Groundwater Hydrology

Rain: Falls on and enters land surface.

- Some will flow over land surface as runoff- relatively common- important when the ground is frozen.
- Some will enter as interflow- just below the surface of the land- a very porous horizon (shallow flow system).
- The rest percolates into the soil

  → A high percentage of that is transferred back into the vapor phase through evaporation and transpiration (in temperate climates).

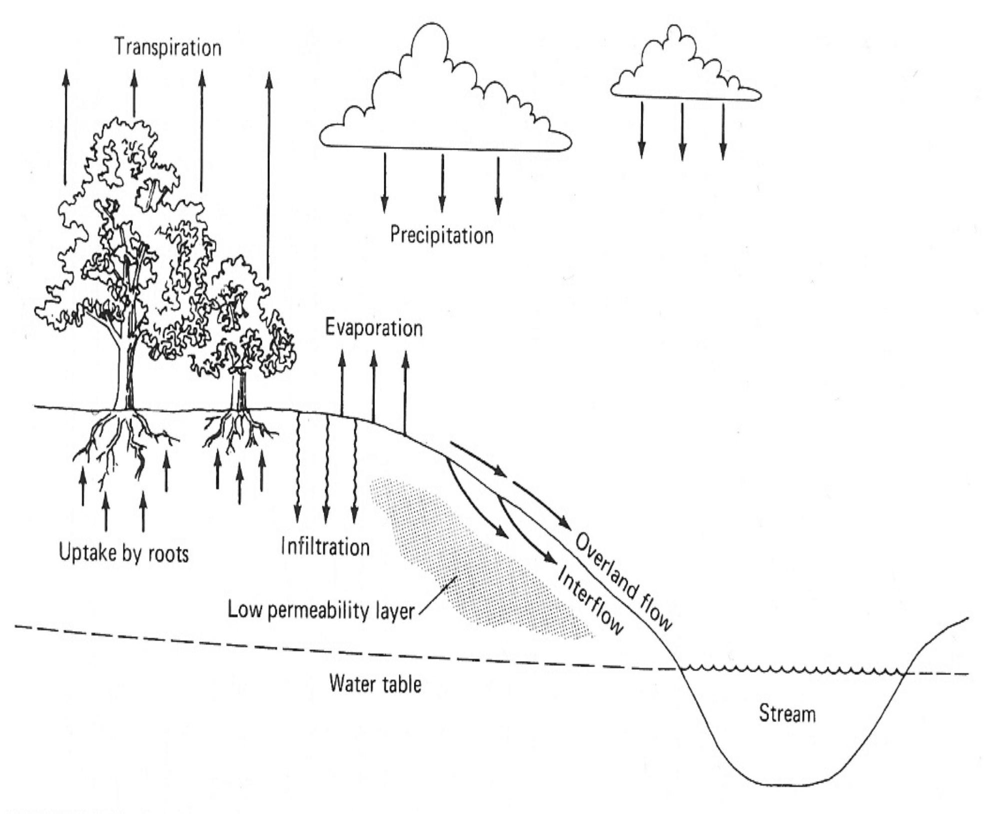


FIGURE 1-6 Near-surface hydrologic processes.

- When it rains, the water table can change dramatically.
- The flow of a stream will increase during/after a storm even though there is little runoff.
  - In this model, the stream represents area where the land is below the water table.
  - Increased stream discharge- should be intuitively obvious why...
    - Rain percolates down and raises the level of the water table.
    - 2 cm rainfall may percolate quickly and dramatically change the level of the water table by about 50 cm! This is because the zone above the saturated zone is not totally devoid of water- only some of the void spaces have to be filled in (ie capillary fringe may be 90% full).

http://www.largest.org/c0d3/image_gimme.cgi?i=968

Change in the water table → increase in the flow of the stream.

- Therefore, the slope of the water table has a direct effect on flow of water.
  - In a flat water table the water wouldn't flow, so must have some gradient to drive the flow therefore need slope.

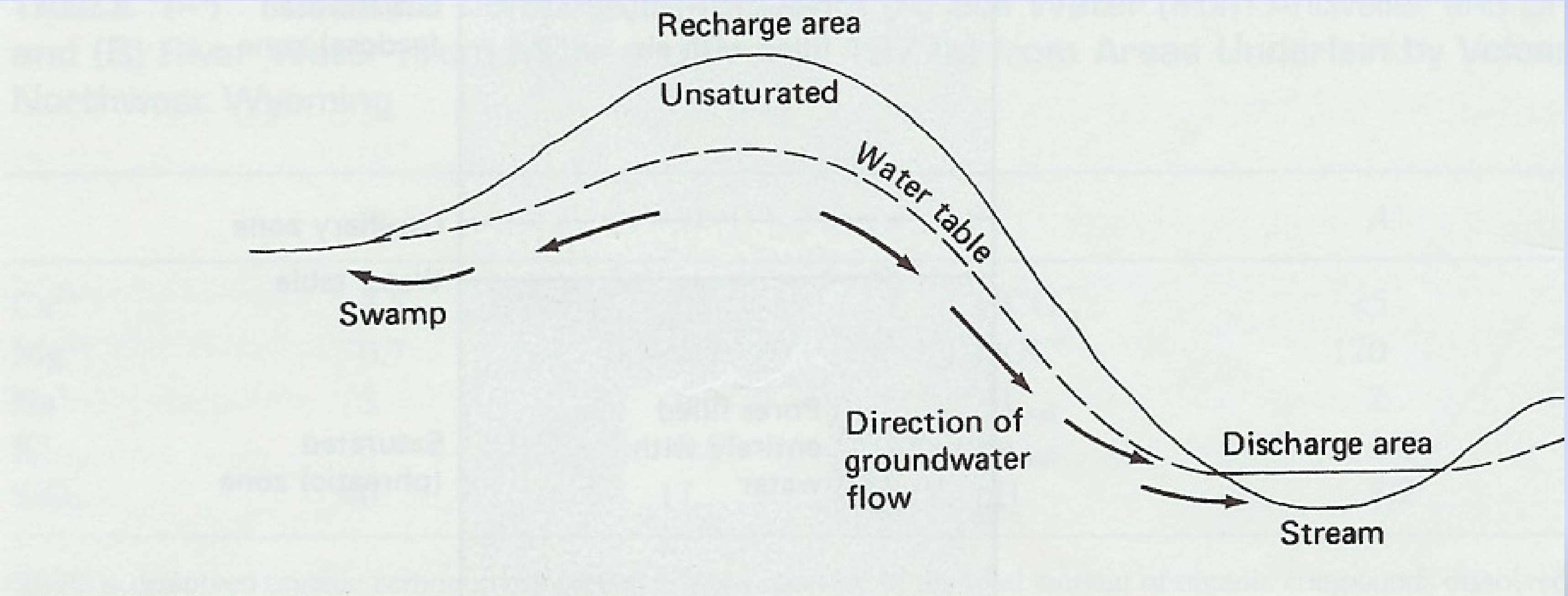


FIGURE 1-9 Groundwater system in a uniform, permeable rock.

Drever, *The Geochemistry of Natural Waters*

Water ‘box’(Weir) constructed to monitor flow.

- During rain events, the flow increases.
- But the water transported is not just the water from the precipitation event but rather water in the subsurface.

→ How does the water flow through the subsurface?

* Need to look at tools to measure flow and factors controlling flow.

- Flow is driven by gradient : height /length (∆h/∆l) of the water table
- The medium the water flows through also has an effect on the flow.

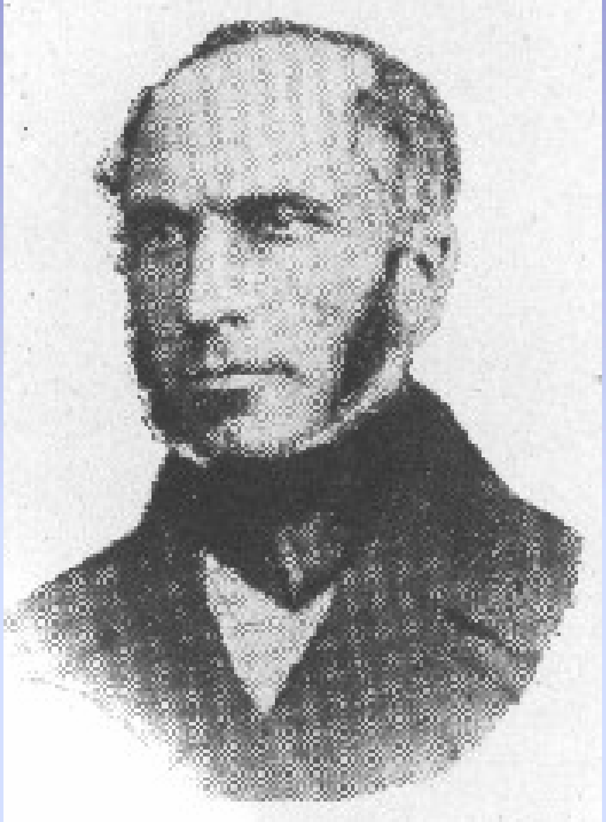
➔ The implications of these observations lead to…

DARCY'S LAW

Background

In 1856, Darcy was the 1st to do experiments with water flow through a tube to see how rapidly it flowed & what the controlling factors were.

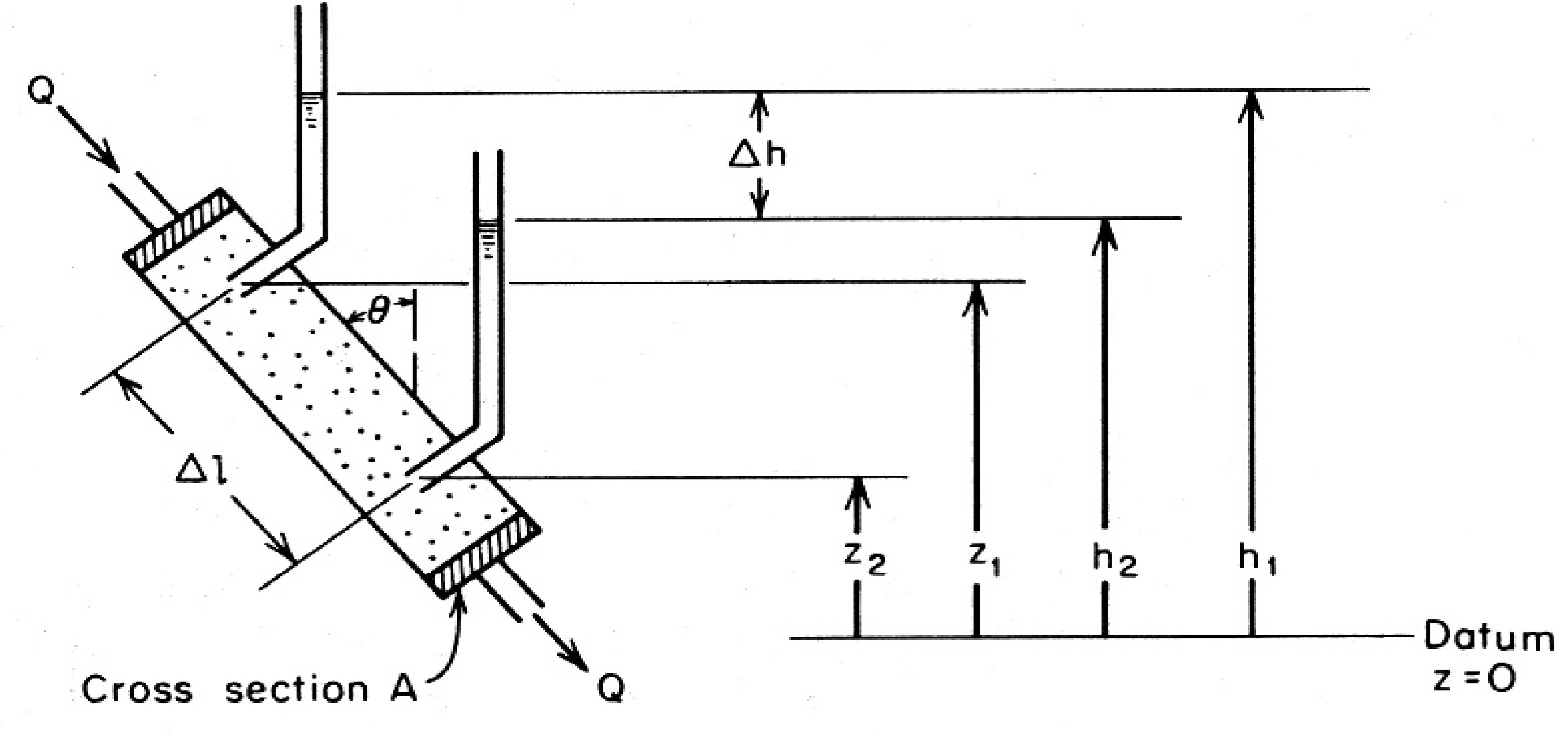
Question of interest: What determines the rate of discharge?



Henry Darcy (1803-1858)

http://www.edge.ou.edu/hydrogeology/page8.html

Experimental Apparatus for illustrating Darcy's Law



$Q = -KA((h_1-h_2)/L)$, where:

Q = volumetric discharge rate (L^3/T)
K = proportionality constant = hydraulic conductivity (L/T)
A = cross sectional area through which flow occurs (L^2)
h_1-h_2 = difference in hydraulic head over the flow distance (L)
L = distance through which flow occurs (L)

http://www.rses.anu.edu.au/~uli/Teaching/Hydro/Berno_Darcy.html

Darcy's Findings

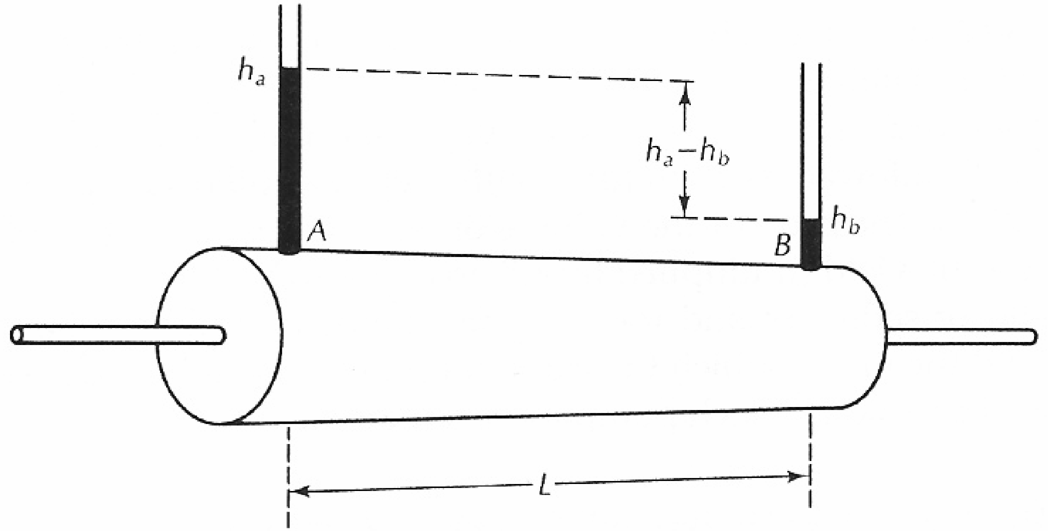
A. rate of discharge (Q) was:

1. proportional to change in height **Δh and change in length Δl.**

→ therefore, Q is proportional to the gradient Δh/ Δl

2. a function of the cross-sectional area (A).

3. **a function of the constant hydraulic conductivity (K) which varied with the medium.**



▲ FIGURE 3.12
Horizontal pipe filled with sand to demonstrate Darcy's experiment. (Darcy's original equipment was actually vertically oriented.)

Fetter, *Applied Hydrogeology 4th Edition*

Darcy's Law

B. Formula:

Q (flux) $= -K_iA(dh/dl) = K*A*(l_1-l_0)/x$ for a pipe

1. Q is negative because we're going from a higher to lower potential → (dh is negative ∴ Q is negative).

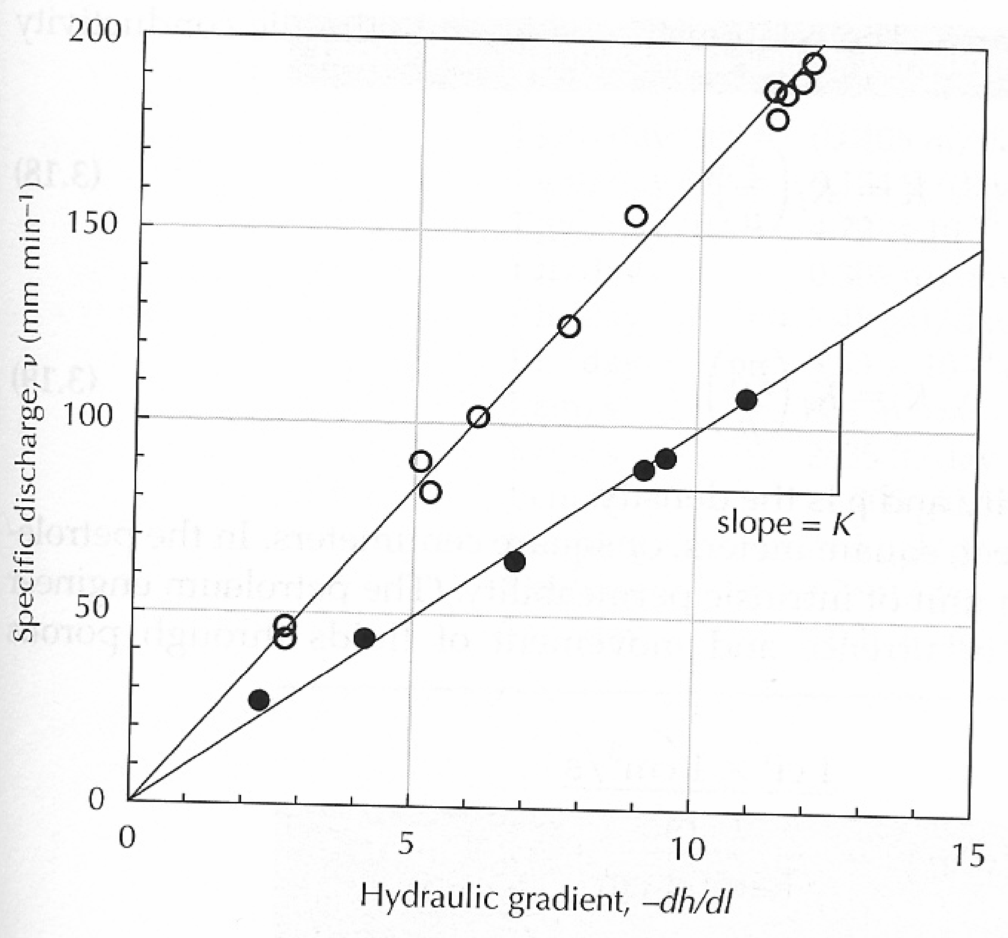


Figure 3.13 Original data from Darcy's 1856 experiments that show a linear relationship between specific discharge and hydraulic gradient for two different sands.

Fetter, *Applied Hydrogeology 4th Edition*

2. **K typically equals the hydraulic conductivity of the medium**(cm/sec), as given in Fetter for sand, silt, & clay

→There is a huge range in how rapidly a certain medium will conduct water – by ≈ 5 orders of magnitude!

range of values for k (m/s)

10^{2}
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}

clean gravels

clean sands
gravel-sand mixtures

very fine sands
silts and silty clays

clay silts (>20% clay)
unfissured clays

http://fbe.uwe.ac.uk/public/geocal/SoilMech/water/water.htm#>PERMSTRAT

Flow in Aquifer Systems

Basic Terminology:

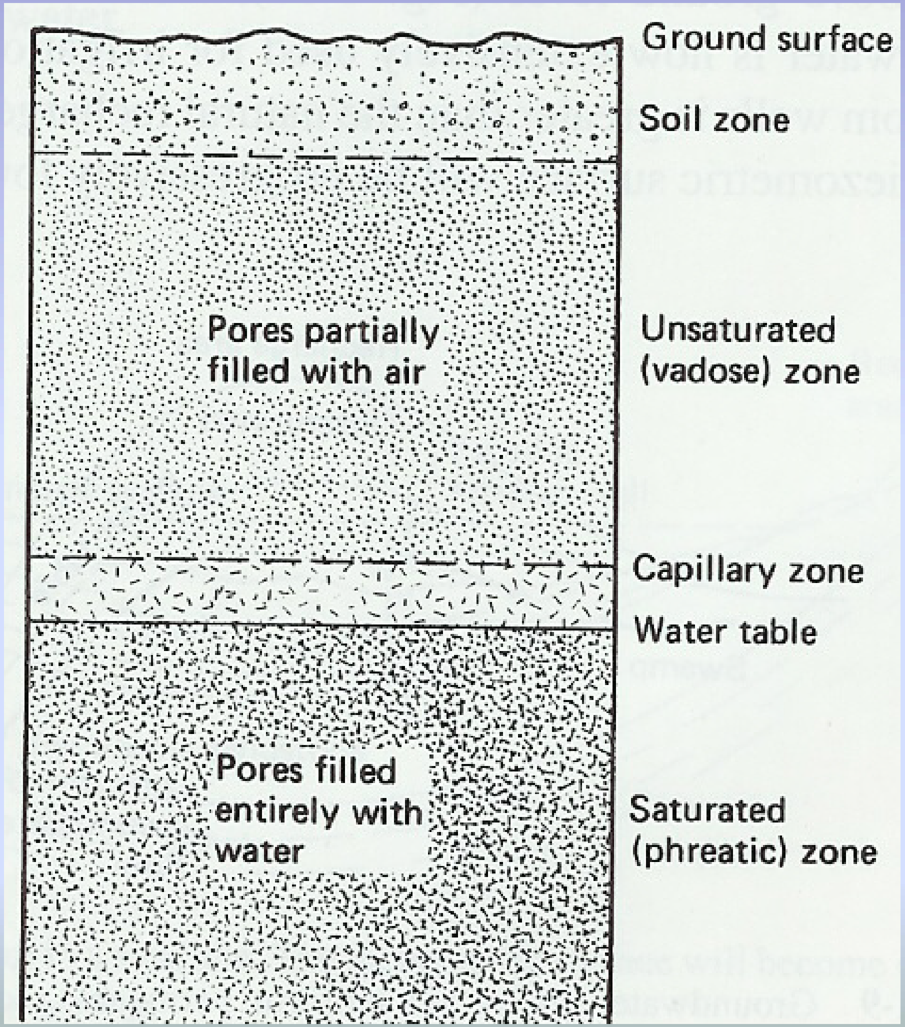
B. ***Water table***:

determined line below which you could put a well and receive water.

C. ***Saturated zone***:

Water percolates down through the unsaturated zone and is composed of sand particles, air space and water. The saturated zone is where all the pore spaces are full of water.

Subsurface features in permeable rock



Drever, *The Geochemistry of Natural Waters, Figure 1-8*

Flow in Aquifer Systems

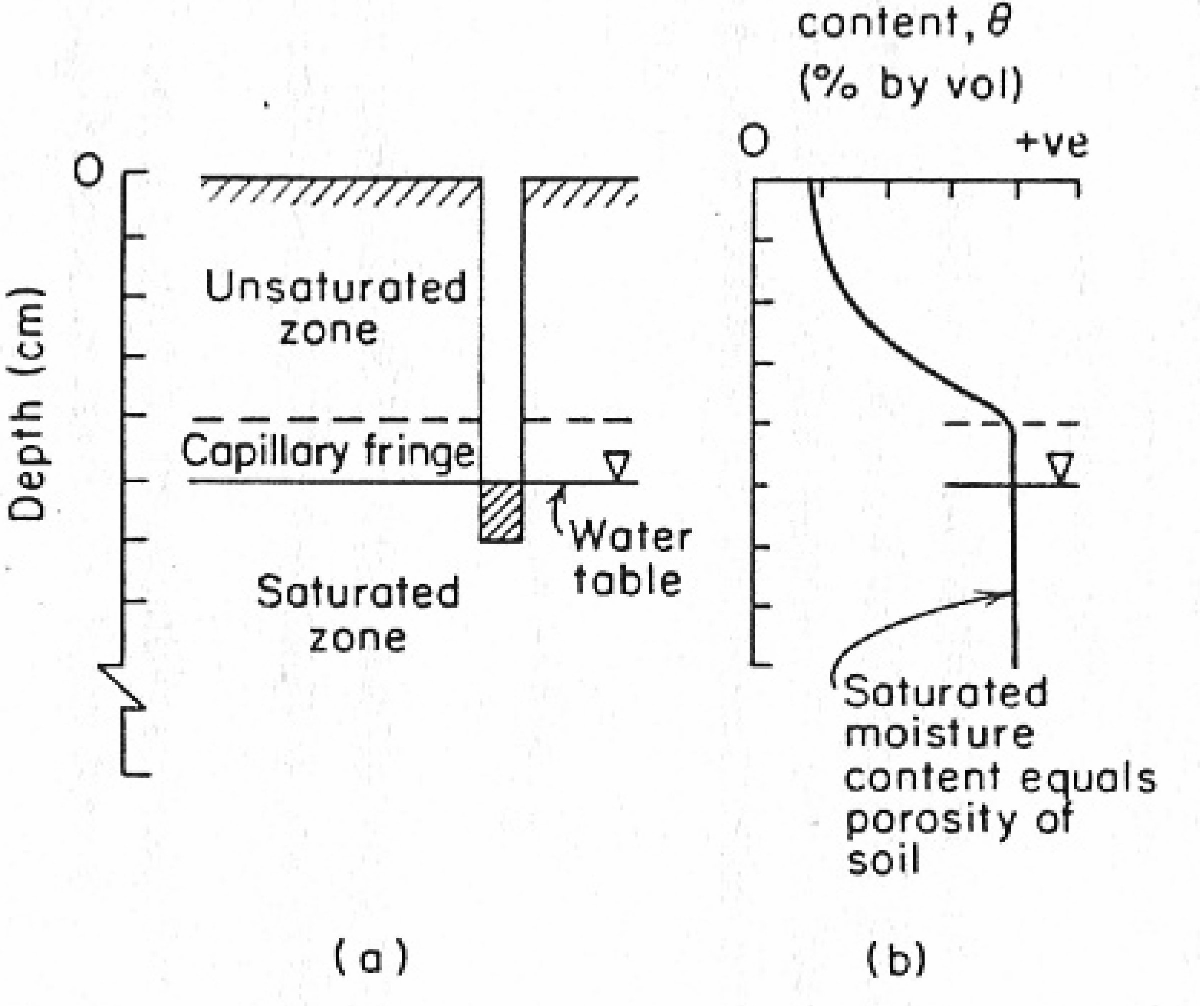
Basic Terminology

D. *Capillary fringe* (the boundary between the water table and the unsaturated zone): has all the pore spaces full of water, but you could not draw water from a well at that depth .

Reason: the surface tension associated with the grain boundary holds the water by the grain, at less than atmospheric pressure

- This zone can be about 5 cm in sand and about 1 meter in silt (higher surface tension effects)

Groundwater conditions near the ground surface



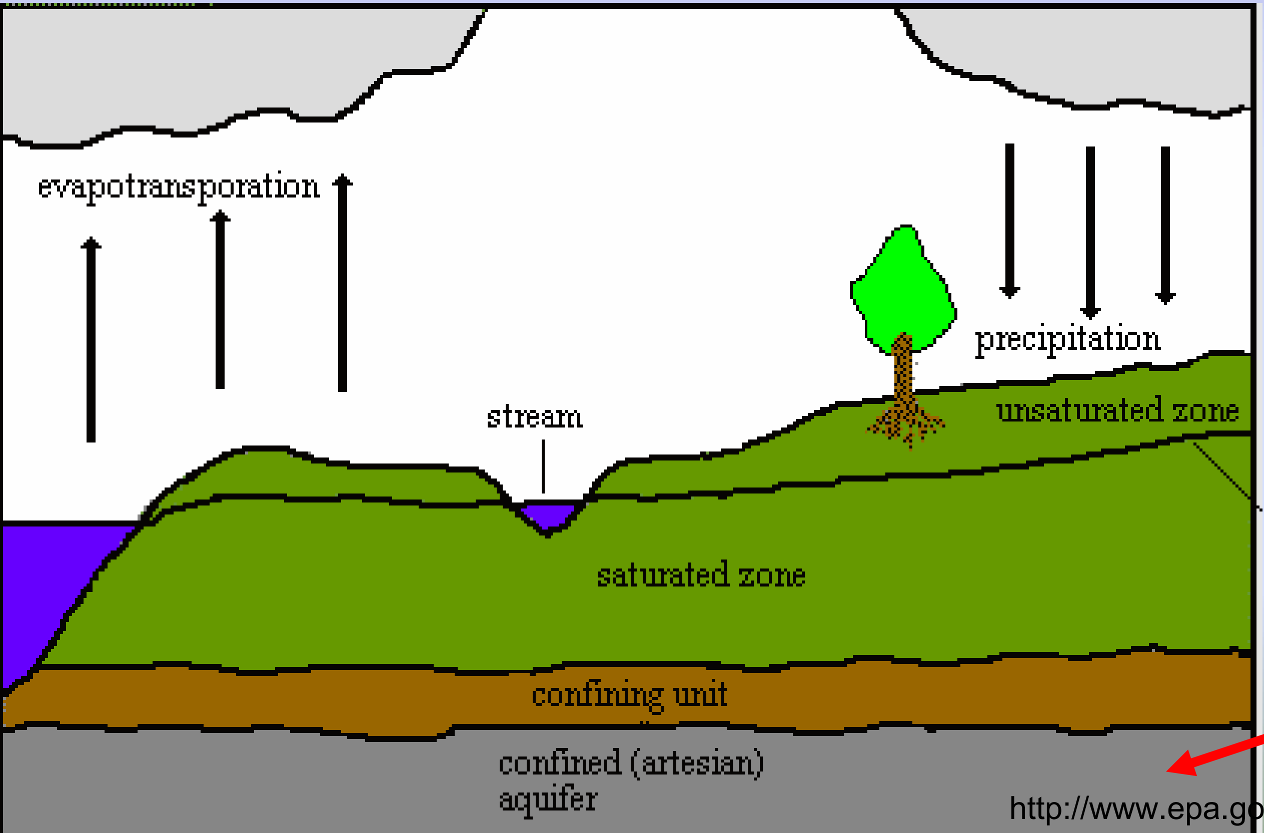
Saturated and unsaturated zones

Profile of moisture content vs. depth

Figure 2.12. Freeze and Cherry, *Groundwater*, Ch. 2

Confined aquifer system characteristics:

* Often get freely flowing well (Artesian) where water flows to surface, because the water is held “prisoner” (i.e. CONFINED) at a point below the water table and the water pressure will drive the water in the well above the water table level.



Root zone

Capillary fringe

Water table

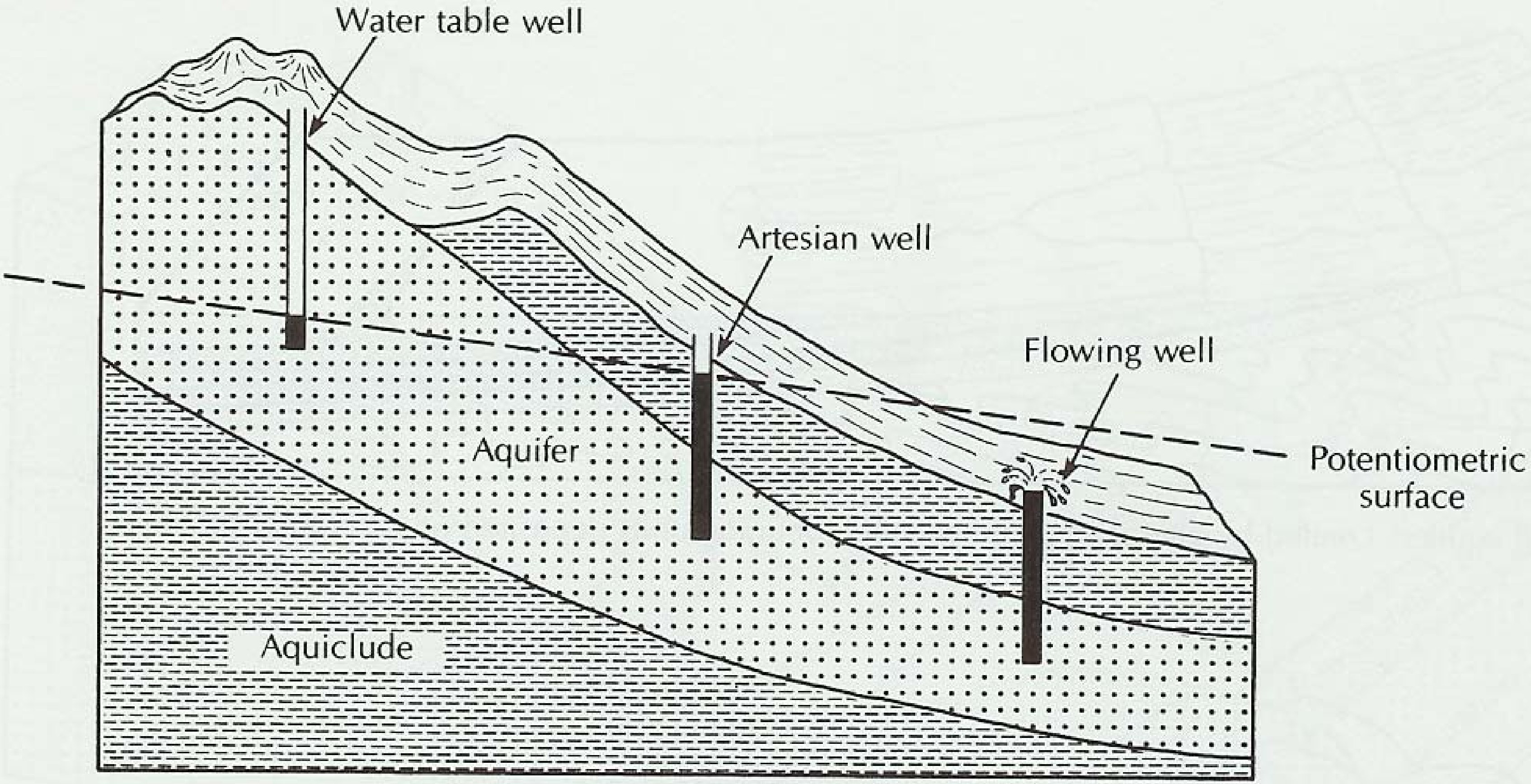
Unconfined aquifer

Confined (artesian aquifer)

http://www.epa.gov/seahome/groundwater/src/watertable.htm

Deep confined system:

* The water in wells from the confined aquifer doesn’t reach up quite as high as the water from the unconfined aquifer.



▲ FIGURE 3.22

Artesian and flowing well in confined aquifer.

Fetter, *Applied Hydrogeology 4th Edition*

Confined and Unconfined Aquifers

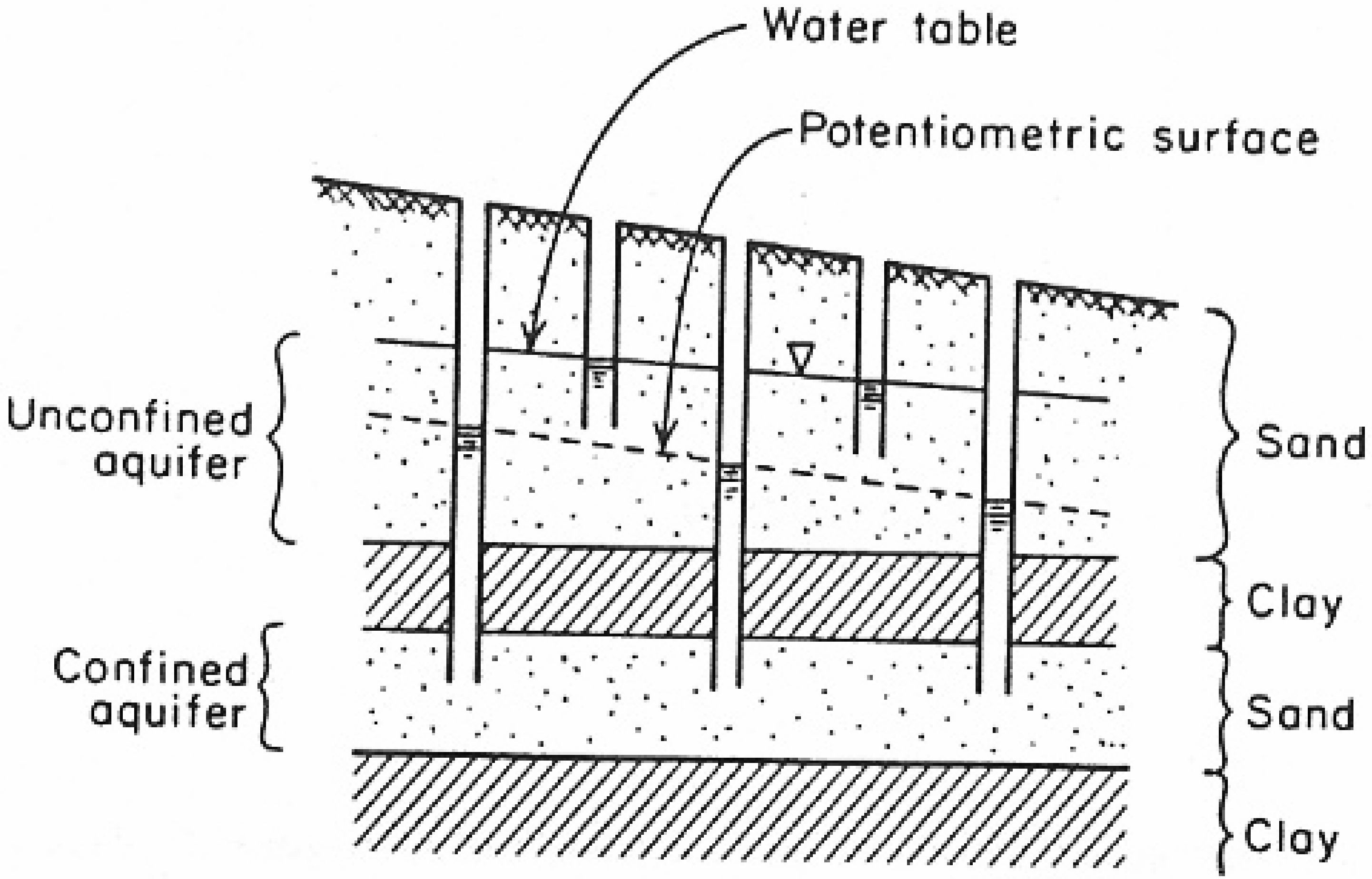


Figure 2.16 Unconfined aquifer and its water table; confined aquifer and its potentiometric surface.

Freeze and Cherry, *Groundwater*, Ch. 2

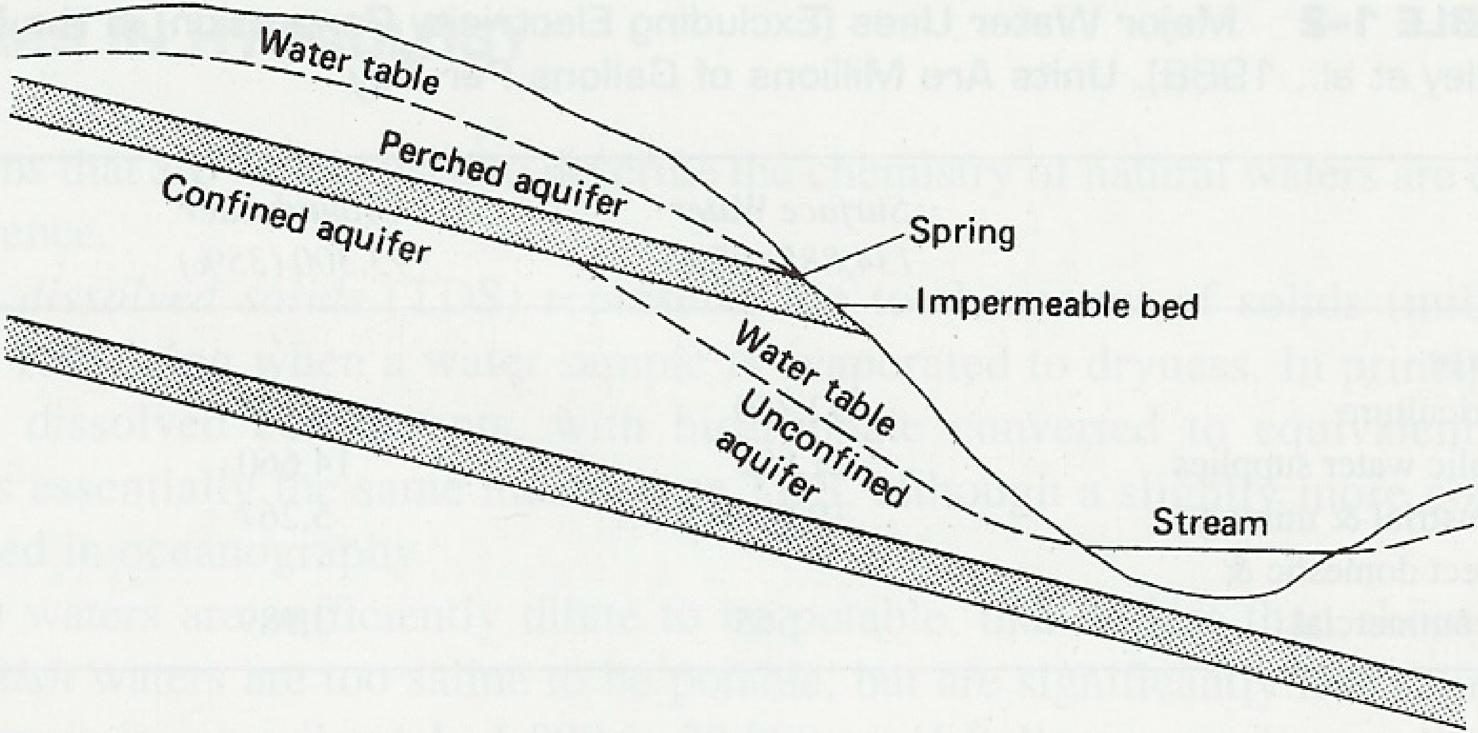


FIGURE 1-10 Perched and confined aquifers.

Drever, *The Geochemistry of Natural Waters*

Steady flow through an unconfined aquifer resting on a horizontal impervious surface

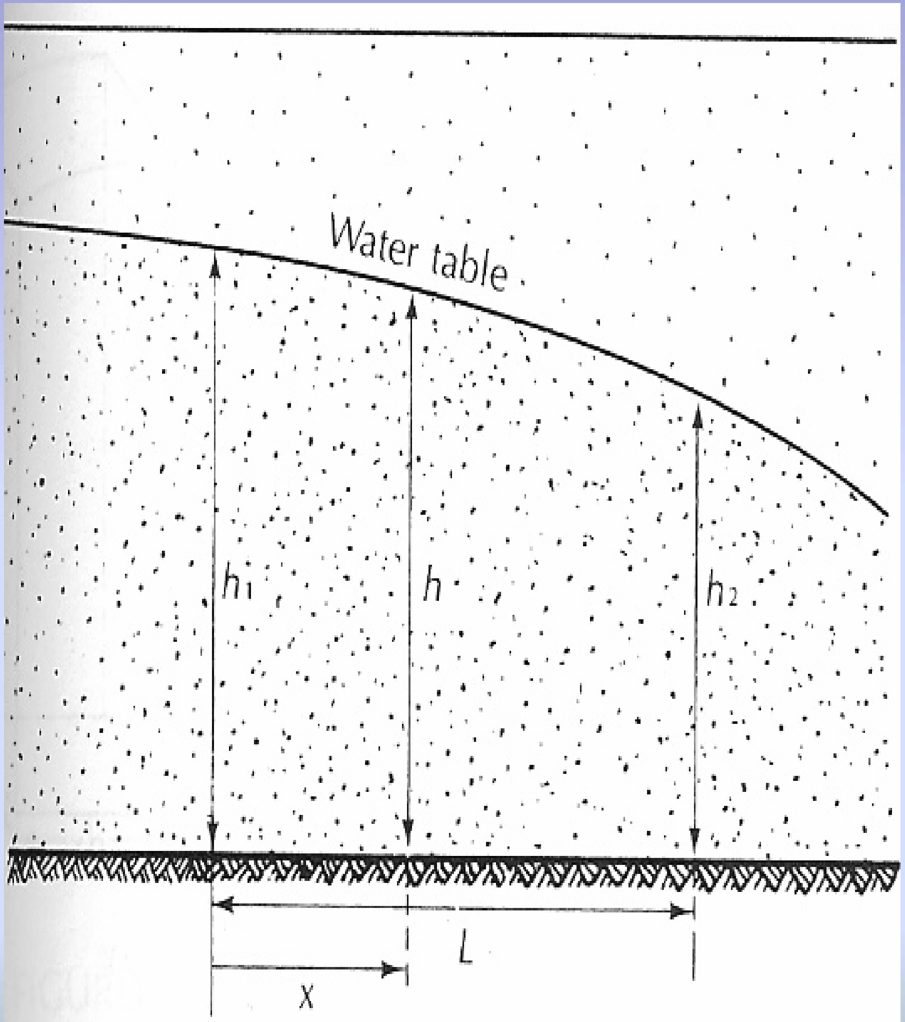


Figure 4.17. Fetter, *Applied Hydrogeology 4^{th} Edition*

Steady flow through a confined aquifer of uniform thickness

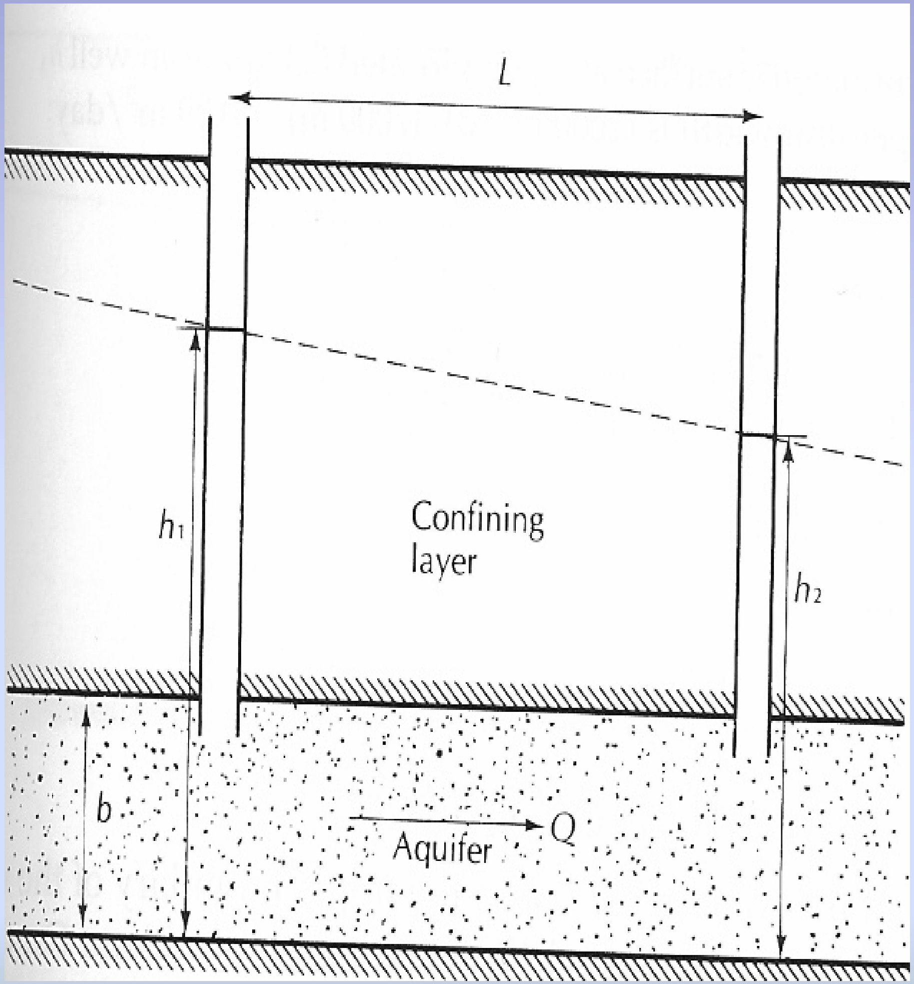
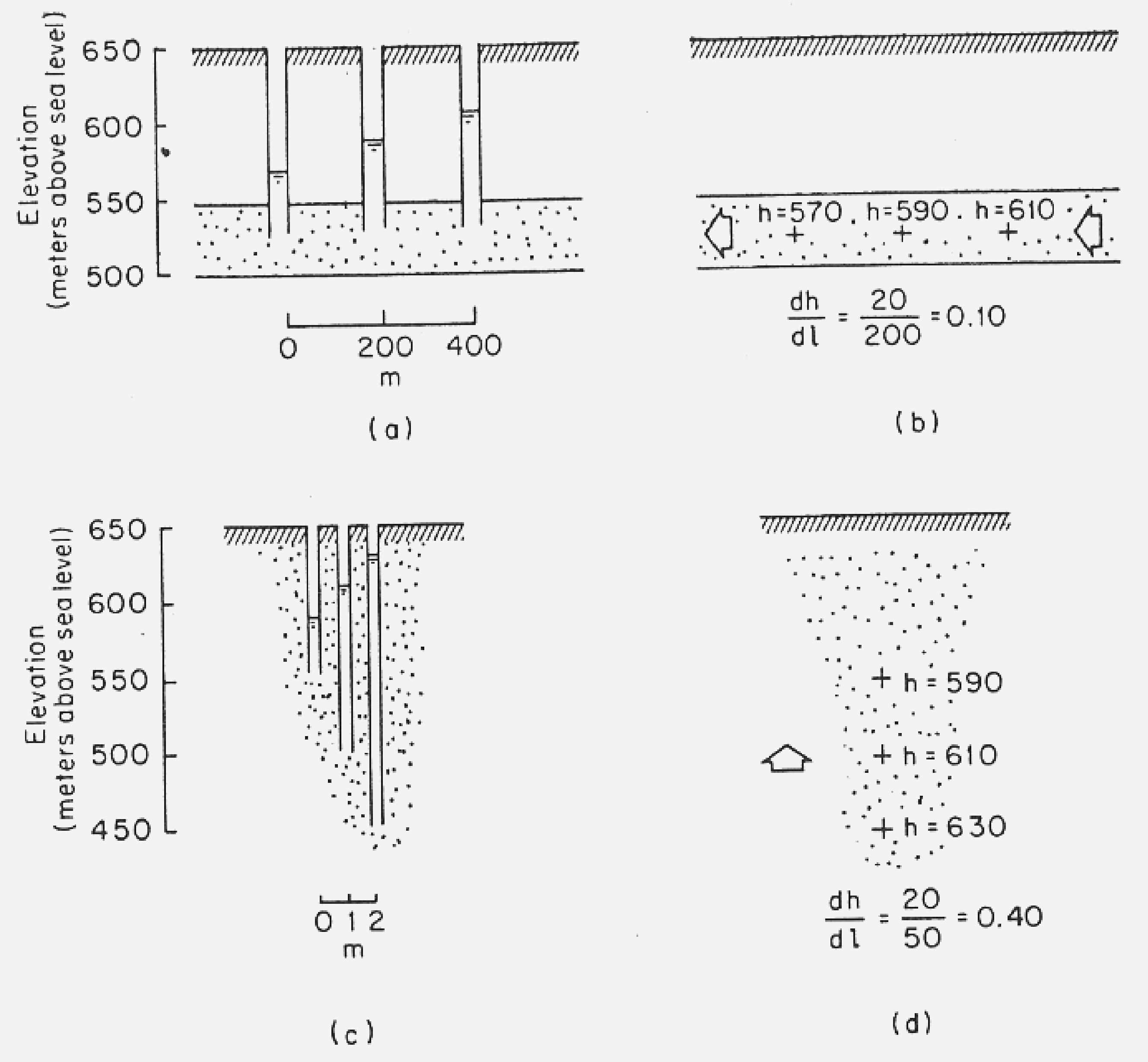


Figure 4.16. Fetter, *Applied Hydrogeology 4^{th} Edition*

Determination of hydraulic gradients from piezometer installations.



Freeze and Cherry, Figure 2.6

In the ground:

$$V_x = \frac{Q}{A*R} = (k/\eta)\frac{dh}{dl}$$

- where η = porosity
- k/η is the conductivity gradient
- gradients (dh/dl) are typically .001→.01

Measurement of hydraulic conductivity: (3 ways)

1. * Apply a hydraulic head and watch how the water flows through the sediments in the lab. One has a continuous supply of water and the other one drains in.

   * Large range of potentials (log K).; i.e. 2 orders of magnitude with peak at 10-5. This is a log normal distribution-- Where graph peaks equals the average conductivity.

Constant-head permeameter apparatus. This is similar to Darcy's original test apparatus.

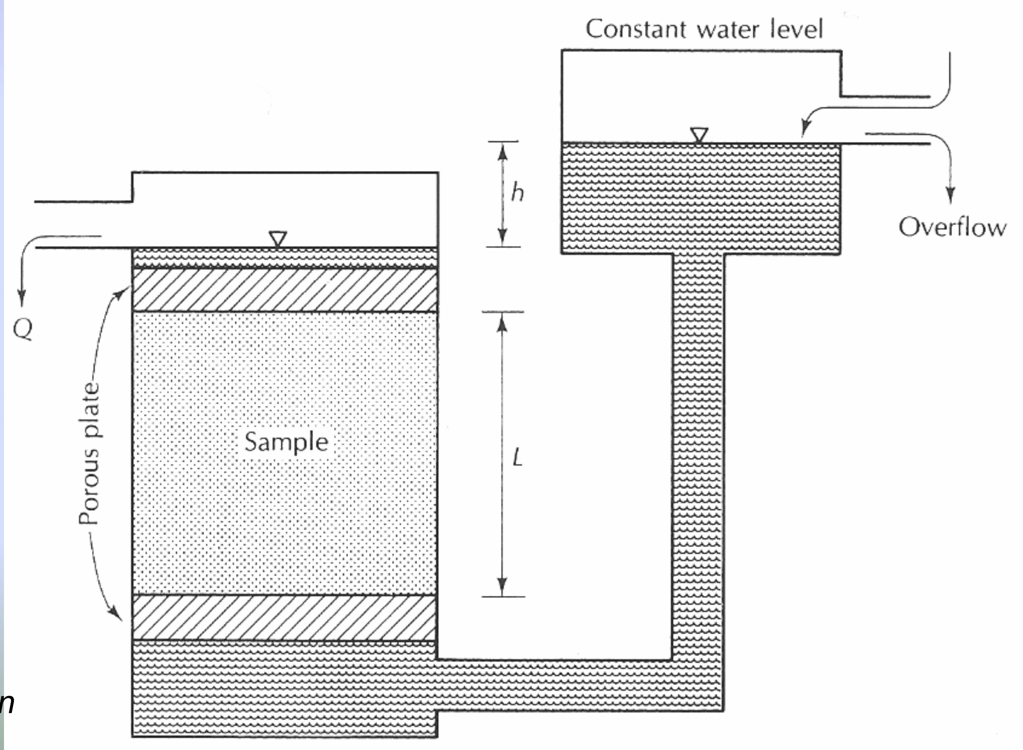


Figure 3.16. Fetter. *Applied Hydrogeology 4th Edition*

Falling-head permeameter apparatus

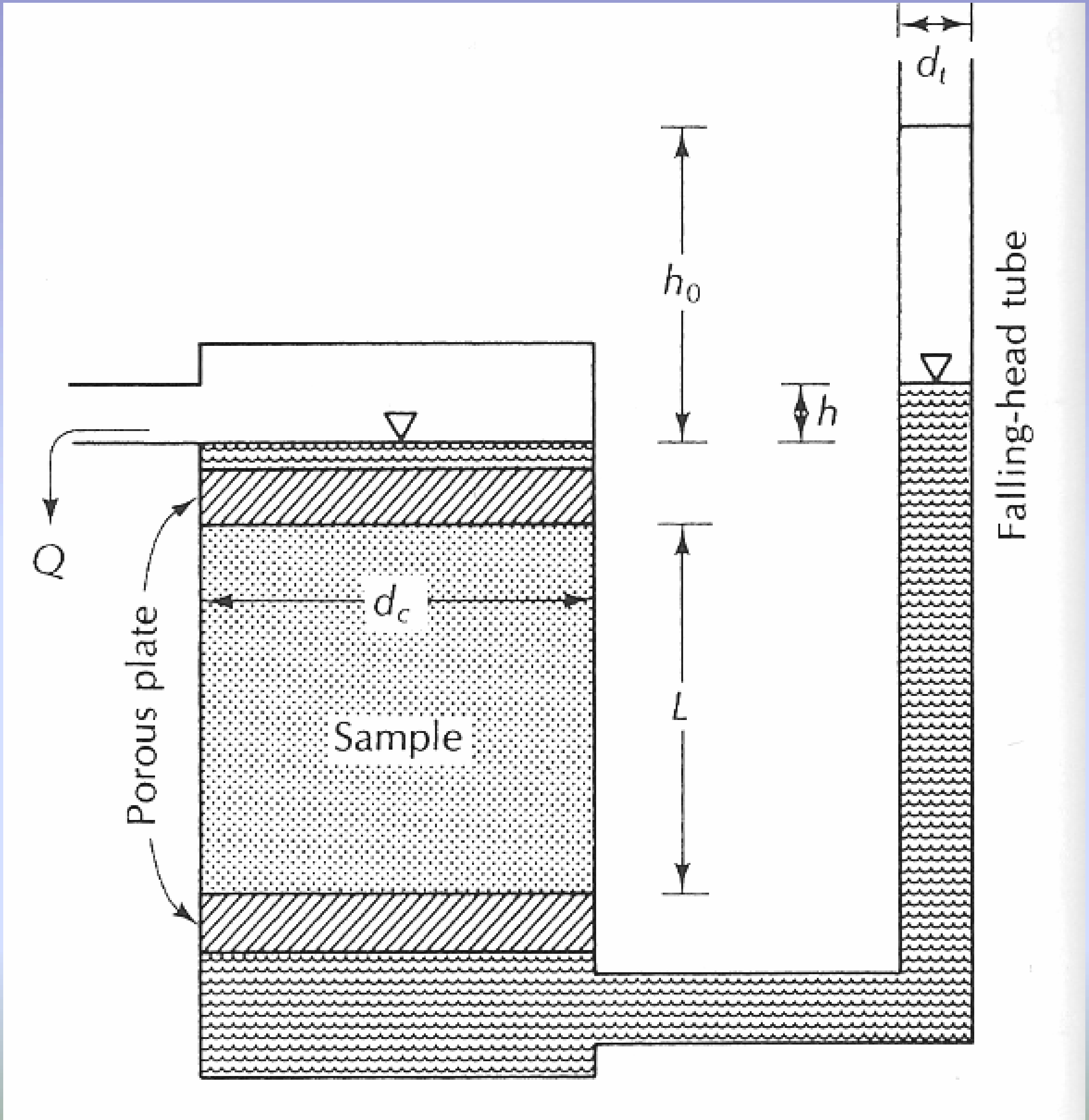
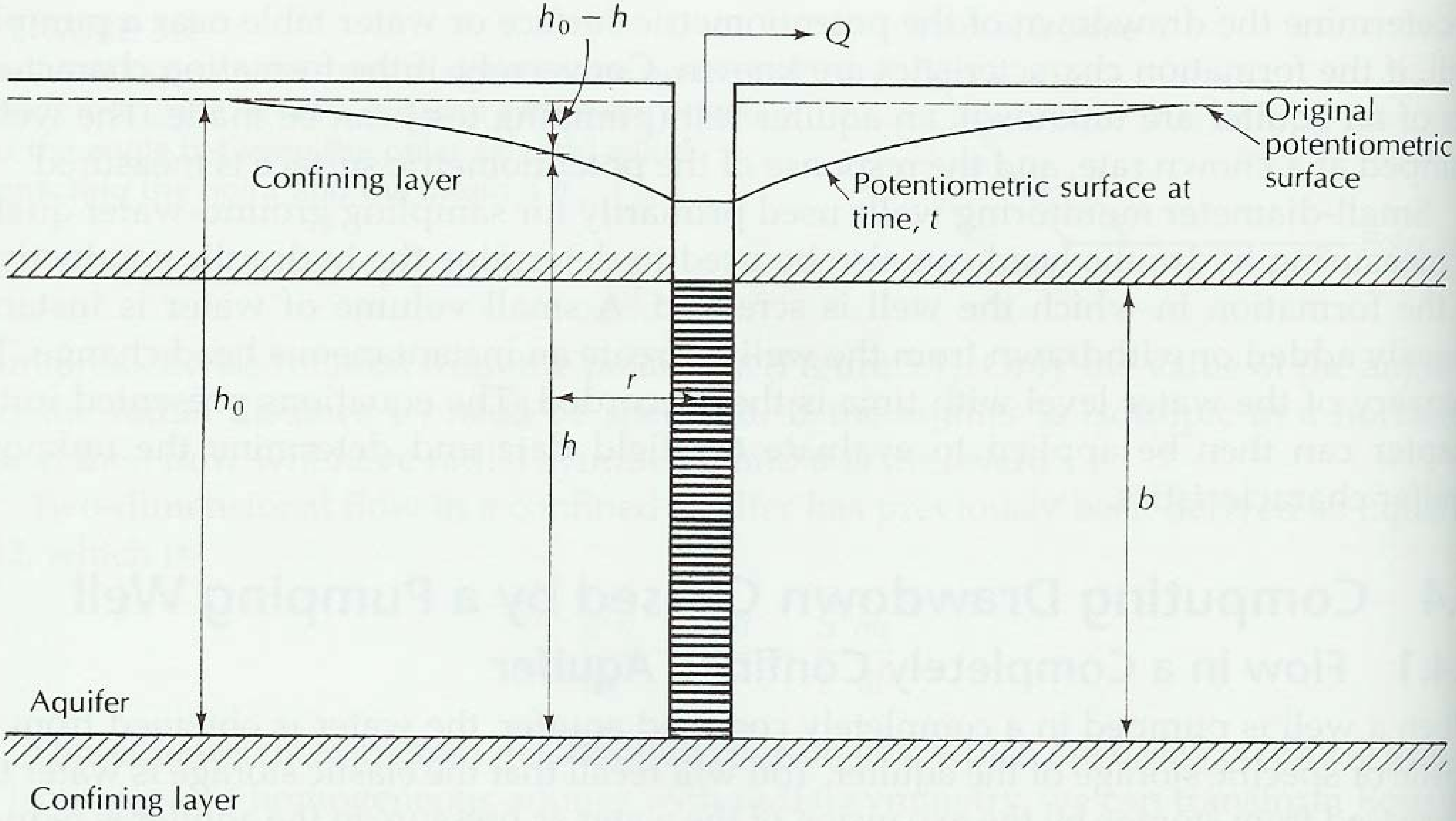


Figure 3.17. Fetter. *Applied Hydrogeology 4th Edition*

Measurement of hydraulic conductivity: (3 ways)

2) Pump testing: Water is removed from the well and the rate at which it fills is measured. If the sediment is a clay, it will slowly return to equilibrium; if it is sand, it will return more quickly to equilibrium.

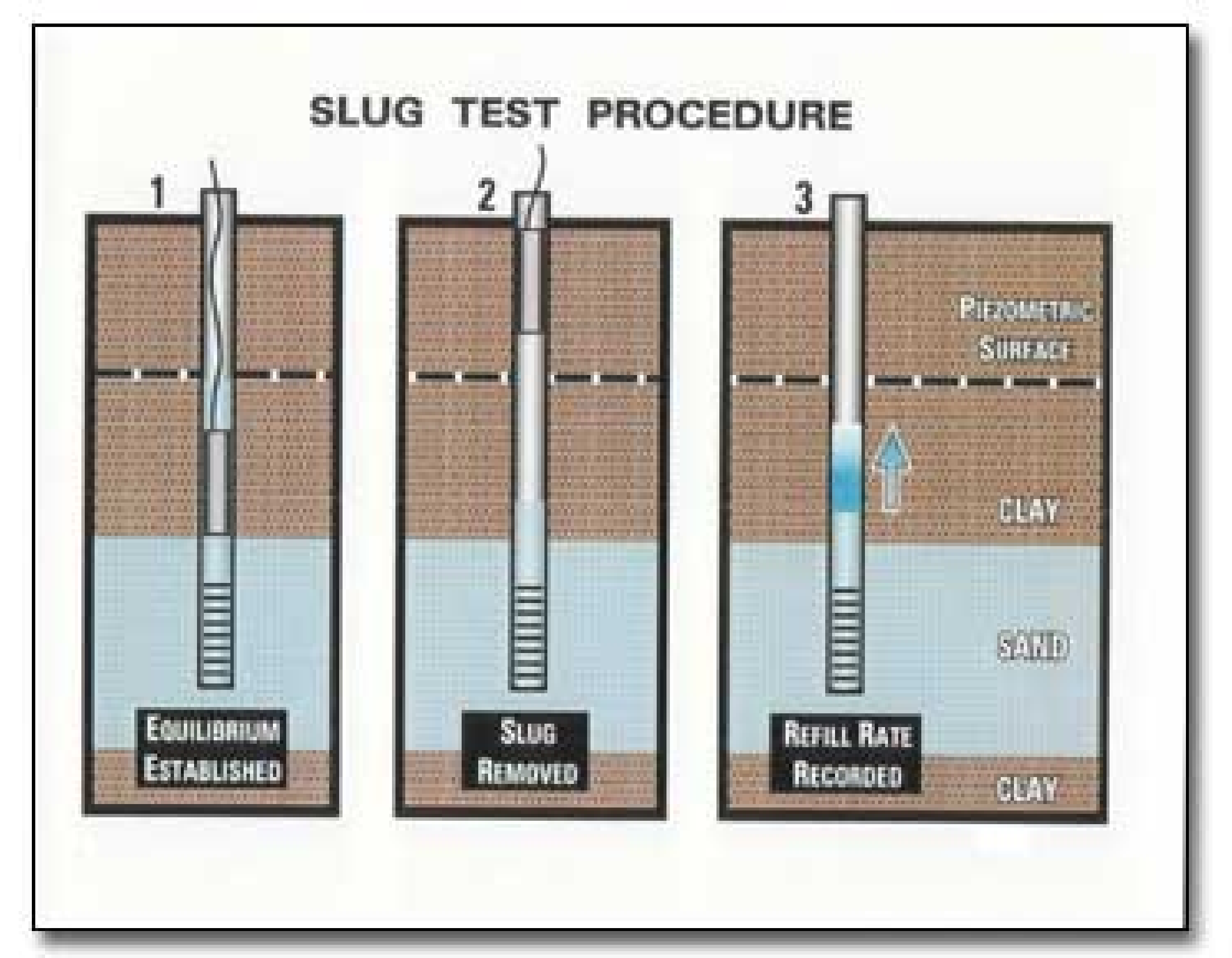


▲ FIGURE 5.2
Fully penetrating well pumping from a confined aquifer.

Fetter, *Applied Hydrogeology 4th Edition*

Measurement of hydraulic conductivity: (3 ways)

3. Slug test:



http://www.theshop.net/xibits/litigation/diagrams5.htm

Hvorslev constructed an algorithm:

$$K = \frac{r^2 \ln(L/R)}{2Lt_o}$$

r = well radius

L = length

- Can calculate standard K for a medium.

- Can also use a slug test where you drop a slug in to raise the surface of the water and watch the time it takes for the water to sink back down.

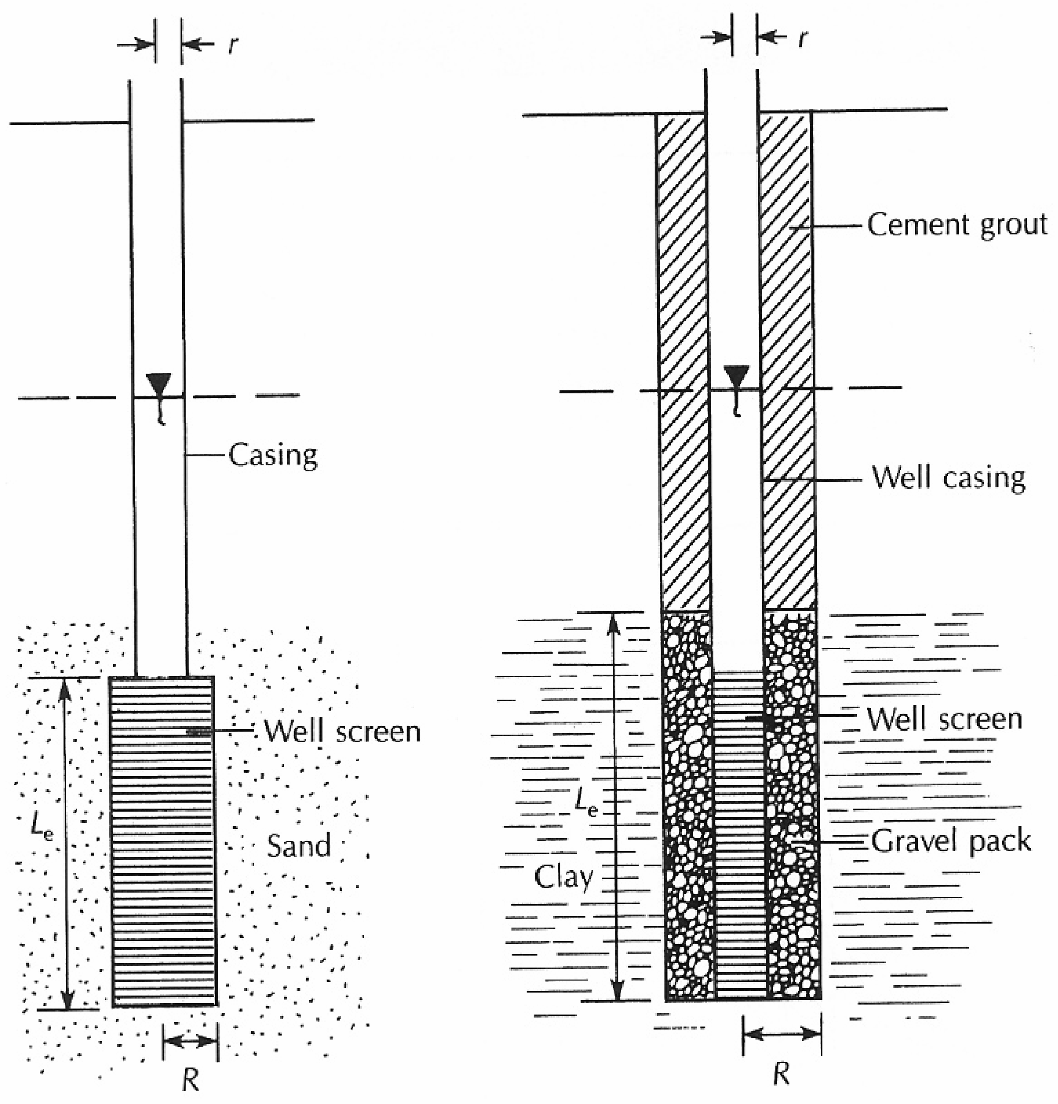


Figure 5.21. Piezometer geometry for Hvorslev method. Note that for a piezometer installed in a low-permeability unit the value R is the radius of the highest permeable zone that includes the gravel pack zone and L is the length of the gravel pack zone.

Fetter, *Applied Hydrogeology 4th Edition*

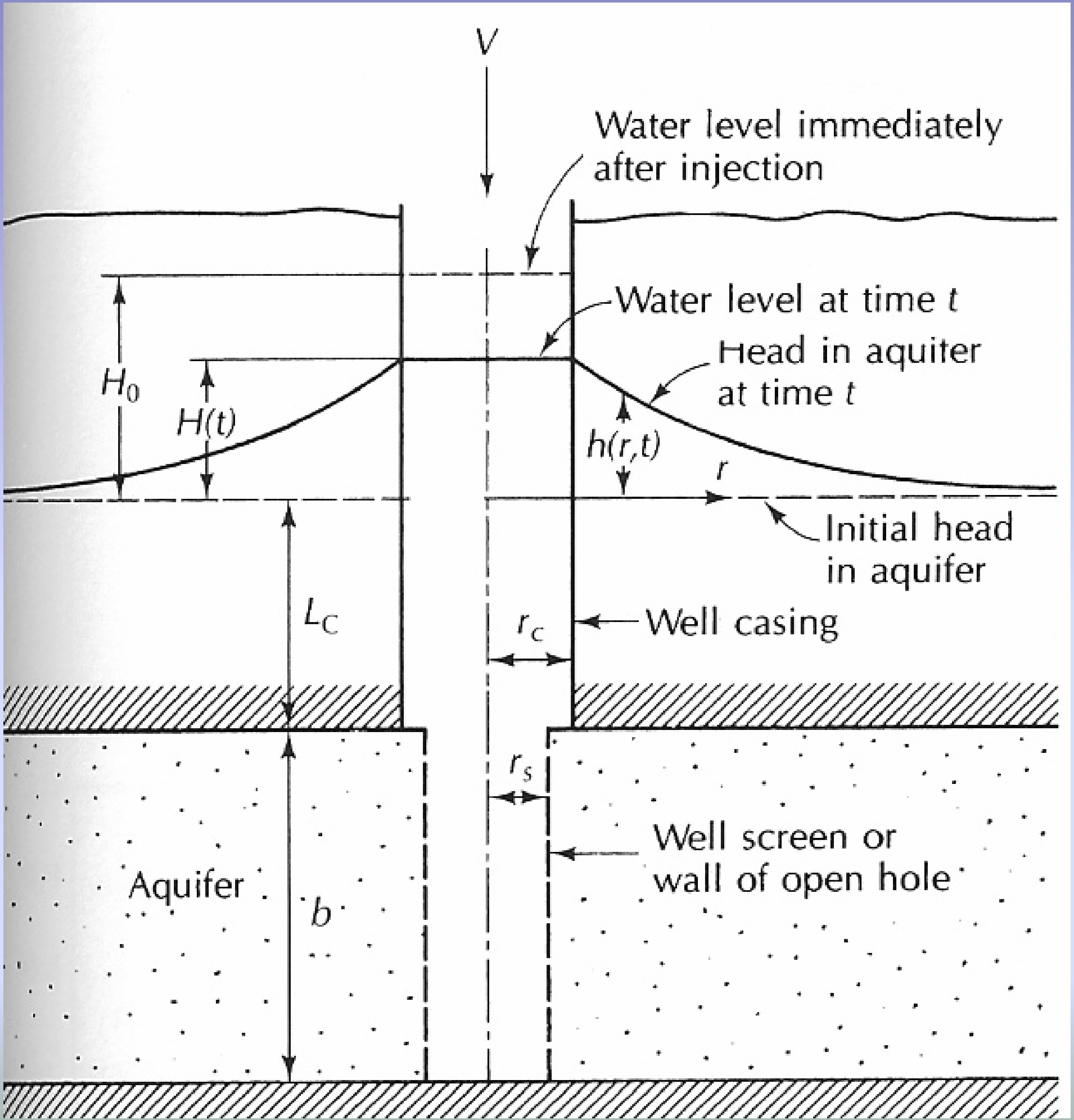
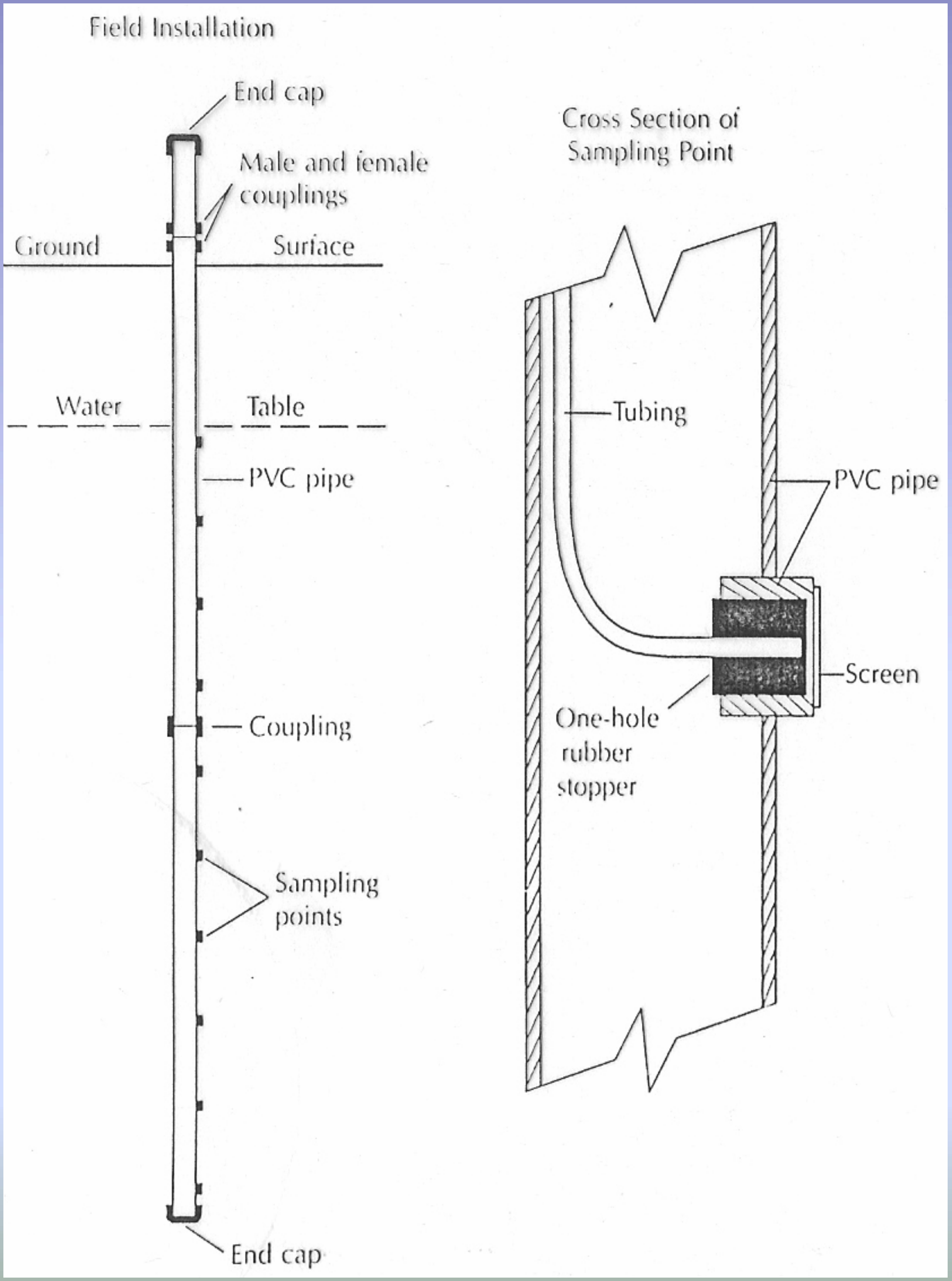


Figure 5.18
Well into which a volume, V, of water is suddenly injected for a slug test of a confined aquifer.

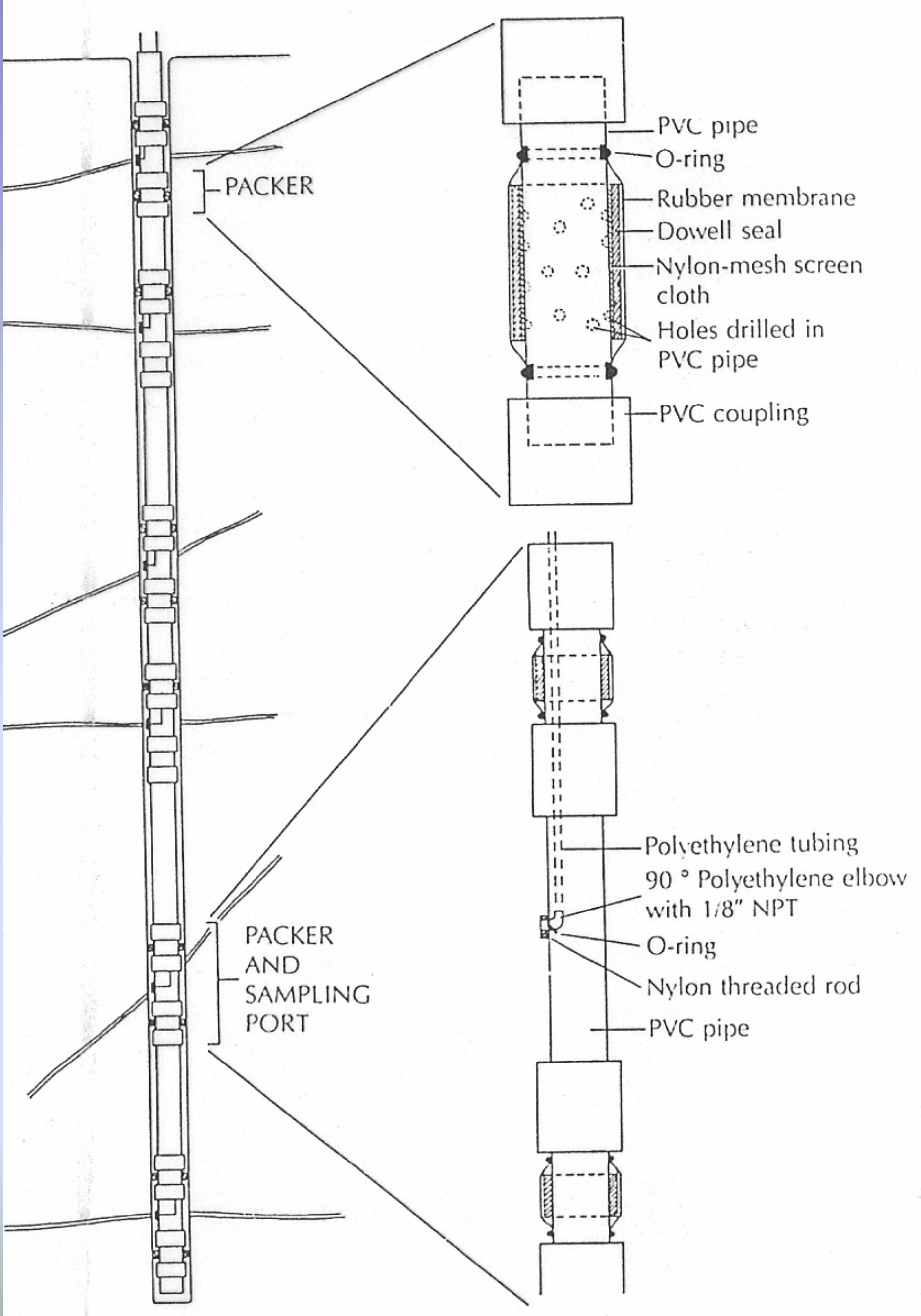
Fetter, *Applied Hydrogeology 4th Edition*



Multilevel ground-water sampling device for use in sandy soil.

Source: J.F. Pickens and others. *Ground Water Monitoring Review*, 1, no.1 (1981):48-51.

Multilevel ground-water sampling device for use in fractured rock.



Source: J.A. Cherry and P.E. Johnson, *Ground Water Review*, 2, no.1 (1982): 41-44

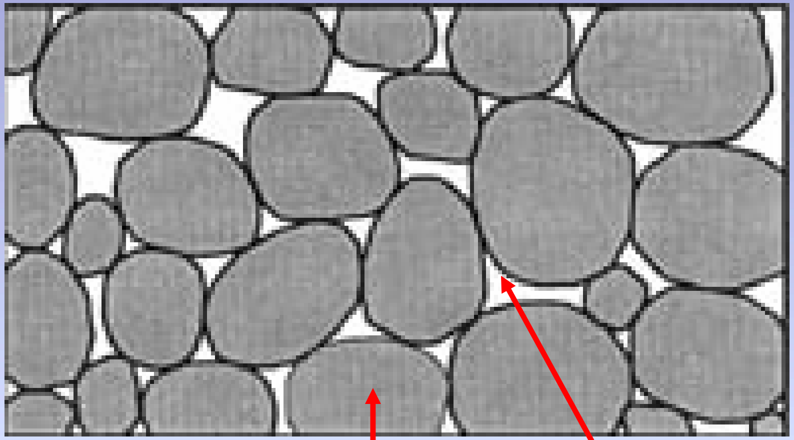
- → **All of these methods measure the horizontal conductivity → how fast it comes from the sides to recover.**
  - **vertical conductivity is often quite different;** hard to get at by the way these pump tests are done.
  - **Vertical is different because of anisotropy** → related to layering which can impede flow vertically but less so horizontally.

K_V= 1/10 (K_h) generally.

(h = horizontal).

II. Controlling factors of the medium:

1. Size and porosity of the grains



http://www.who.int/docstore/water_sanitation_health/wqassess/ch14.htm

A. Porosity = Solid material / Pore Space → a ratio, often given as a %

1) Sedimentary rocks:

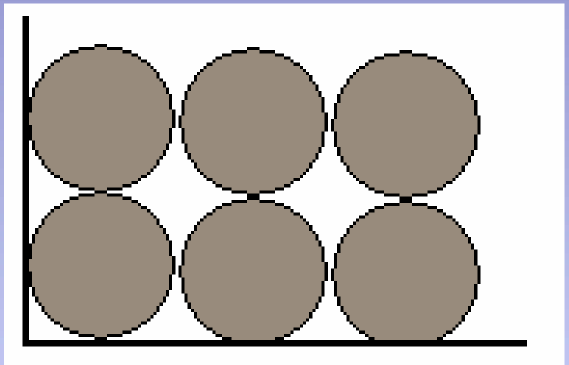
-generally a high primary porosity

http://www.who.int/docstore/water_sanitation_health/wqassess/ch14.htm

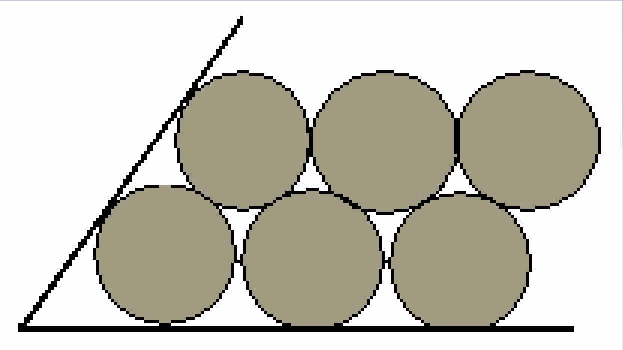
Controlling factors of the medium:

2. Packing of grains:

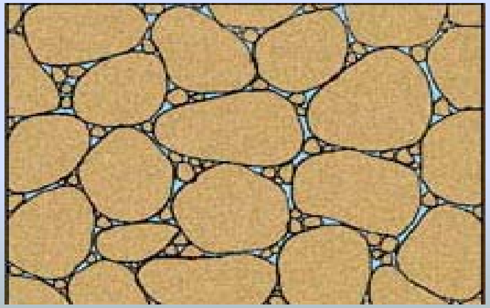
- **Cubic packing** - all grains the same size and packed with edges touching → 48% porosity.



- **Rhombohedral** - the 2nd layer of grains lays on top of the large pore spaces of the first layer → 26% porosity.



- **Poorly sorted** - i.e. Glacial till; very low porosity - much less than 15-20%.



→ *Most* systems have about 30-35%.

http://www.dpiwe.tas.gov.au/inter.nsf/WebPages/RPIO-4YD8NU?open

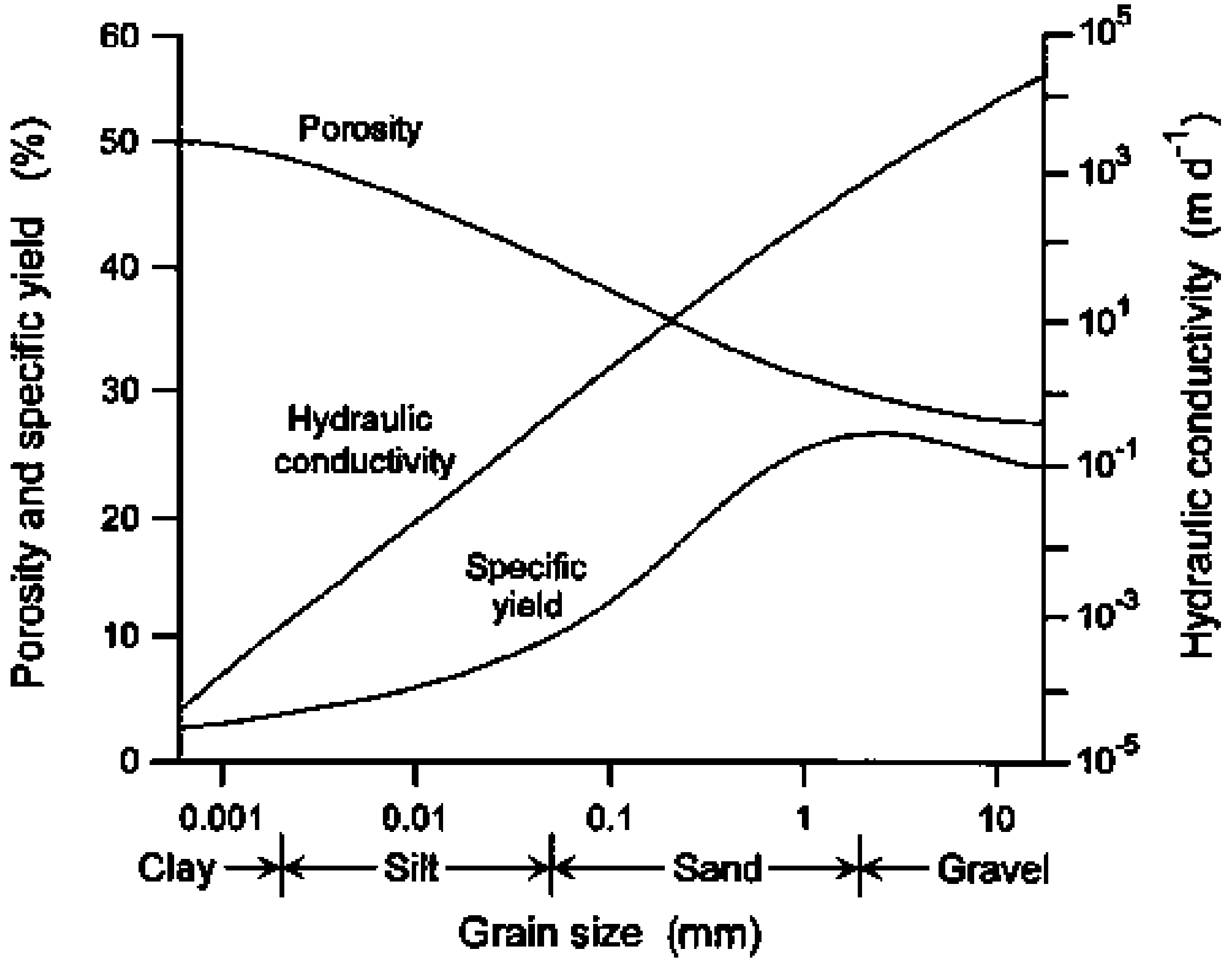
Range of Values of Porosity

	Porosity (%)
Unconsolidated deposits	
Gravel	25-40
Sand	25-50
Silt	35-50
Clay	40-70
Rocks	
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

Freeze and Cherry, *Groundwater,* Ch. 2, Table 2.4

Porosity, specific yield and hydraulic conductivity of granular materials

(Modified from Davis and De Wiest, 1966)



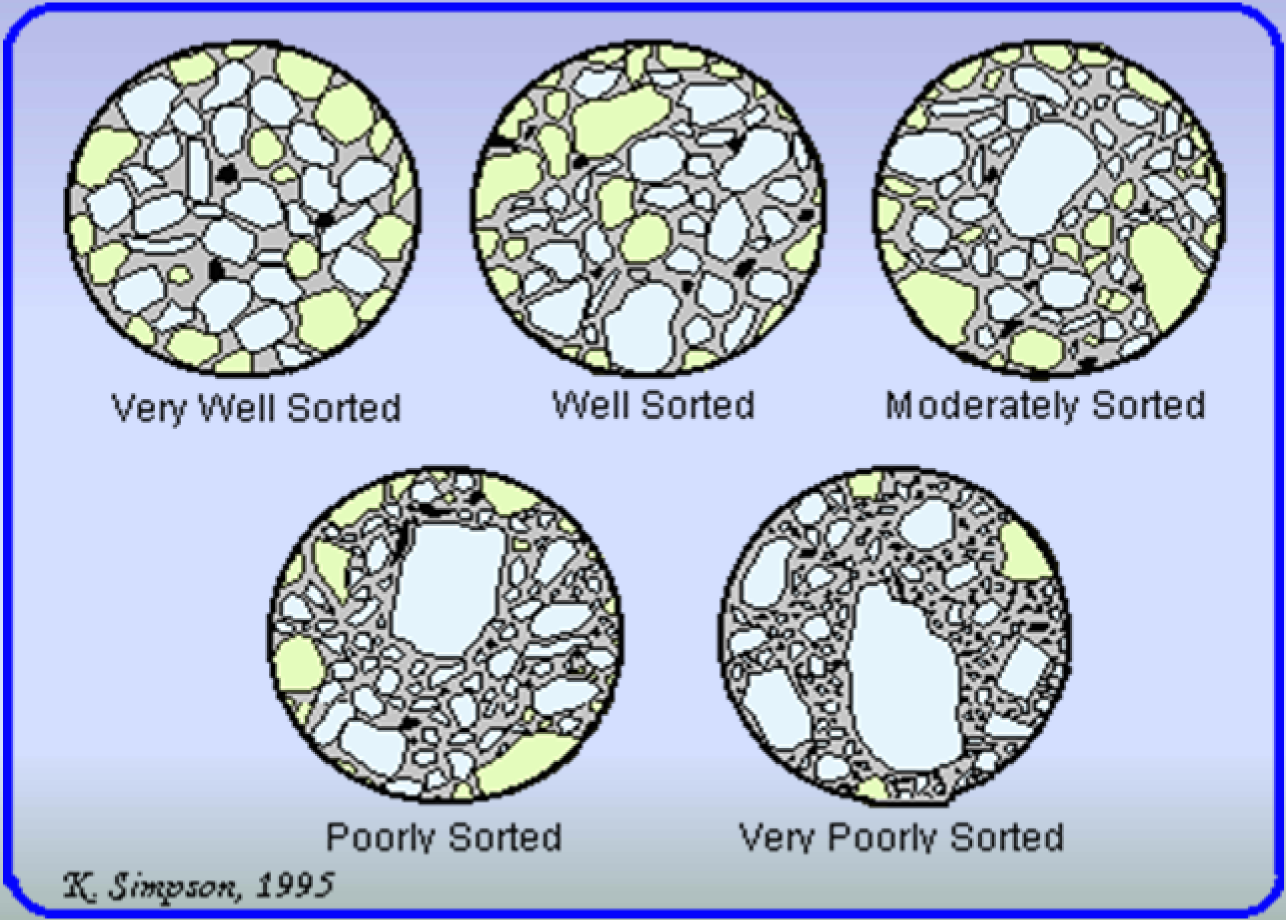
http://www.who.int/docstore/water_sanitation_health/wqassess/ch14.htm#b2-9.2.%20Characteristics%20of%20groundwater%20bodie

Controlling factors of the medium:

B. Features of natural systems:

1) grains are usually sorted by size

2) there is typically a large size distribution of grains present, although some may be more concentrated in a single size fraction.

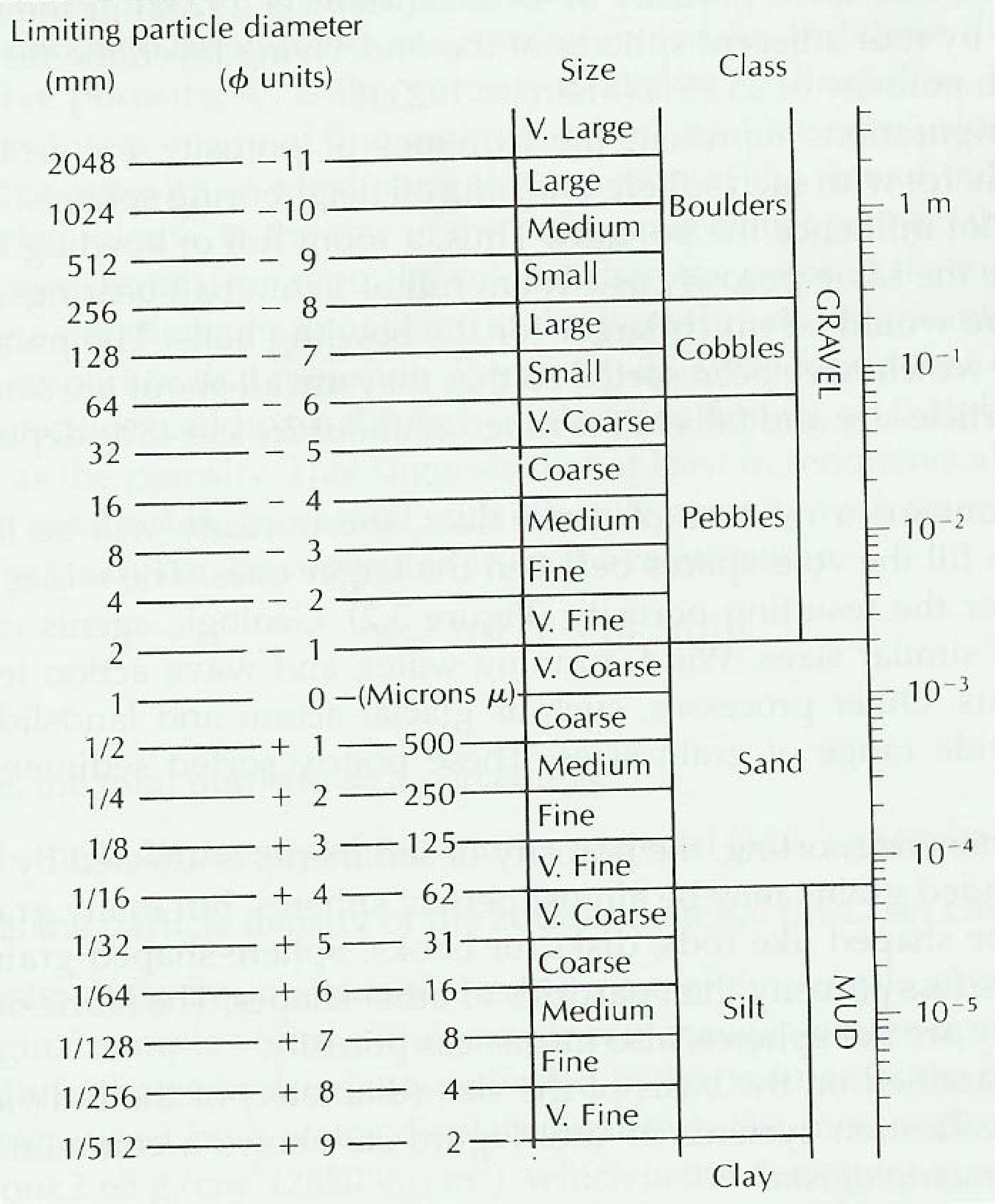


http://www.eos.ubc.ca/courses/eosc221/sed/sili/siligsize.html

Grain Size of Sediments

http://www.brookes.ac.uk/geology/8320/grainsize.html

Standard sizes of sediments

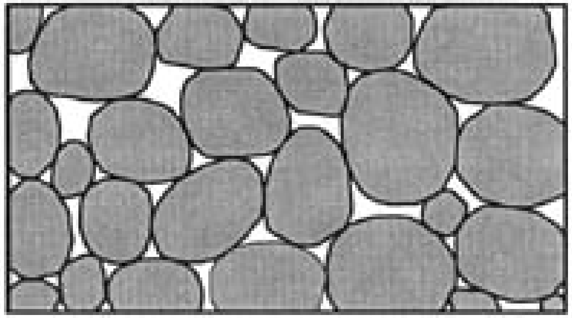


Limiting particle diameter (mm)	(φ units)	(Microns μ)	Size	Class		
			V. Large	Boulders	GRAVEL	
2048	−11		Large			
1024	−10		Medium			1 m
512	− 9		Small			
256	− 8		Large	Cobbles		
128	− 7		Small			10^{-1}
64	− 6		V. Coarse	Pebbles		
32	− 5		Coarse			
16	− 4		Medium			10^{-2}
8	− 3		Fine			
4	− 2		V. Fine			
2	− 1		V. Coarse	Sand		
1	0		Coarse			10^{-3}
1/2	+ 1	500	Medium			
1/4	+ 2	250	Fine			
1/8	+ 3	125	V. Fine			10^{-4}
1/16	+ 4	62	V. Coarse	Silt	MUD	
1/32	+ 5	31	Coarse			
1/64	+ 6	16	Medium			10^{-5}
1/128	+ 7	8	Fine			
1/256	+ 8	4	V. Fine			
1/512	+ 9	2		Clay		

Figure 3.3
Standard sizes of sediments with limiting particle diameters and the Φ scale of sediment size in which Φ is equal to $\log_2 s$ (the particle diameter).

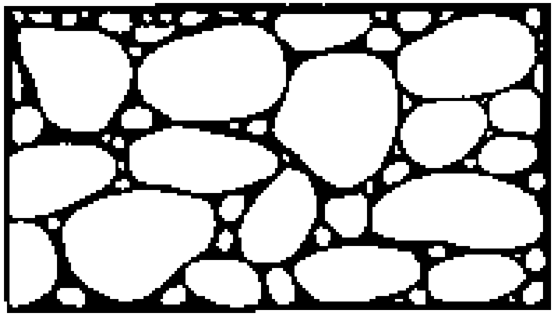
Relation between texture and porosity

Well-sorted sedimentary Deposit with high porosity.



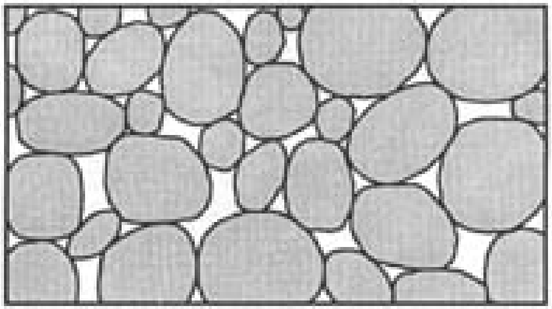
(a)

Poorly sorted sedimentary deposit with low porosity.



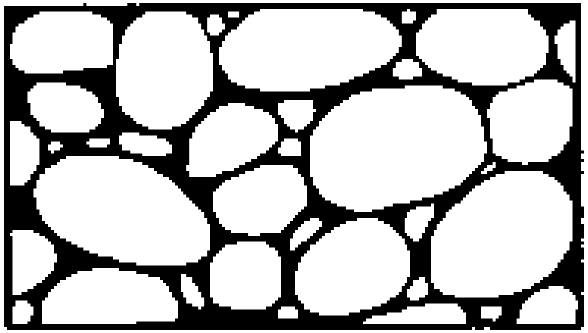
(b)

Well-sorted sedimentary deposit consisting of pebbles that are themselves porous; deposit has high porosity.



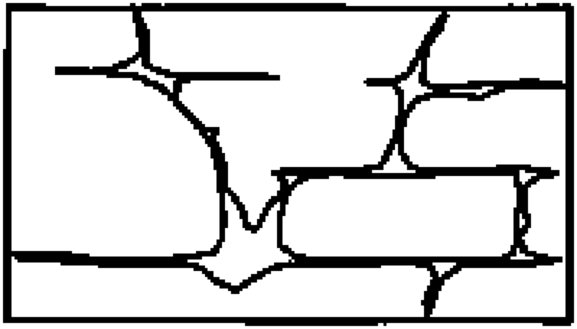
(c)

Well-sorted sedimentary deposit whose porosity has been diminished by the deposition of mineral matter in the interstices.



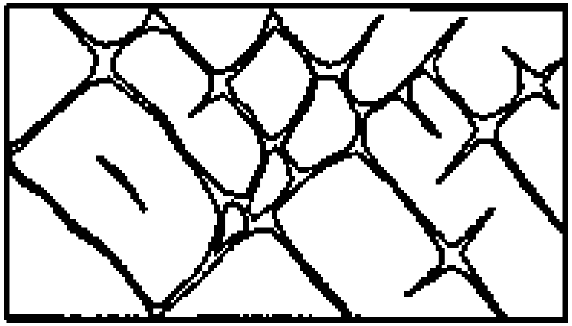
(d)

Rock rendered porous by solution



(e)

Rock rendered porous by fracturing.

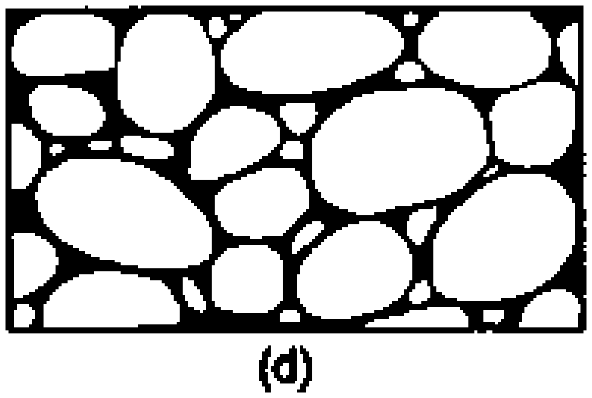


(f)

Freeze and Cherry, *Groundwater*, Ch. 2, Figure 2.11

Controlling factors of the medium:

3) **Note: Well sorted sand with initial high primary porosity can be filled with mineral deposits (such as $CaCO_3$ cements) leaving a lower porosity**.



→ Aside: This is a big problem is golf course where they use $CaCO_3$ sand as opposed to quartz sand. Caretakers add acidic fertilizer so grass will grow well and water the lawns, which dissolves the calcium carbonate and it re-crystallizes between the grains. Now the green will not drain properly when they try to water again- the grass dies.

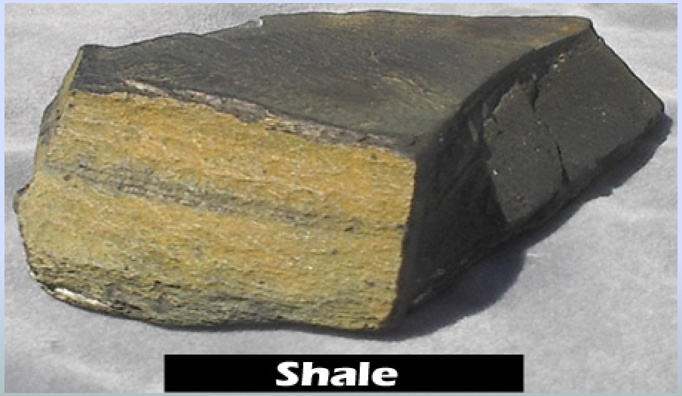
2) Igneous and Metamorphic rocks have a low primary porosity because the grains are in fairly intimate contact. However, fractures can control the water flow in these rocks.

→ This also occurs in shales (a sedimentary rock with low primary porosity) but higher secondary porosity.

Metamorphic

Igneous

http://www.mcmullans.org/canal/alum_hill_deep_cut.htm



http://www2.vscc.cc.tn.us/svinson/geo100/library/sedimentary/large/shale.jpg

Marble (Metamorphosed Limestone)

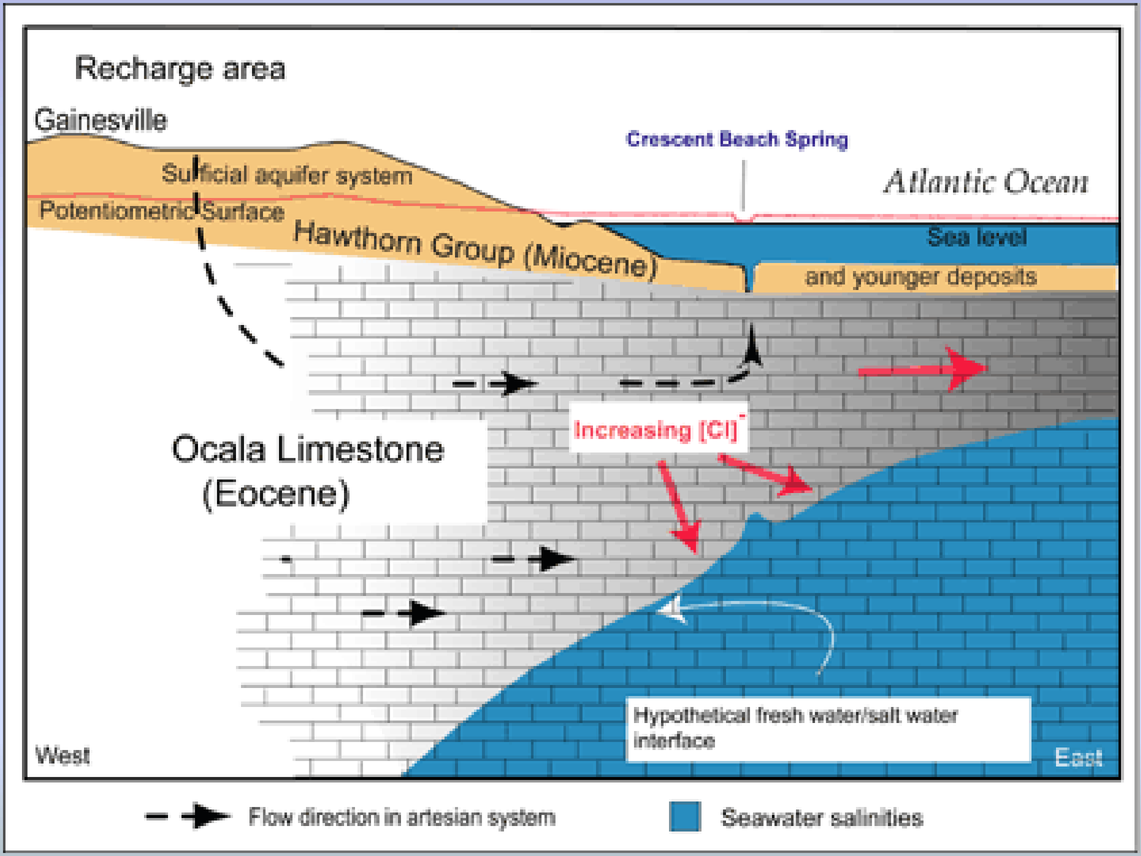
fracture

http://www.uwsp.edu/geo/faculty/ritter/glossary/l_n/metamorphic_rock.html

Controlling factors of the medium:

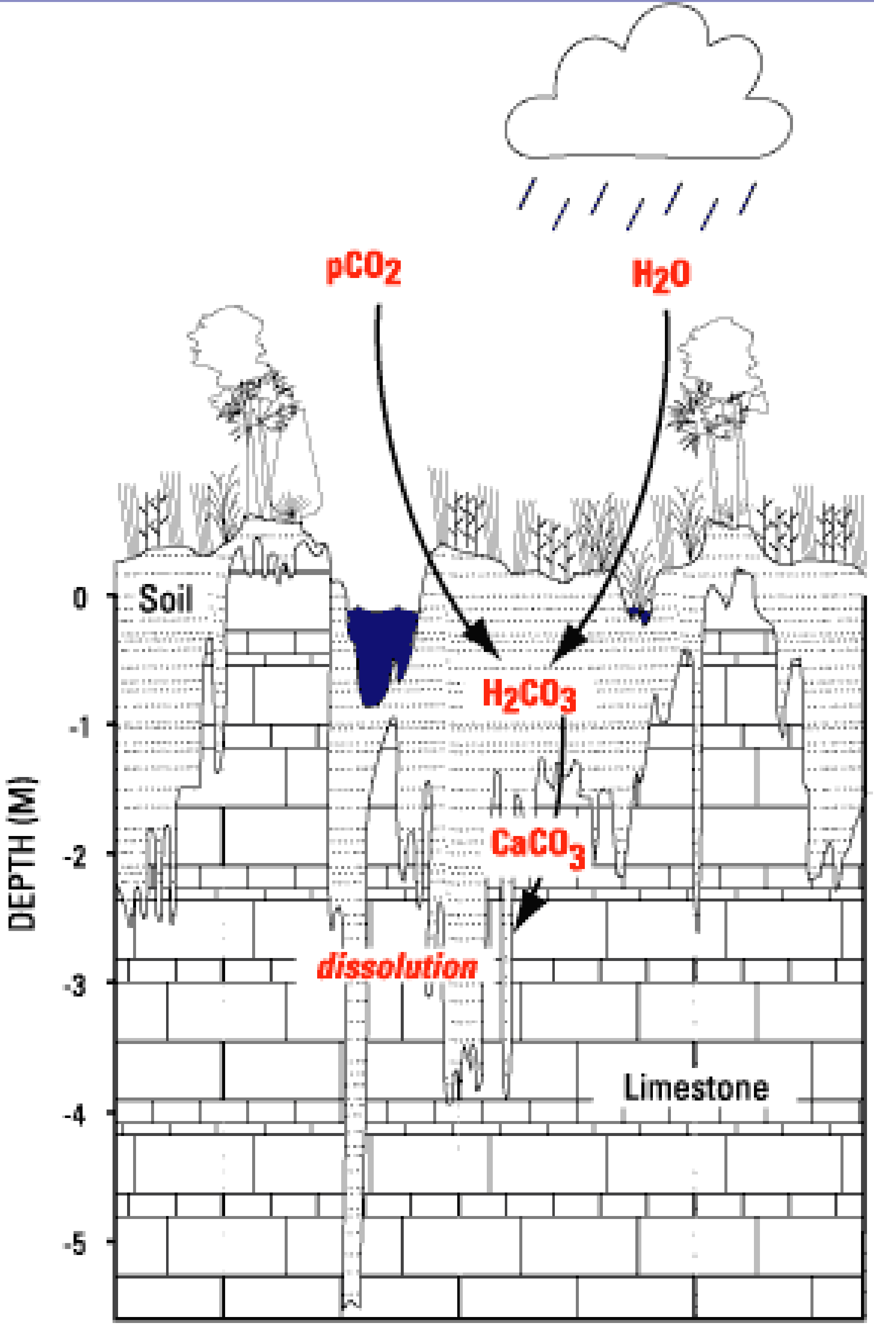
4) **Also, $CaCO_3$ (limestone) can dissolve → large secondary porosity**

→ This is the cause of the large karst formation in limestone in Florida



http://soundwaves.usgs.gov/2001/03/meetings5.html

Carbonate Dissolution Process and Karst Formation



$CaCO_3 + H_2O + CO_2 \longrightarrow Ca^{2+} + 2HCO_3$

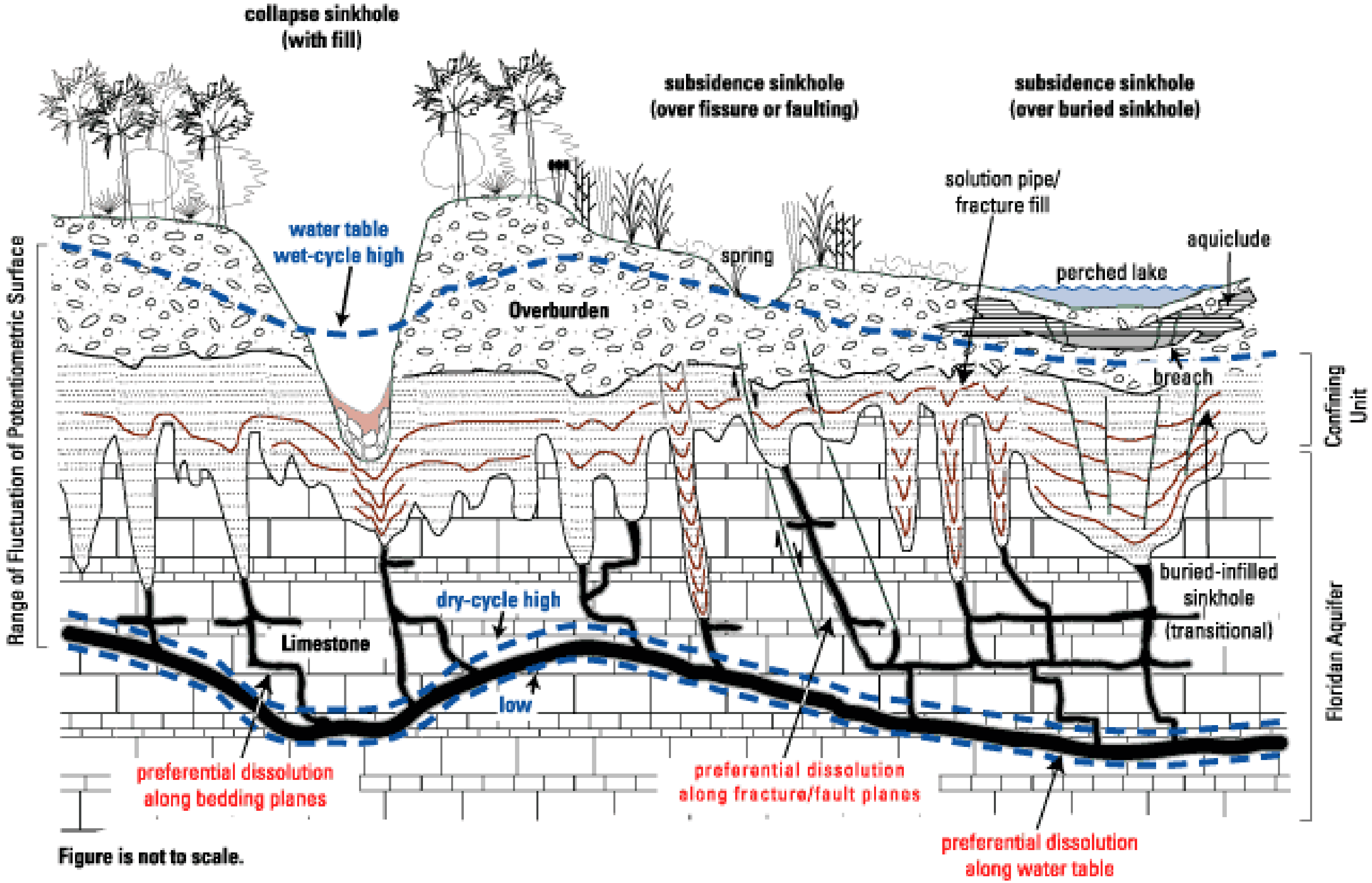
- Bacterial and root respiration in the soil increase pCO_2
- As pCO_2 increases, so do dissolution rates

Tropical latitudes = high evapotranspiration
+ well developed soil
+ high atm. pCO_2
= KARST

(Yucatan, Caribbean, Florida, South China...)

http://coastal.er.usgs.gov/publications/ofr/00-180/intro/karst.html

Solution and collapse features of karst and karren topography



http://coastal.er.usgs.gov/publications/ofr/00-180/intro/karst.html

Transport mechanisms:

* Diffusion

- Advection

- Dispersion → same units as diffusion but is mechanical (H_2O follows a twisted & tortuous path—not straight)

- ALSO, Chemical retardation→

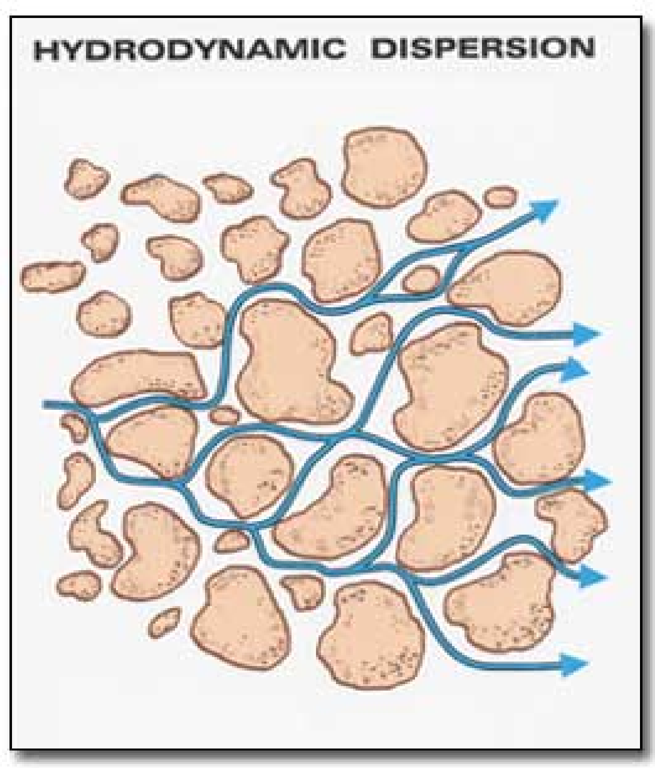
  1. Physical adsorption 2. Retardation

A. Dispersion: spreading of plumes

*water flowing through a porous medium takes different routes

*important components: longitudinal & transverse dispersion

→ velocity dependent, so equivalent only for very slow flow



- D* = 10-5 m2/day. (D* = diffusion constant)
- α_L = .1m/day (dispersion constant, longitudinal).
- α_r = .001m/day (dispersion constant, transverse).
- (αL)(Vx) + D* = DL → longitudinal
- (αT)(Vz) + D* = DT → transverse

http://www.theshop.net/xibits/litigation/diagrams9.

Factors causing pore-scale longitudinal dispersion

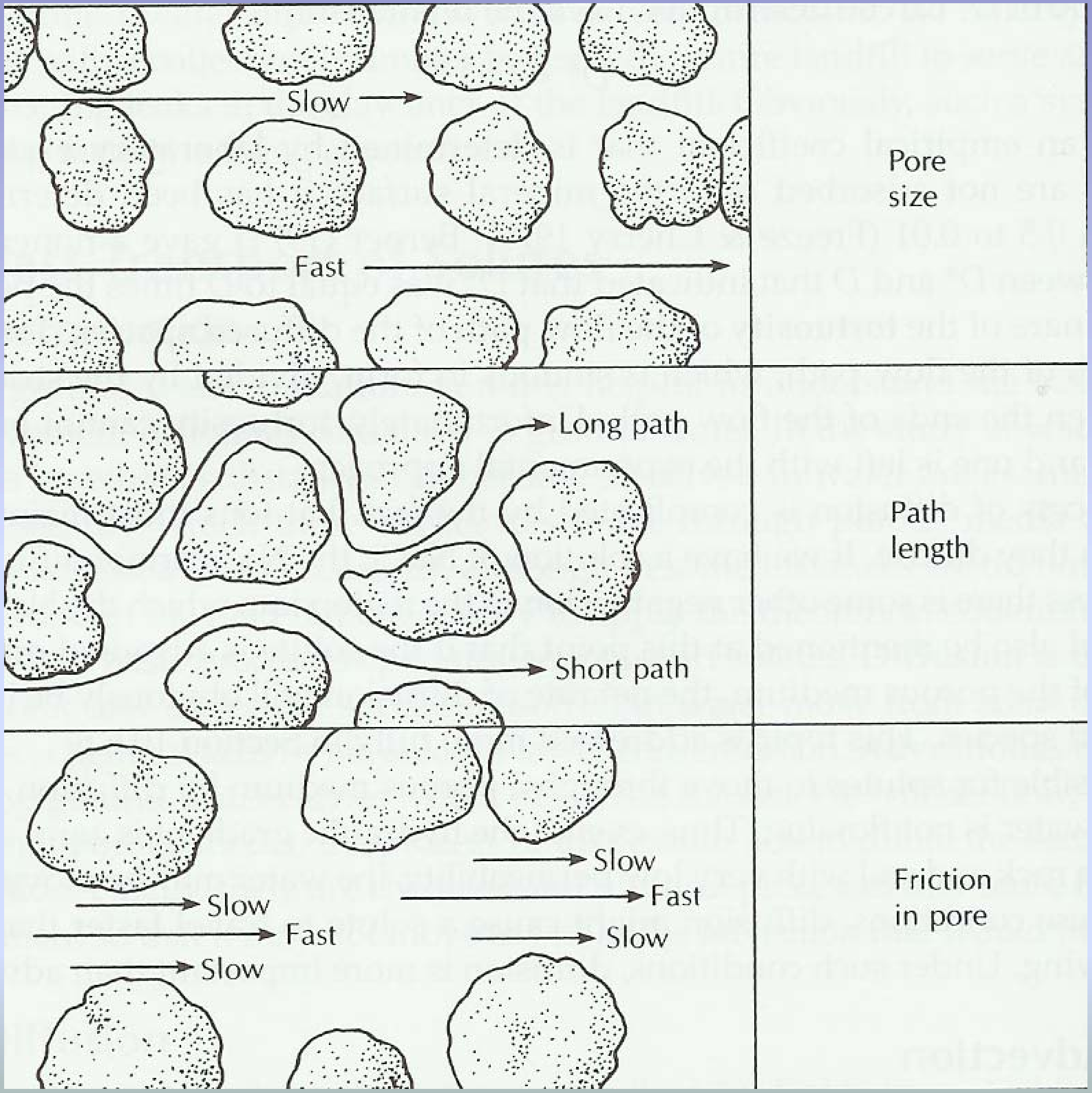


Figure 10.8 Fetter, *Applied Hydrogeology 4th Editio*

B. **Advection**: horizontal velocity

Advective transport and the influence of dispersion and diffusion on “breakthrough” of a solute

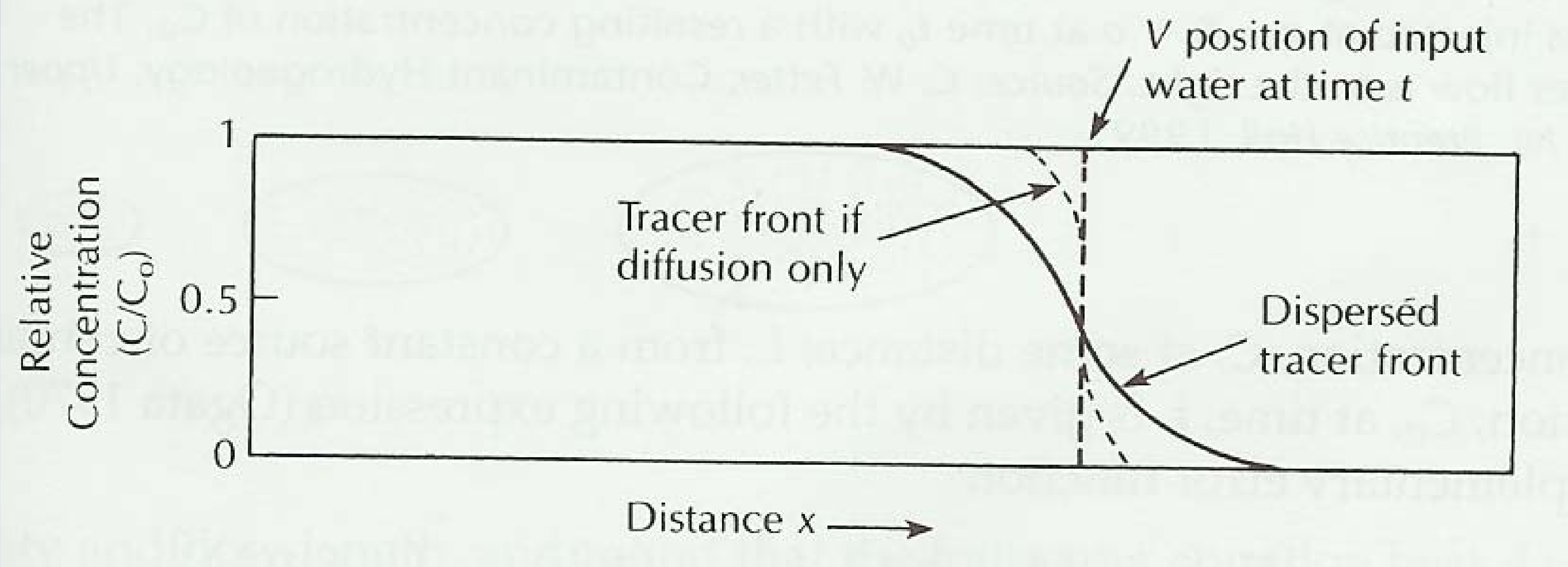


Figure 10.10 Fetter, *Applied Hydrogeology 4th Edition*

Transport and spreading of a solute slug with time due to advection and dispersion. A slug of solute was injected at $x = 0 + \alpha$ at time t_0 with a resulting concentration of C_0. The ground-water flow is to the right.

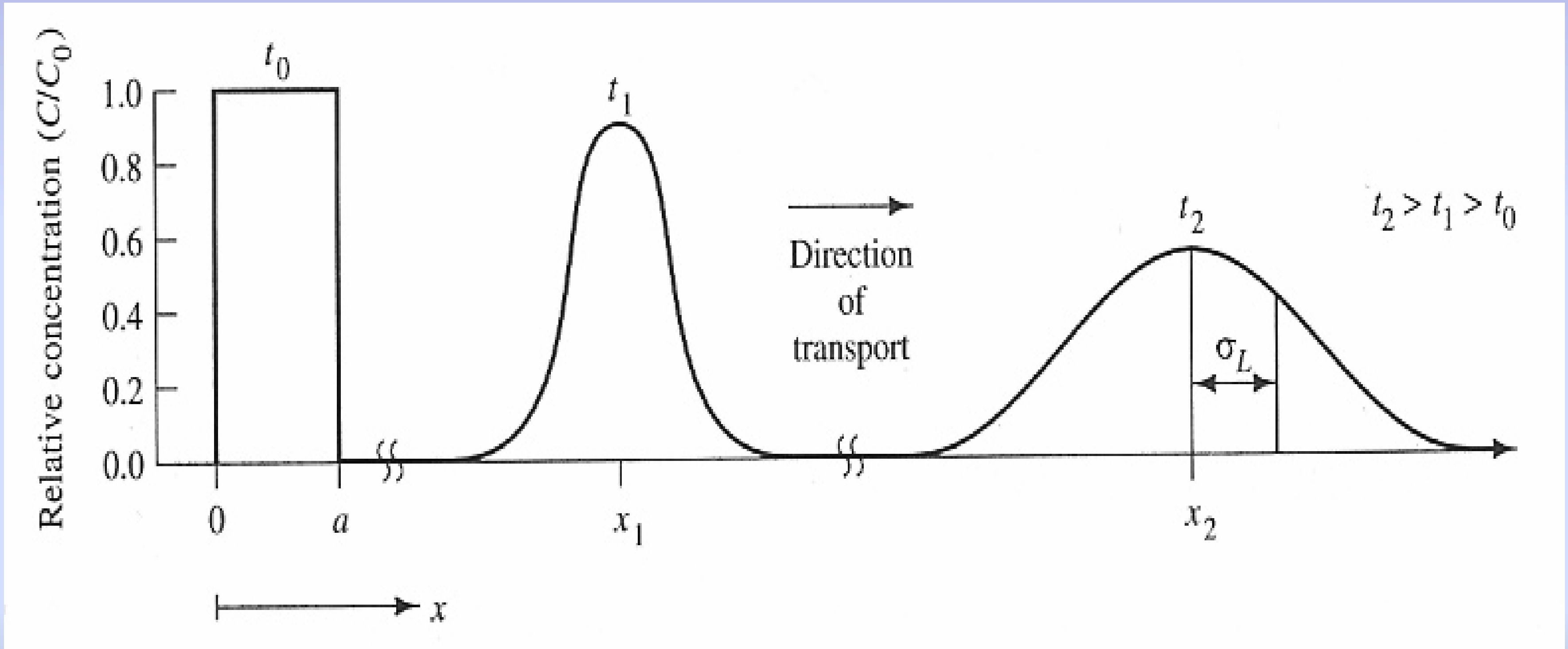


Figure 2.6. Fetter, *Contaminant Hydrogeology 3rd Edition*

C. **Diffusion**: function of concentration & diffusion coefficient

Spreading of a solute slug with time due to diffusion. A slug of solute was injected into the aquifer at time t_0 with a resulting initial concentration of C_0.

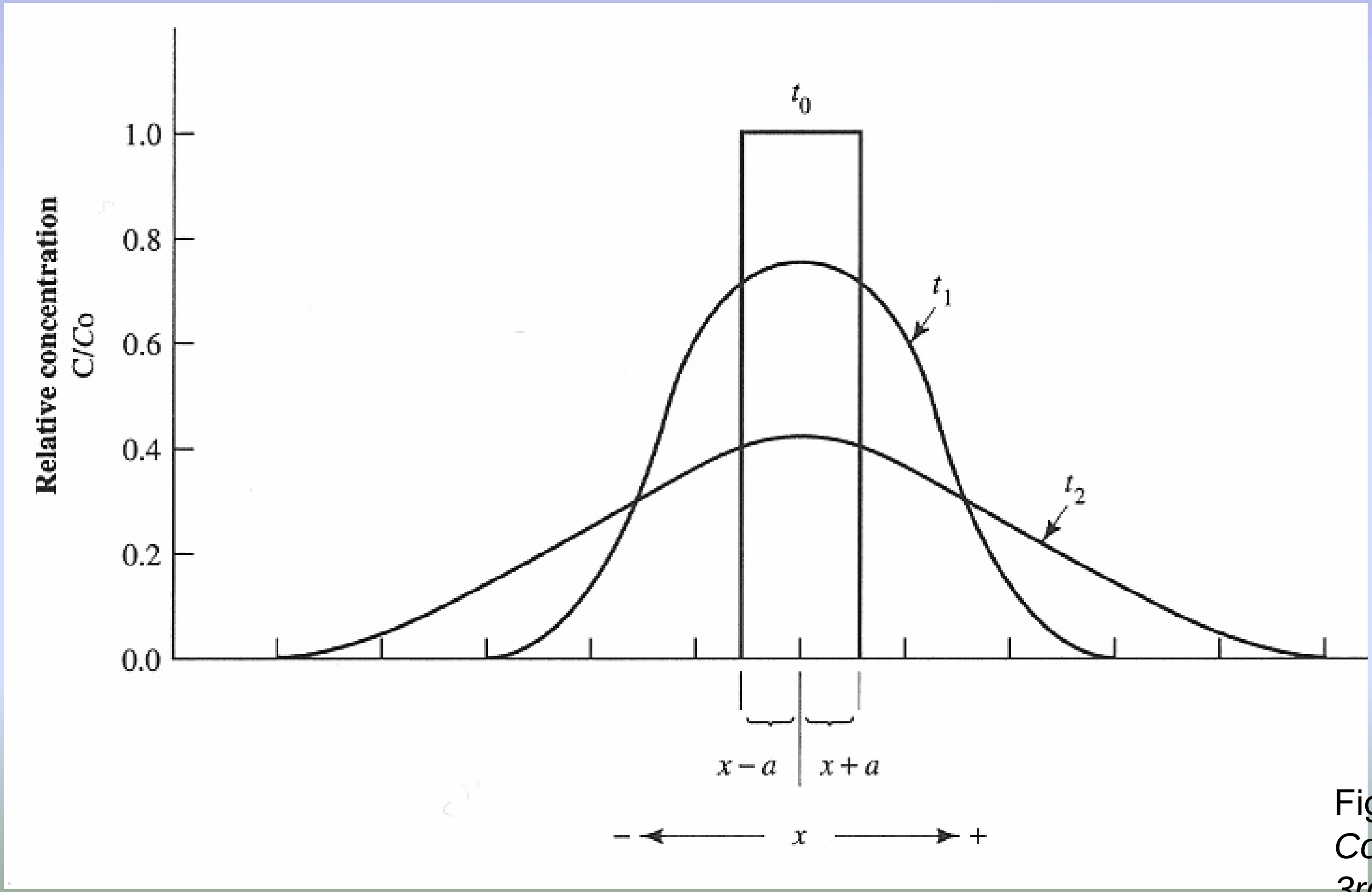
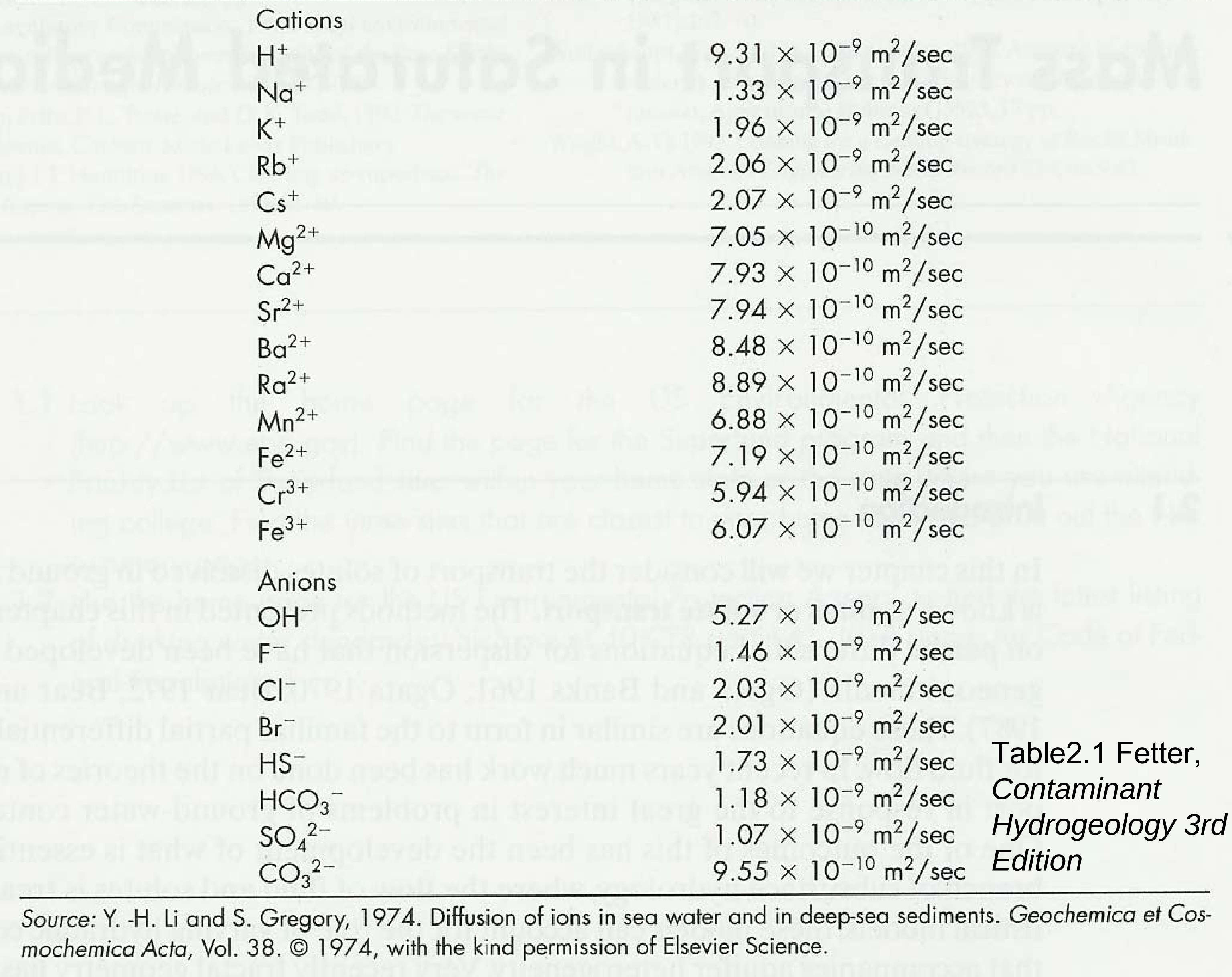


Figure 2.1. Fetter, *Contaminant Hydrogeology 3rd Edition*

Diffusion Coefficients in water at 25oC



Cations	
H^+	9.31×10^{-9} m^2/sec
Na^+	1.33×10^{-9} m^2/sec
K^+	1.96×10^{-9} m^2/sec
Rb^+	2.06×10^{-9} m^2/sec
Cs^+	2.07×10^{-9} m^2/sec
Mg^{2+}	7.05×10^{-10} m^2/sec
Ca^{2+}	7.93×10^{-10} m^2/sec
Sr^{2+}	7.94×10^{-10} m^2/sec
Ba^{2+}	8.48×10^{-10} m^2/sec
Ra^{2+}	8.89×10^{-10} m^2/sec
Mn^{2+}	6.88×10^{-10} m^2/sec
Fe^{2+}	7.19×10^{-10} m^2/sec
Cr^{3+}	5.94×10^{-10} m^2/sec
Fe^{3+}	6.07×10^{-10} m^2/sec
Anions	
OH^-	5.27×10^{-9} m^2/sec
F^-	1.46×10^{-9} m^2/sec
Cl^-	2.03×10^{-9} m^2/sec
Br^-	2.01×10^{-9} m^2/sec
HS^-	1.73×10^{-9} m^2/sec
HCO_3^-	1.18×10^{-9} m^2/sec
SO_4^{2-}	1.07×10^{-9} m^2/sec
CO_3^{2-}	9.55×10^{-10} m^2/sec

Source: Y. -H. Li and S. Gregory, 1974. Diffusion of ions in sea water and in deep-sea sediments. *Geochemica et Cosmochemica Acta*, Vol. 38. © 1974, with the kind permission of Elsevier Science.

Table2.1 Fetter, *Contaminant Hydrogeology 3rd Edition*

D. Retardation:

KD = concentration absorbed/ concentration dissolved in water = ml/g

- metals attach onto clays.
- contaminants attach onto organic carbons.
- the higher the KD, the slower things will move in water.

→ equations in Fetter

Influence of retardation on movement of a solute front in a one-dimensional column

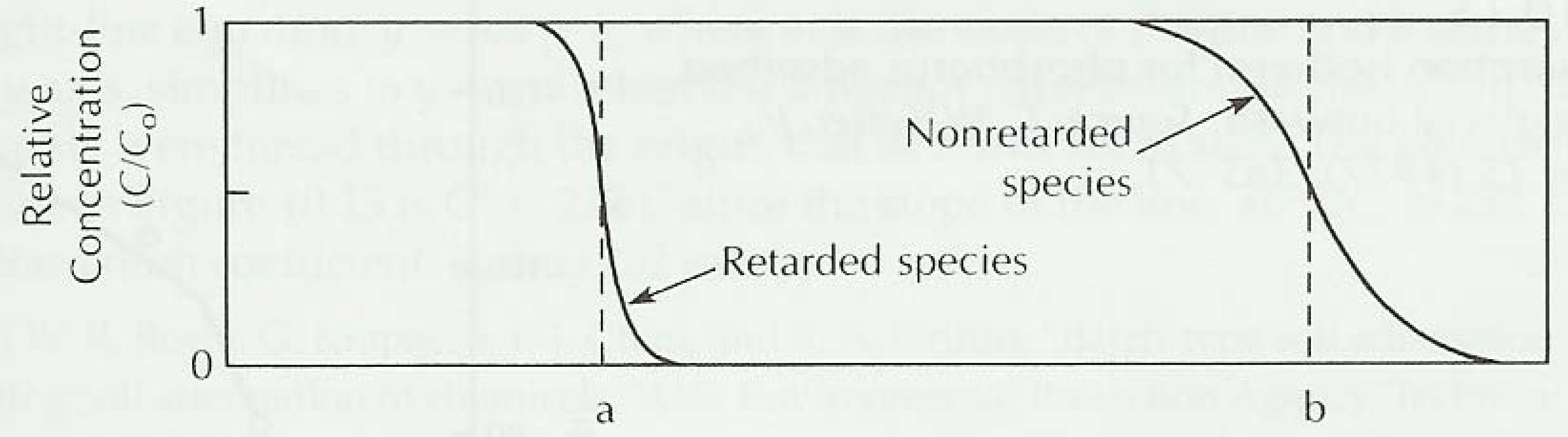


Figure 10.14 Fetter, *Applied Hydrogeology 4th Edition*

Lead adsorption by Cecil clay loam at pH 4.5 and at 25°C described by a linear Freundlich equation through the origin.

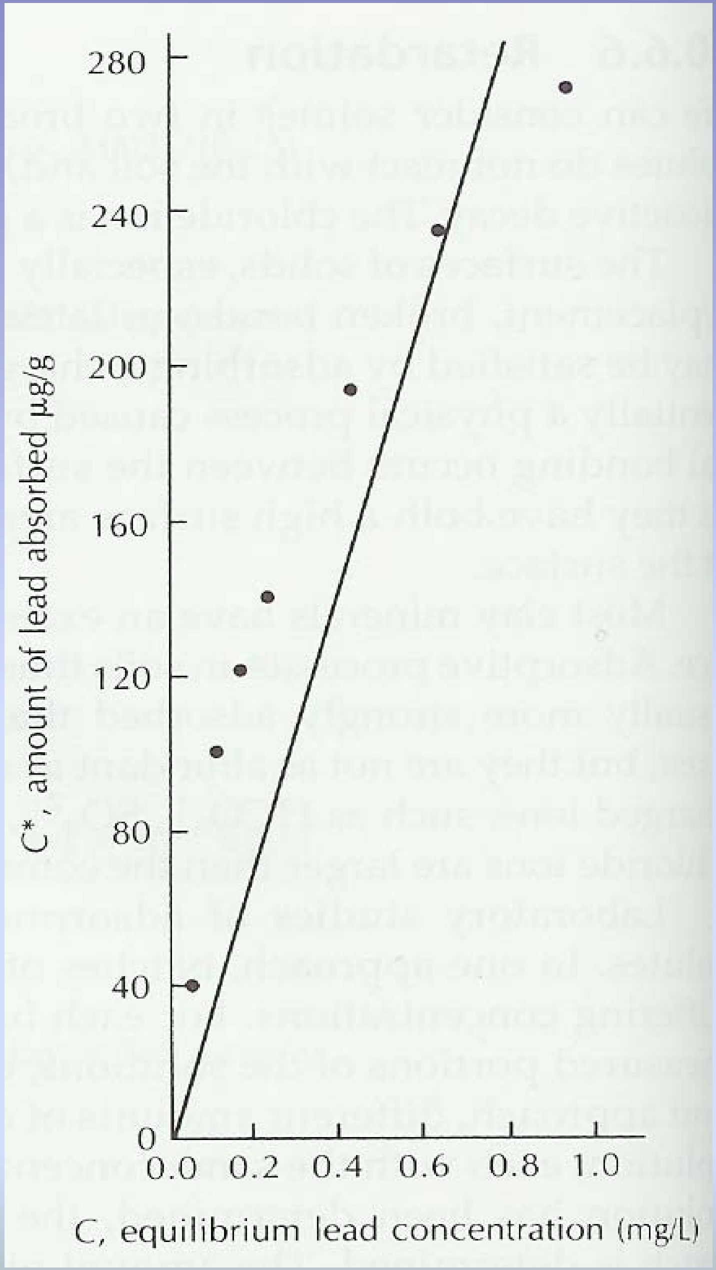
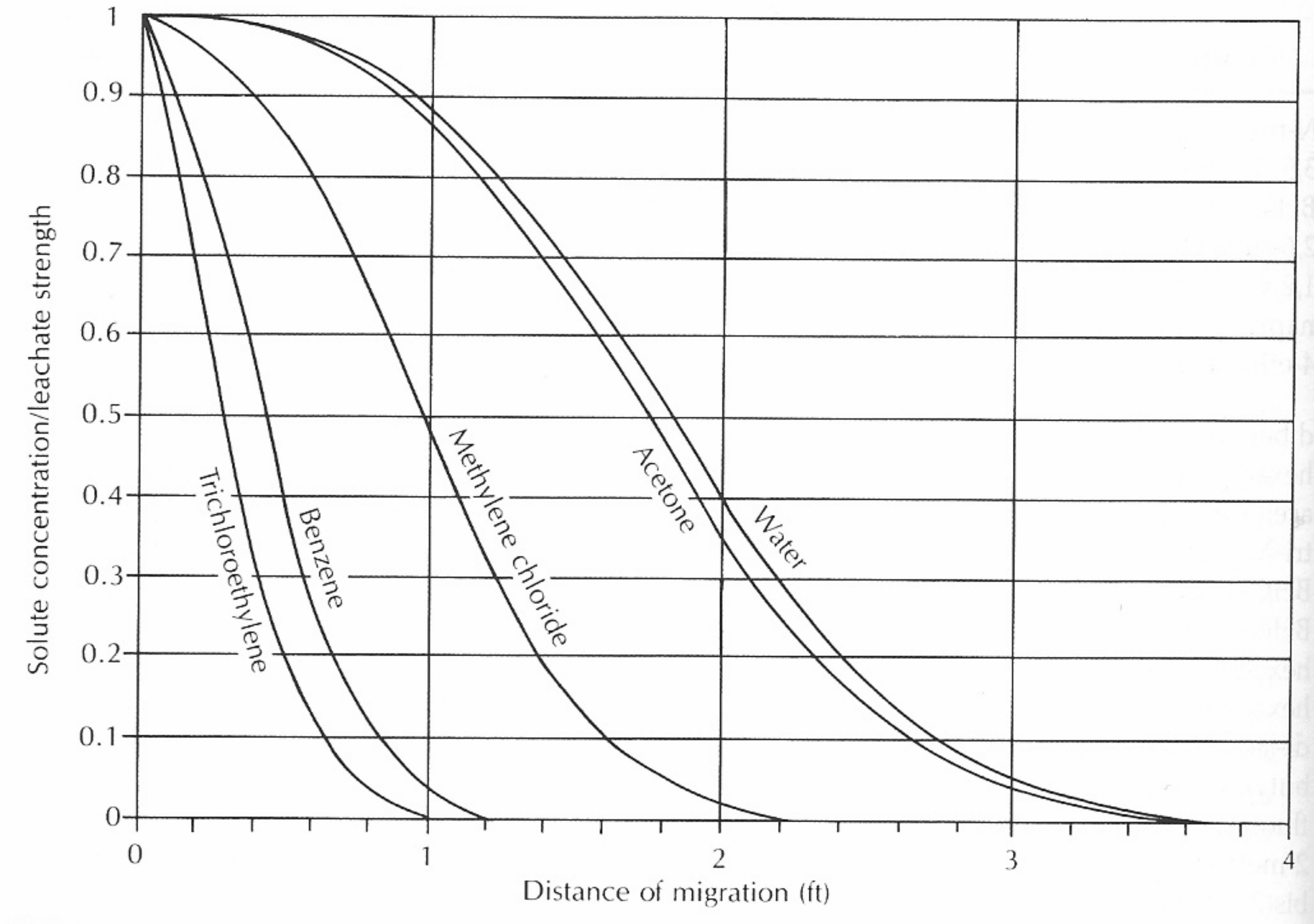


Figure 10.13 Fetter, *Applied Hydrogeology 4th Edition*

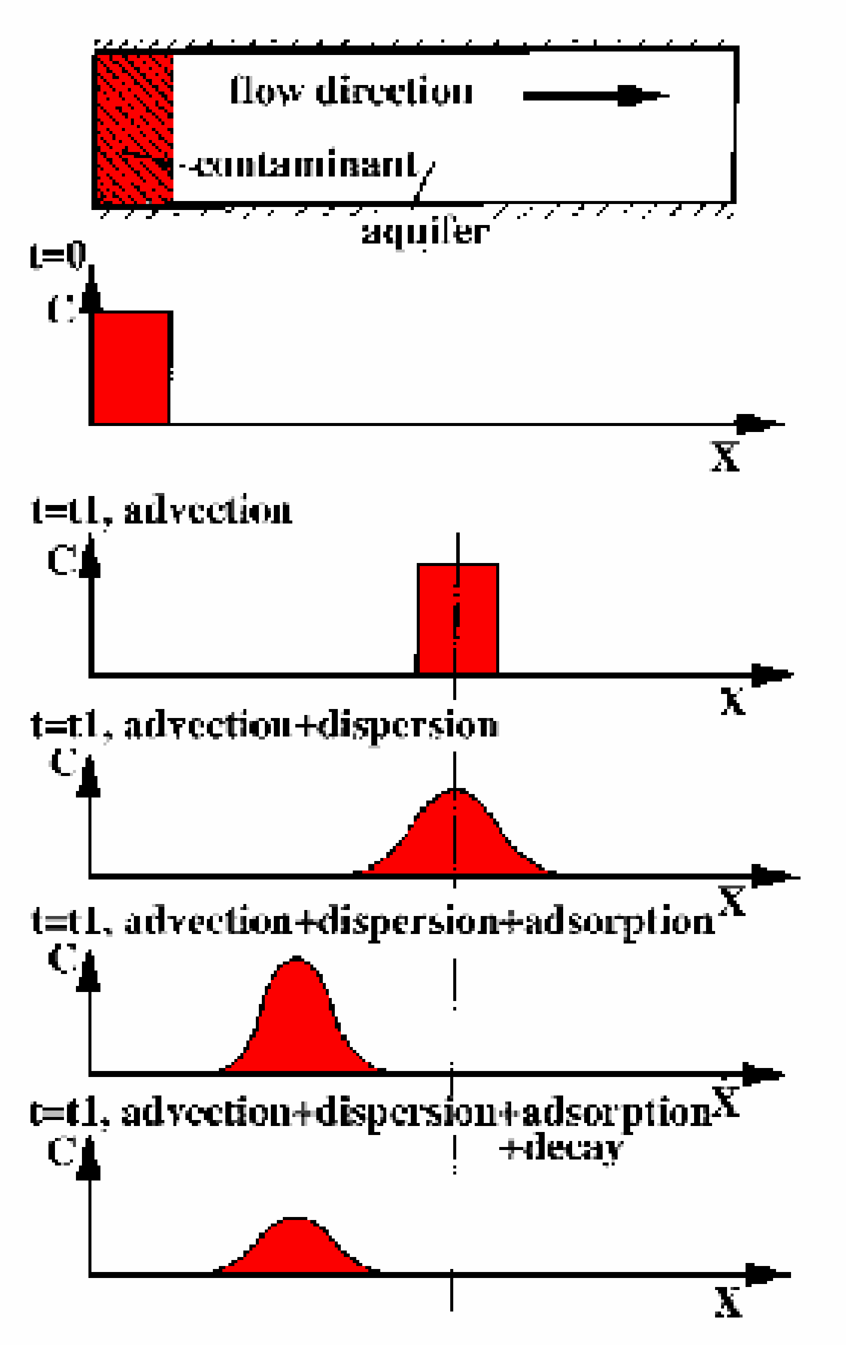
$V_x = V_{H_2O} / [1 + K_D (\rho/\eta)]$ Solubility of organics in H_2O

- KD is proportional to Koc (octonal and water).
- KD is proportional to the organic carbon content -- the higher the KD, the more things attach onto organic carbon, and it moves slower.



Vertical migration, in feet per 100 y, of various synthetic organic compounds through a soil with hydraulic conductivity of 1.6 x 10^{-8} cm/s, hydraulic gradient of 0.222, bulk density of 2.00 g/cm3, particle density of 2.65, effective porosity of 0.22, and soil organic carbon content of 0.5%.

Figure 10.16. Fetter, *Applied Hydrogeology 4th Edition*



http://www.ldeo.columbia.edu/~martins/plumeflow/ppt/ppt2_1_00/sld010.htm