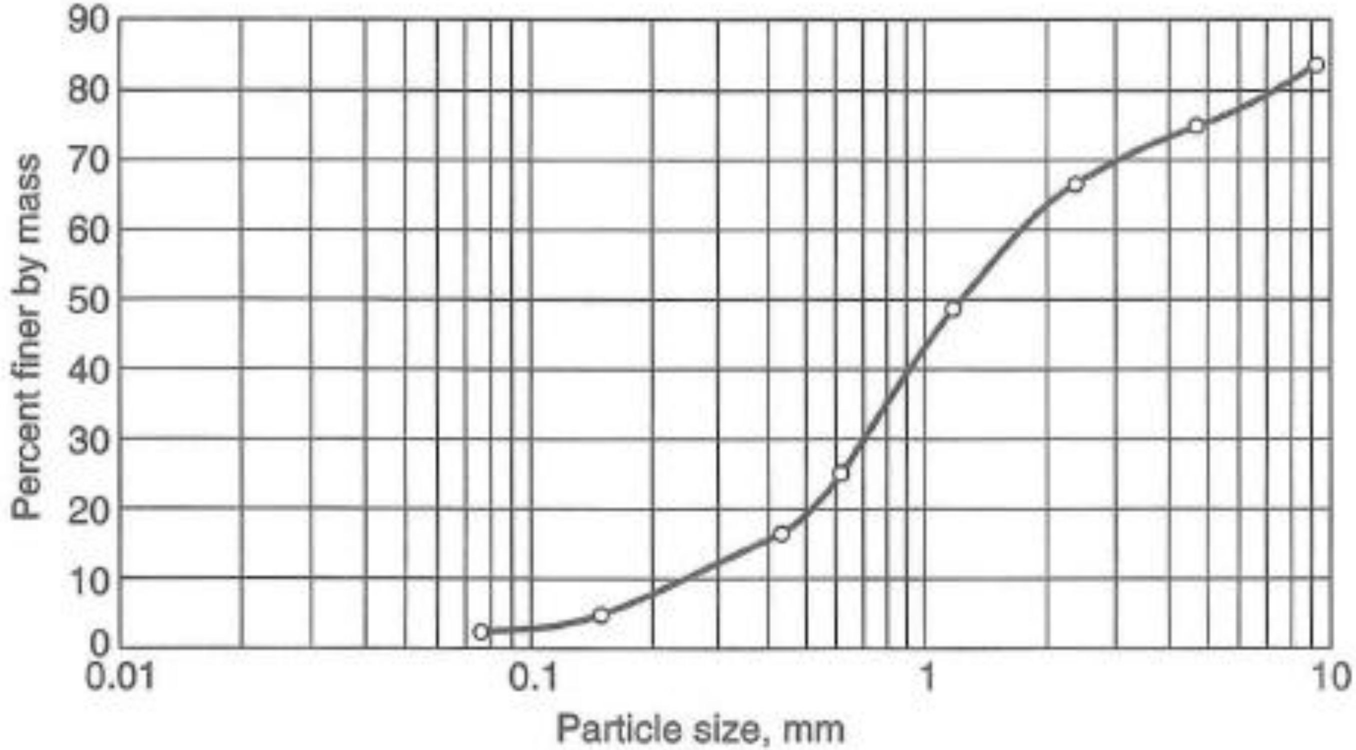
(c) Classify the sample using Table 2.2.2.

(d) What would be reasonable porosity values for this sample?

U.S. Standard Sieve Number	Mass retained (g)
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
Pan (passes through #200 sieve)	8.28
Total sample weight	300.00

(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:

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

From Equation 2.2.4, the uniformity coefficient is

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

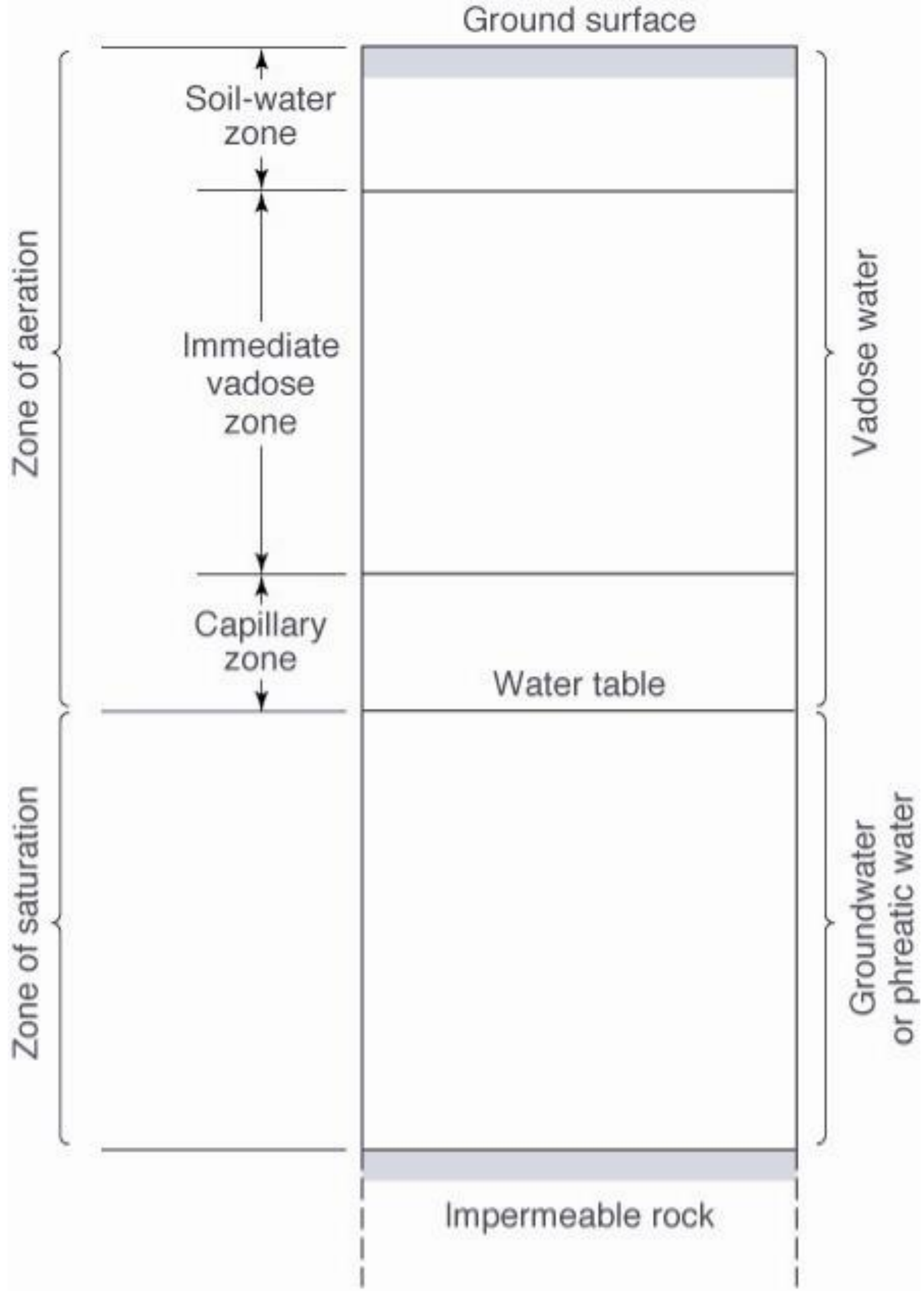
Since $U_c > 6$, the sample can be described as well graded (i.e., low uniformity).

(c) The percentage of clay and silt in the sample is approximately 2–3 percent, while about 60 percent of the sample is sand. The remaining 37–38 percent is composed of very fine to coarse gravel.

(d) The porosity of the sample could be somewhere between 20 and 35 percent based on our classification in part (c). ■

Vertical distribution of groundwater

Zone of aeration



Zone of saturation

Specific retention and Specific yield

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,

$$S_r = \frac{w_r}{V_t} \tag{2.5.1}$$

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

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,

$$S_y = \frac{w_y}{V_t} \tag{2.5.2}$$

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

$$V_v = w_r + w_y \tag{2.5.3}$$

or

$$\alpha = S_r + S_y \tag{2.5.4}$$

where all pores are interconnecting.

Table 2.5.1 Representative Values of Specific Yield (after Johnson[25])

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

Example 2.5.1

Estimate the average drawdown over an area where 25 million m^3 of water has been pumped through a number of uniformly distributed wells. The area is 150 km^2 and the specific yield of the unconfined aquifer is 25 percent.

The volume of water drained is $w_y = 25 \times 10^6$ m^3. Eq. 2.5.2 is used to determine the bulk volume, V_t, of the aquifer to extract this volume of water:

$$S_y = \frac{w_y}{V_t}$$

$$0.25 = \frac{25 \times 10^6 \text{ m}^3}{V_t} \rightarrow V_t = 1 \times 10^8 \text{ m}^3$$

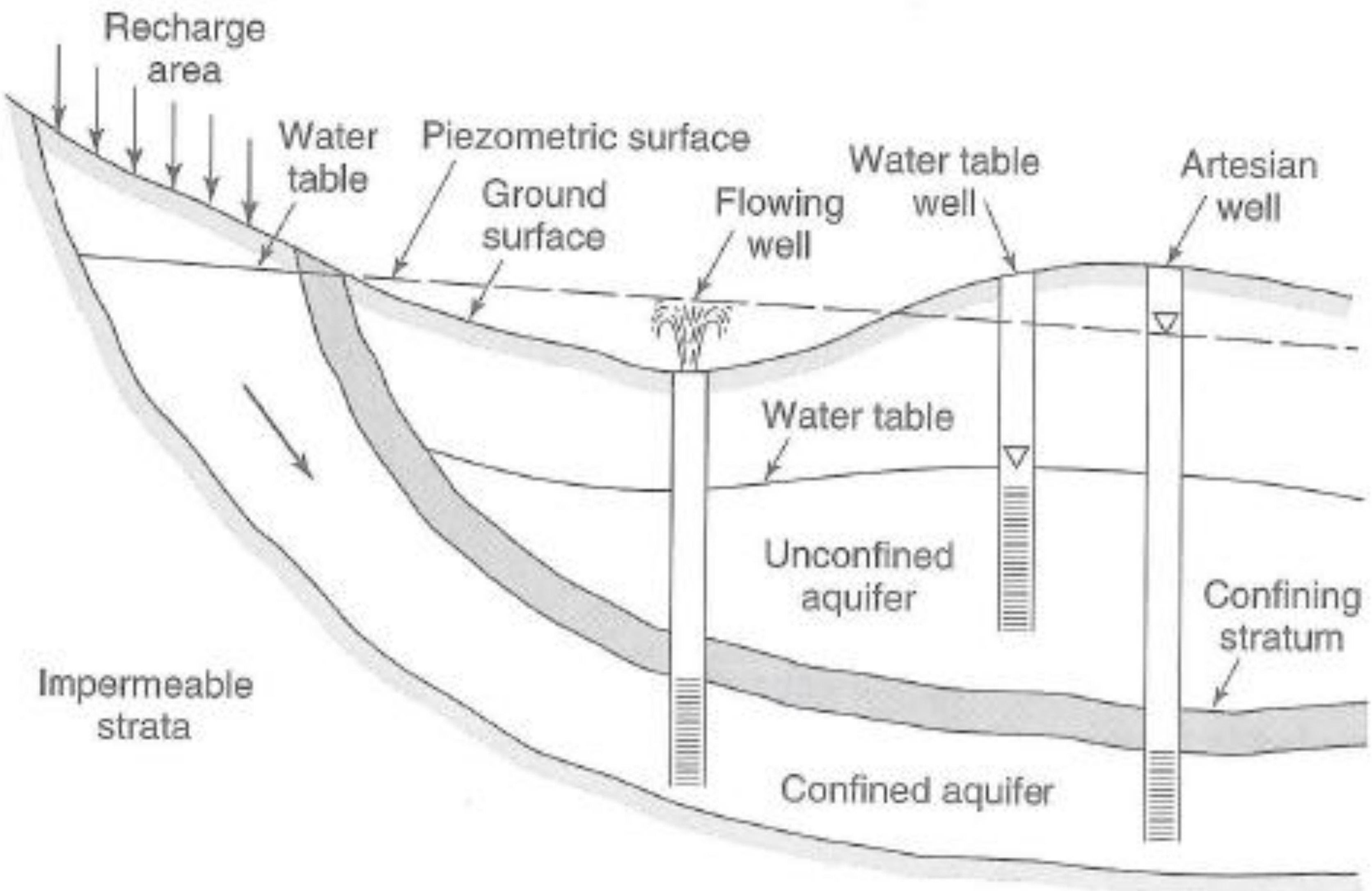
Thus, the average water level drop over the area is $\Delta h = \frac{V_t}{A} = \frac{1 \times 10^8 \text{ m}^3}{150 \times 10^6 \text{ m}^2} = 0.67 \text{ m}$.

Geologic formations as aquifers

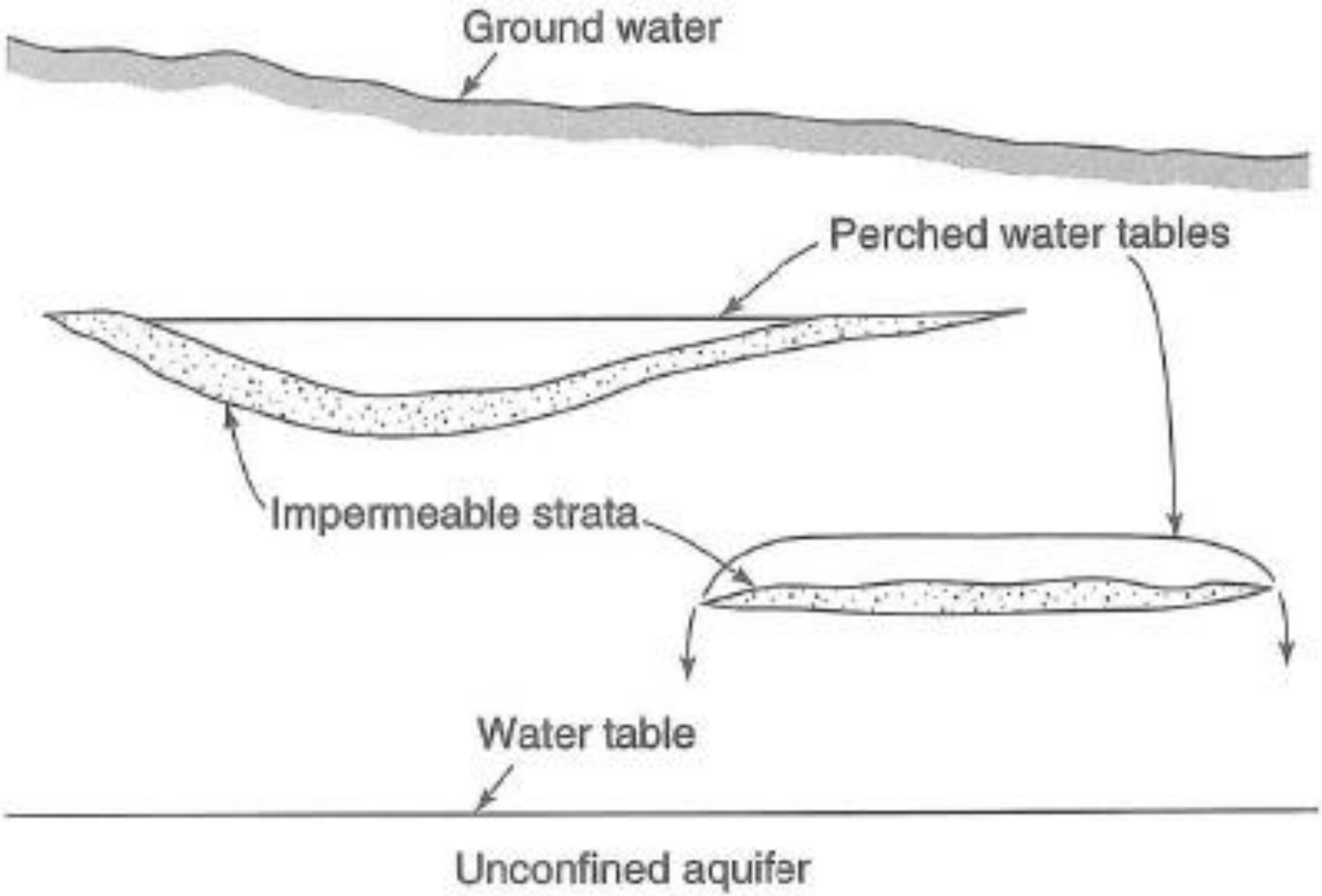
Table 2.6.1 Geologic Origin of Aquifers Based on Type of Porosity and Rock Type (after Dept. of Economic and Social Affairs[16])

Type of porosity	Sedimentary			Igneous and metamorphic	Volcanic	
	Consolidated	*Unconsolidated*	*Carbonates*		*Consolidated*	*Unconsolidated*
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	

Types of aquifers



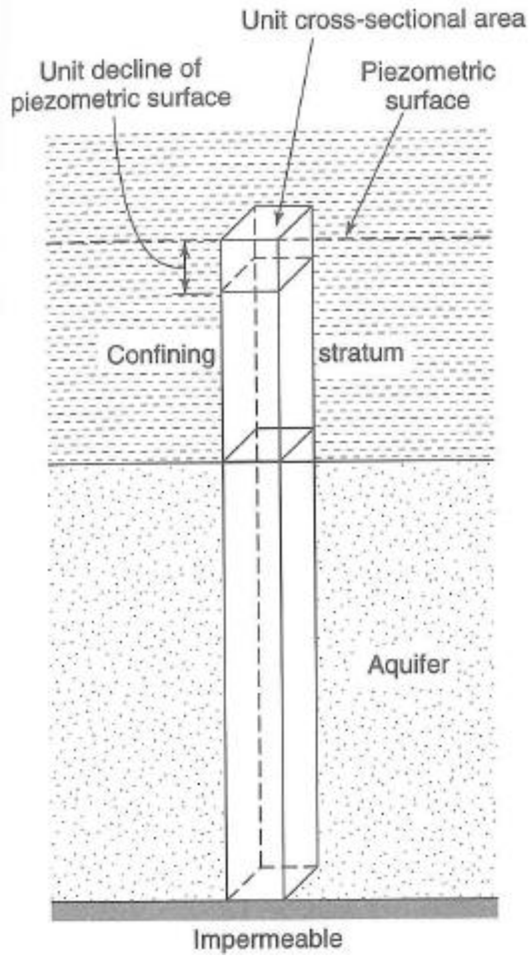
Types of aquifers

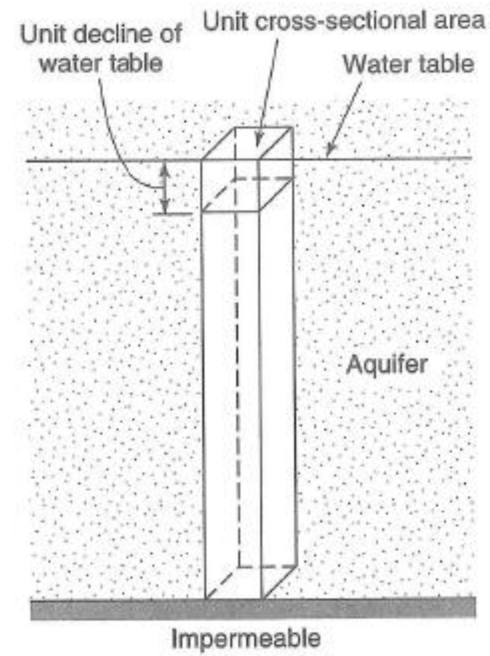


Storage coefficient

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, 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

Springs

A spring is a concentrated discharge of groundwater appearing at the ground surface as a current of flowing water. To be distinguished from springs are seepage areas, which indicate a slower movement of groundwater to the ground surface. Water in seepage areas may pond and evaporate or flow, depending on the magnitude of the seepage, the climate, and the topography.

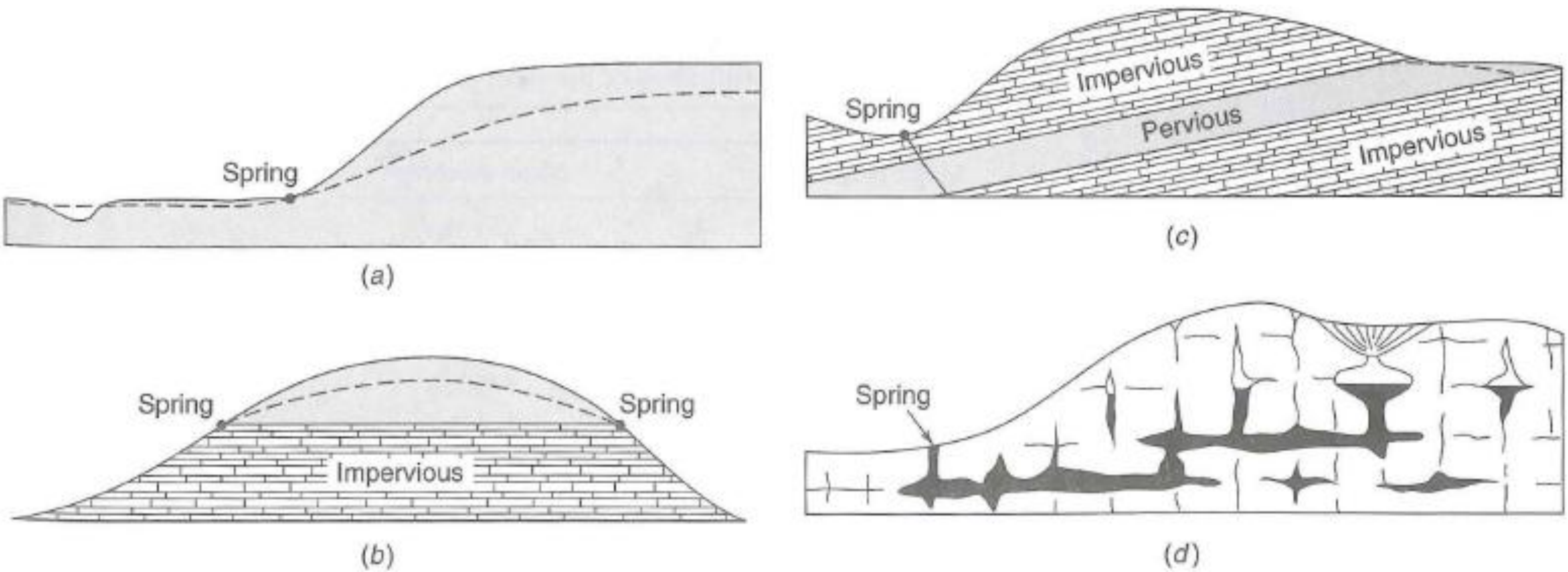


Figure 2.10.1. Diagrams illustrating types of gravity springs. (*a*) Depression spring. (*b*) Contact spring. (*c*) Fracture artesian spring. (*d*) Solution tubular spring (after Bryan,[10] copyright © 1919 by the University of Chicago Press).