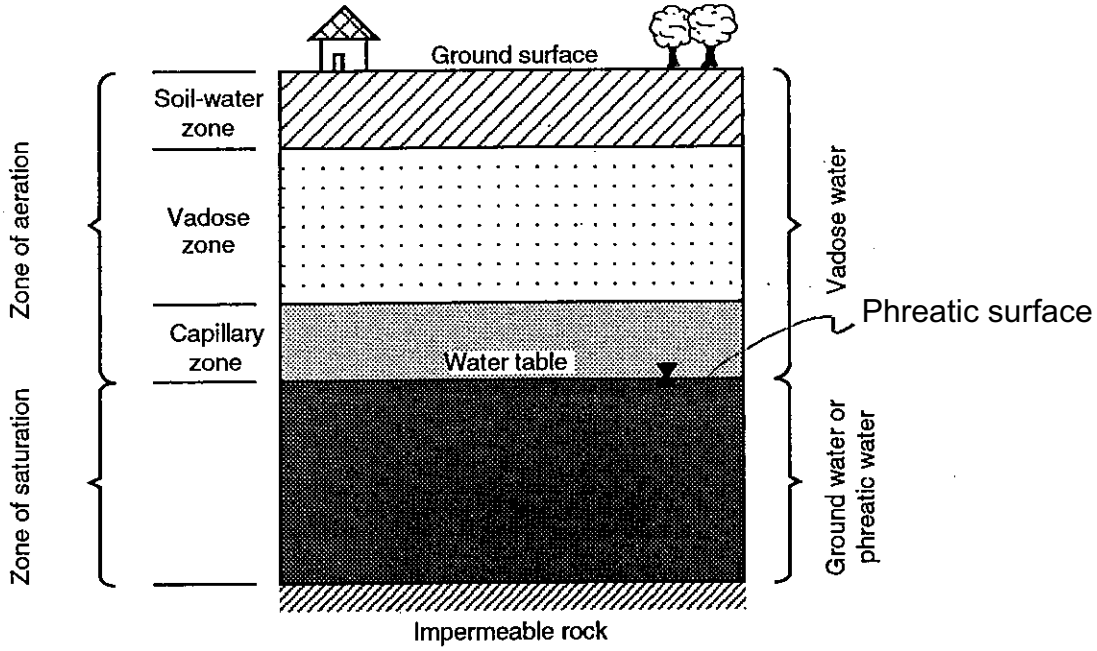


Figure 2.1 Vertical zones of subsurface water. Source: Bedient and Huber, 1992.

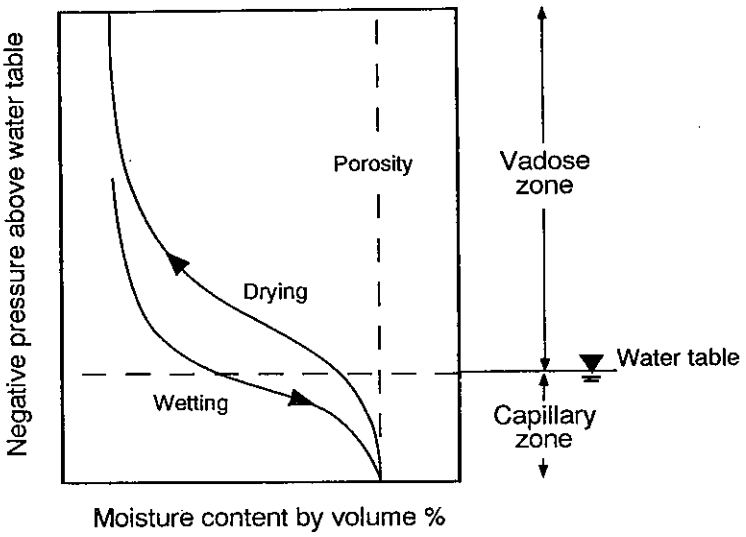


Figure 2.2 Typical soil-moisture relationship. Source: Bedient and Huber, 1992.

Bedient, Rafai & Newell
"Ground Water Contamination"

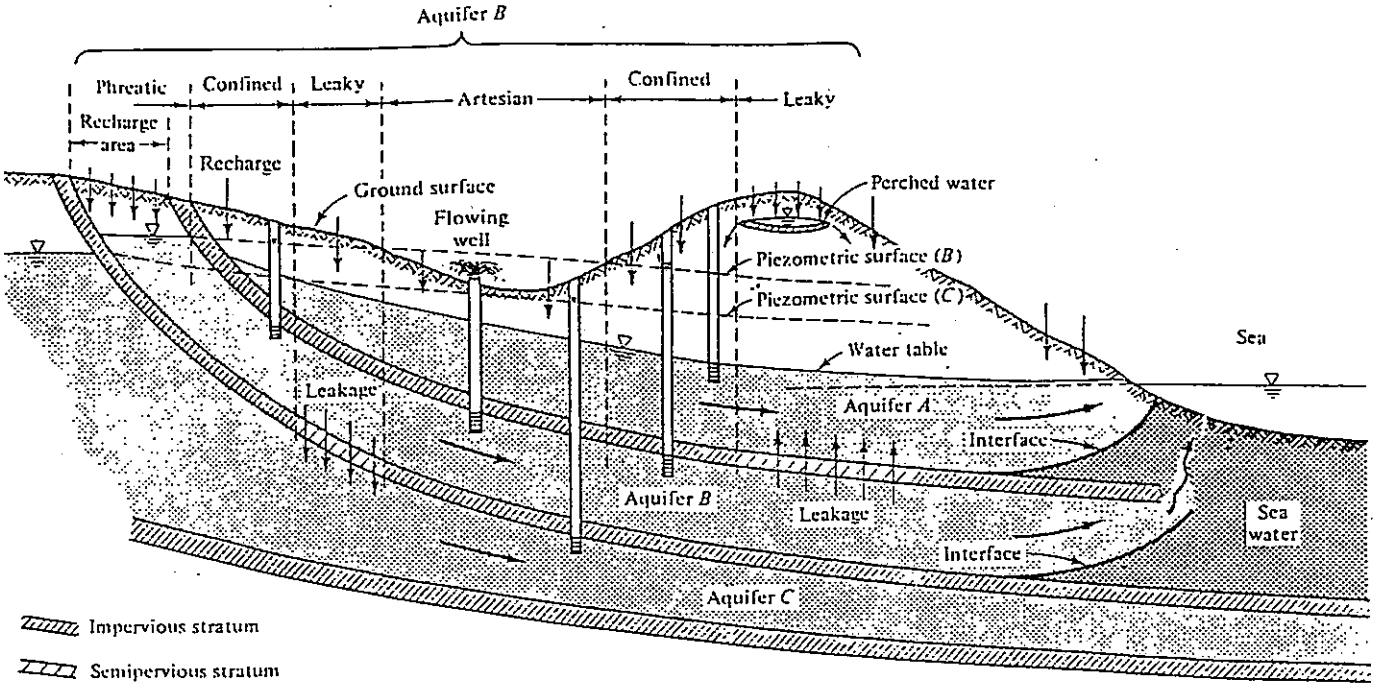
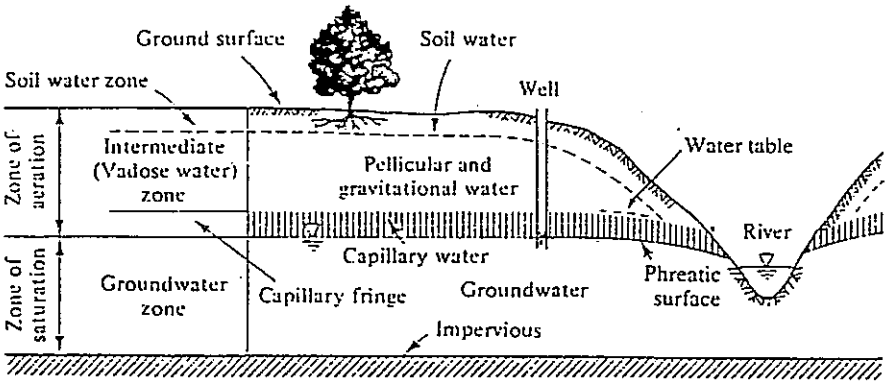


Figure 2 (Bear and Verruijt 1987)



Subsurface moisture zones.

Figure 3 (Bear and Verruijt 1987)

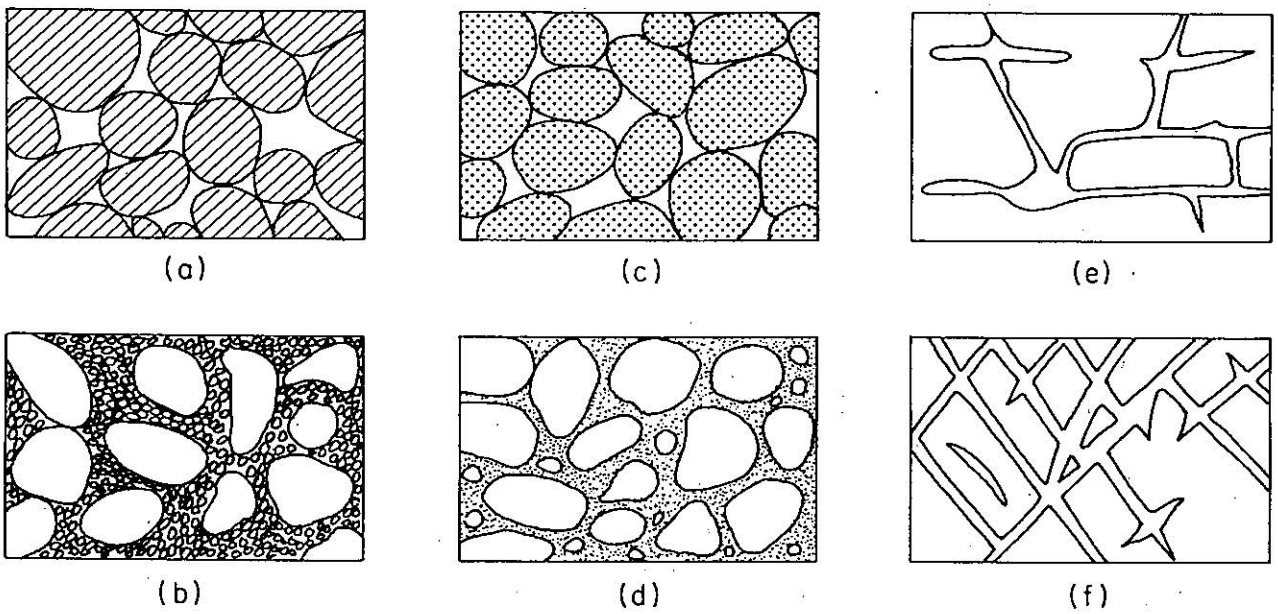


Figure 2.11 Relation between texture and porosity. (a) Well-sorted sedimentary deposit having high porosity; (b) poorly sorted sedimentary deposit having low porosity; (c) well-sorted sedimentary deposit consisting of pebbles that are themselves porous, so that the deposit as a whole has a very high 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 (after Meinzer, 1923).

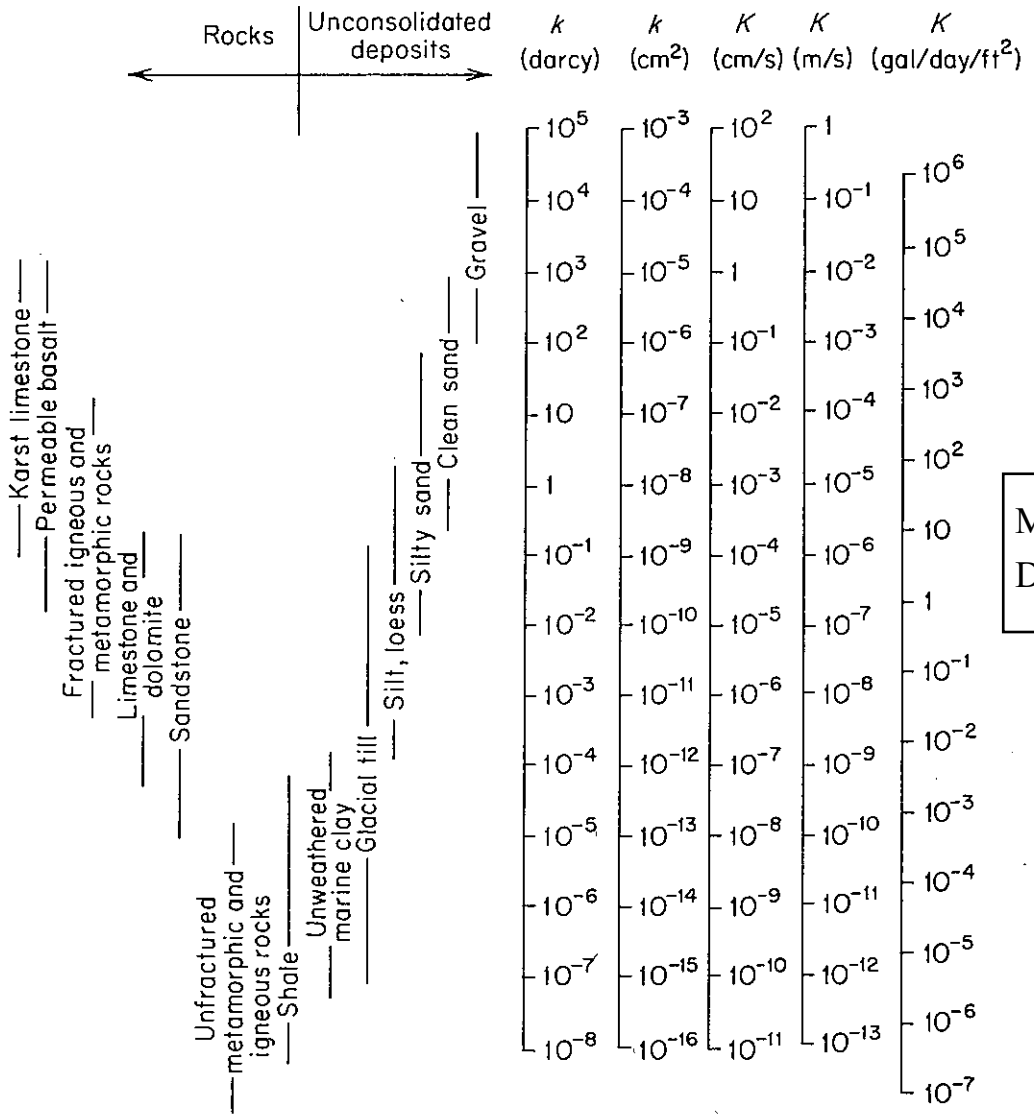
(Freeze & Cherry, 1979)

Table 2.4 Range of Values of Porosity

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

(Freeze & Cherry, 1979)

Table 2.2 Range of Values of Hydraulic Conductivity and Permeability



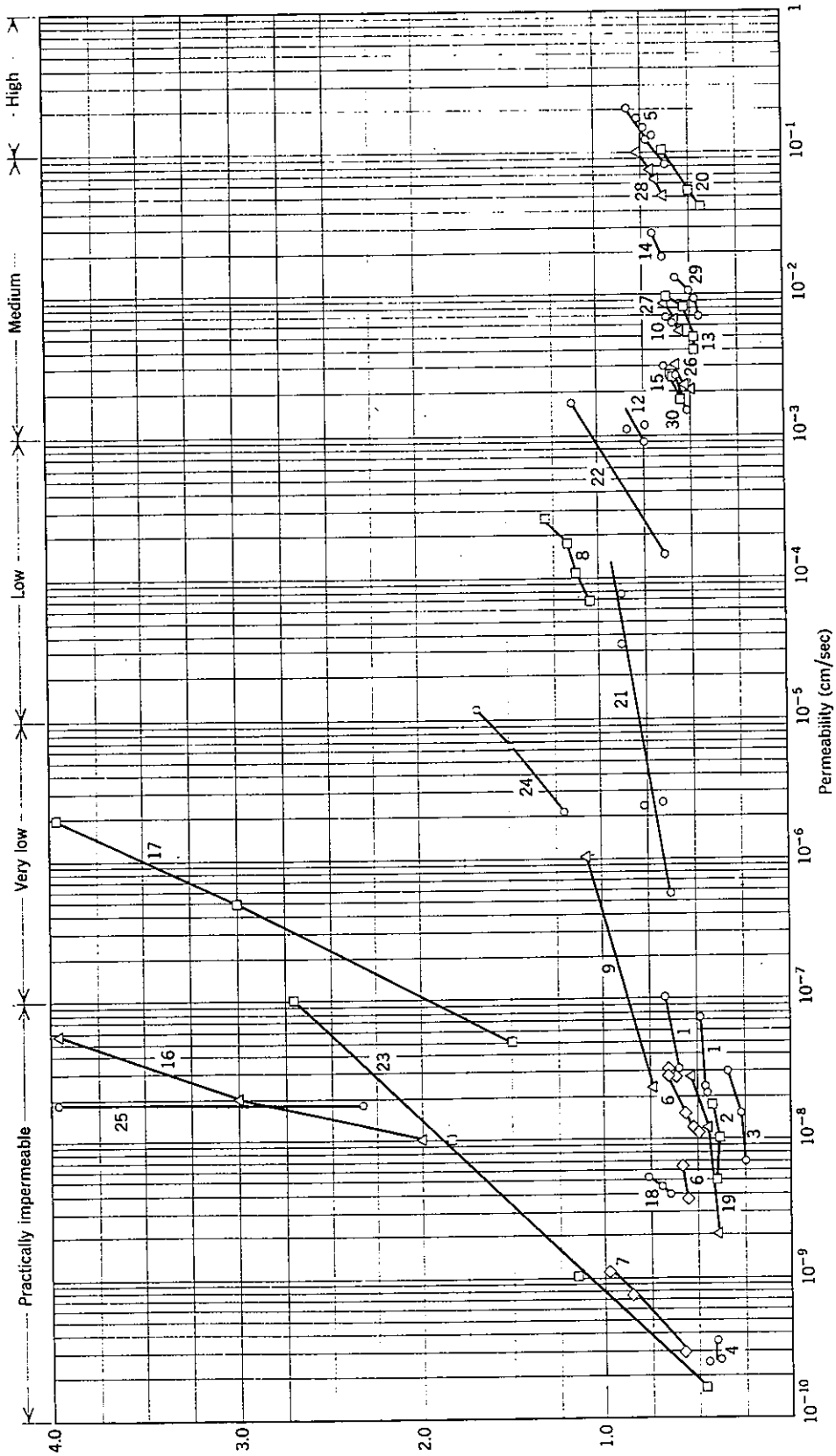
More than 10 orders Difference!!

Table 2.3 Conversion Factors for Permeability and Hydraulic Conductivity Units

	Permeability, k*			Hydraulic conductivity, K		
	cm^2	ft^2	darcy	m/s	ft/s	U.S. gal/day/ft^2
cm^2	1	1.08×10^{-3}	1.01×10^{8}	9.80×10^{2}	3.22×10^{3}	1.85×10^{9}
ft^2	9.29×10^{2}	1	9.42×10^{10}	9.11×10^{5}	2.99×10^{6}	1.71×10^{12}
darcy	9.87×10^{-9}	1.06×10^{-11}	1	9.66×10^{-6}	3.17×10^{-5}	1.82×10^{1}
m/s	1.02×10^{-3}	1.10×10^{-6}	1.04×10^{5}	1	3.28	2.12×10^{6}
ft/s	3.11×10^{-4}	3.35×10^{-7}	3.15×10^{4}	3.05×10^{-1}	1	6.46×10^{5}
U.S. gal/day/ft^2	5.42×10^{-10}	5.83×10^{-13}	5.49×10^{-2}	4.72×10^{-7}	1.55×10^{-6}	1

*To obtain k in ft^2, multiply k in cm^2 by 1.08×10^{-3}.

(Freeze and Cherry, 1979)


Practically impermeable
Very low
Low
Medium
High
Permeability (cm/sec)
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
4.0
3.0
2.0
1.0
Soil Identification Code
1 Compacted caliche
2 Compacted caliche
3 Silty sand
4 Sandy clay
5 Beach sand
6 Compacted Boston blue clay
10 Ottawa sand
11 Sand—Gaspee Point
12 Sand—Franklin Falls
13 Sand—Scituate
14 Sand—Plum Island
15 Sand—Fort Peck
19 Lean clay
20 Sand—Union Falls
21 Silt—North Carolina
22 Sand from dike
23 Sodium—Boston blue clay
24 Calcium kaolinite

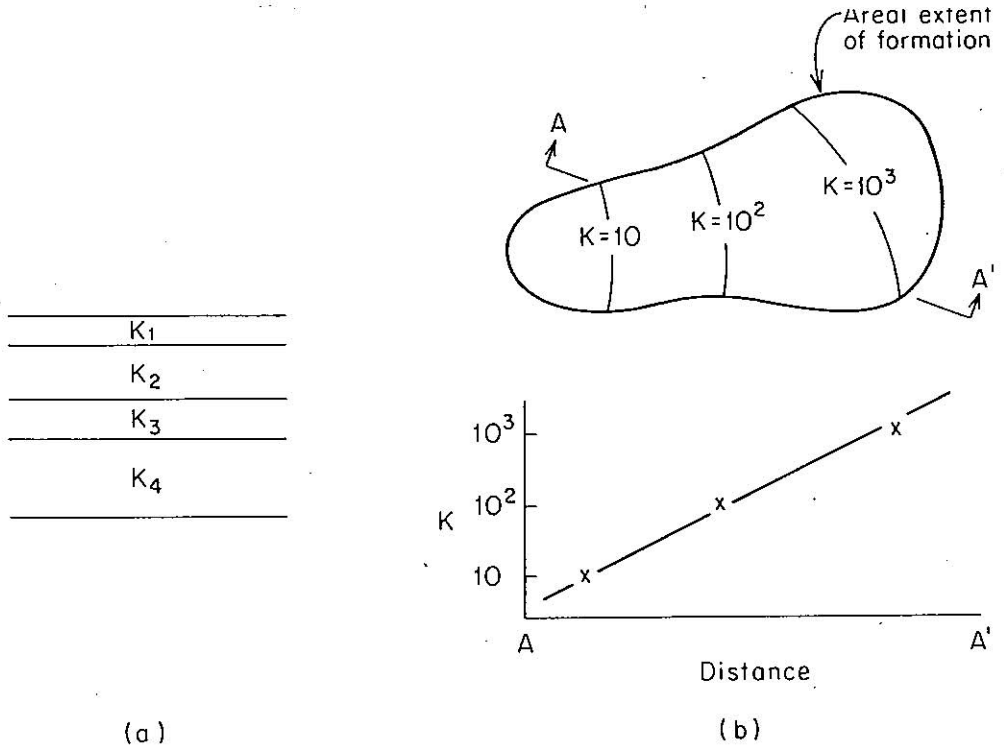


Figure 2.7 Layered heterogeneity and trending heterogeneity. (Freeze & Cherry, 1979)

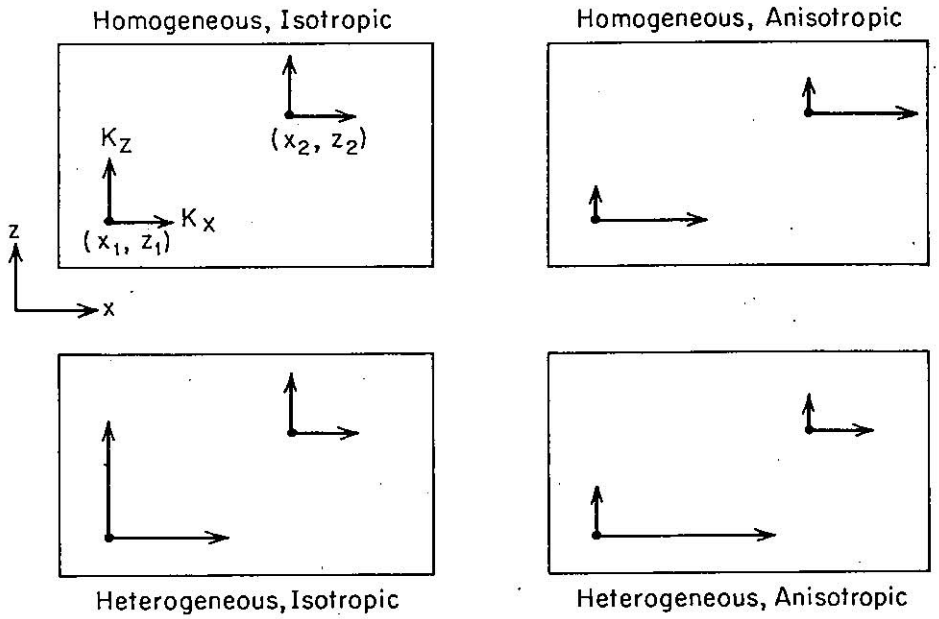


Figure 2.8 Four possible combinations of heterogeneity and anisotropy.

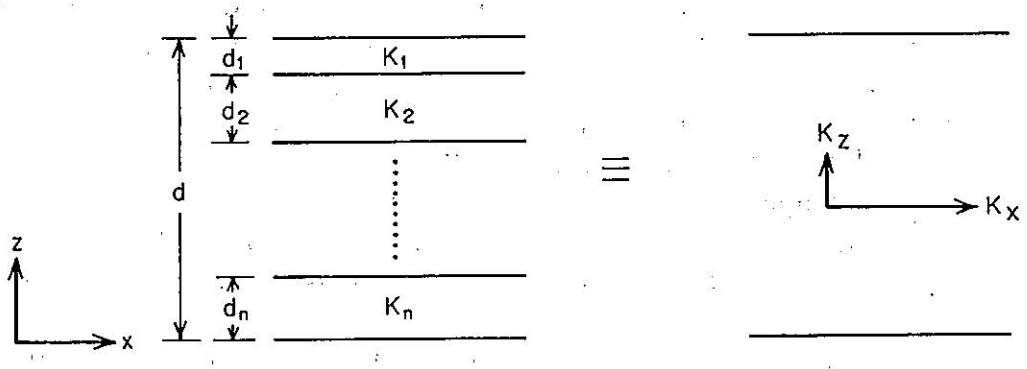


Figure 2.9 Relation between layered heterogeneity and anisotropy.

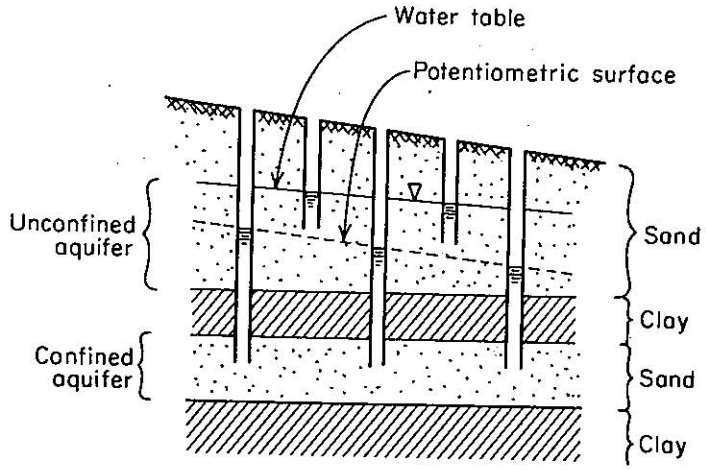


Figure 2.16 Unconfined aquifer and its water table; confined aquifer and its potentiometric surface.

Table 2.5 Range of Values of Compressibility*

	Compressibility, α (m^2/N or Pa^{-1})
Clay	10^{-6}–10^{-8}
Sand	10^{-7}–10^{-9}
Gravel	10^{-8}–10^{-10}
Jointed rock	10^{-8}–10^{-10}
Sound rock	10^{-9}–10^{-11}
Water (β)	4.4×10^{-10}

*See Table A1.3, Appendix I, for conversion factors.

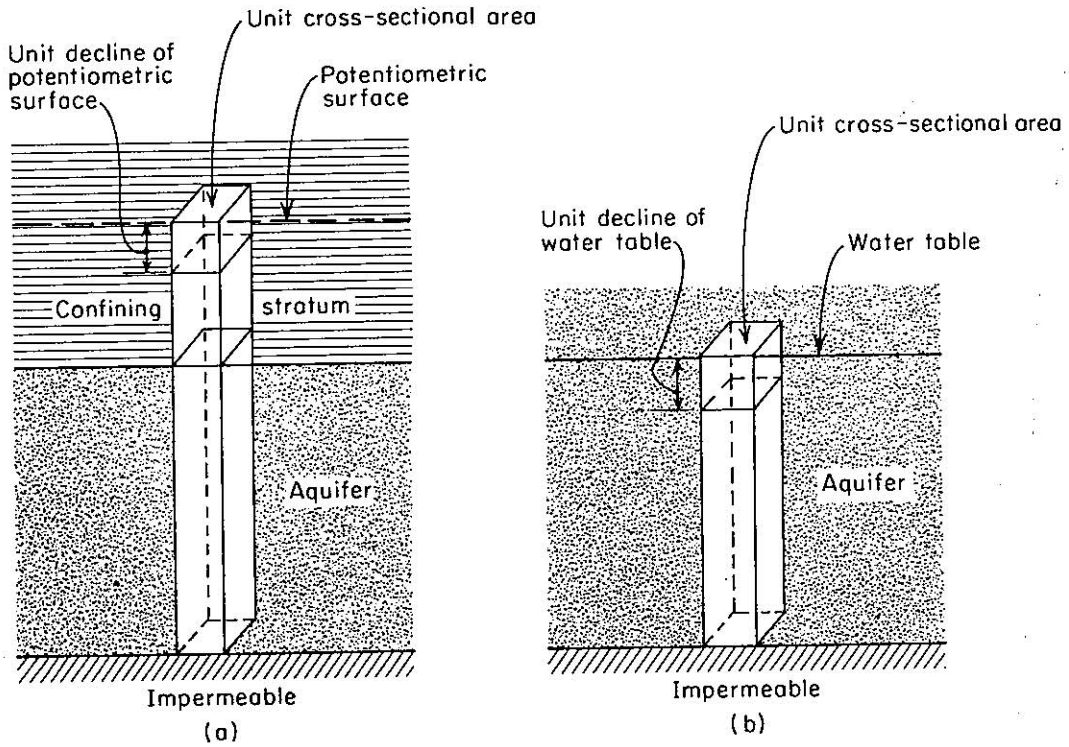


Figure 2.22 Schematic representation of the storativity in (a) confined and (b) unconfined aquifers (after Ferris et al., 1962).

(Freeze & Cherry, 1979)

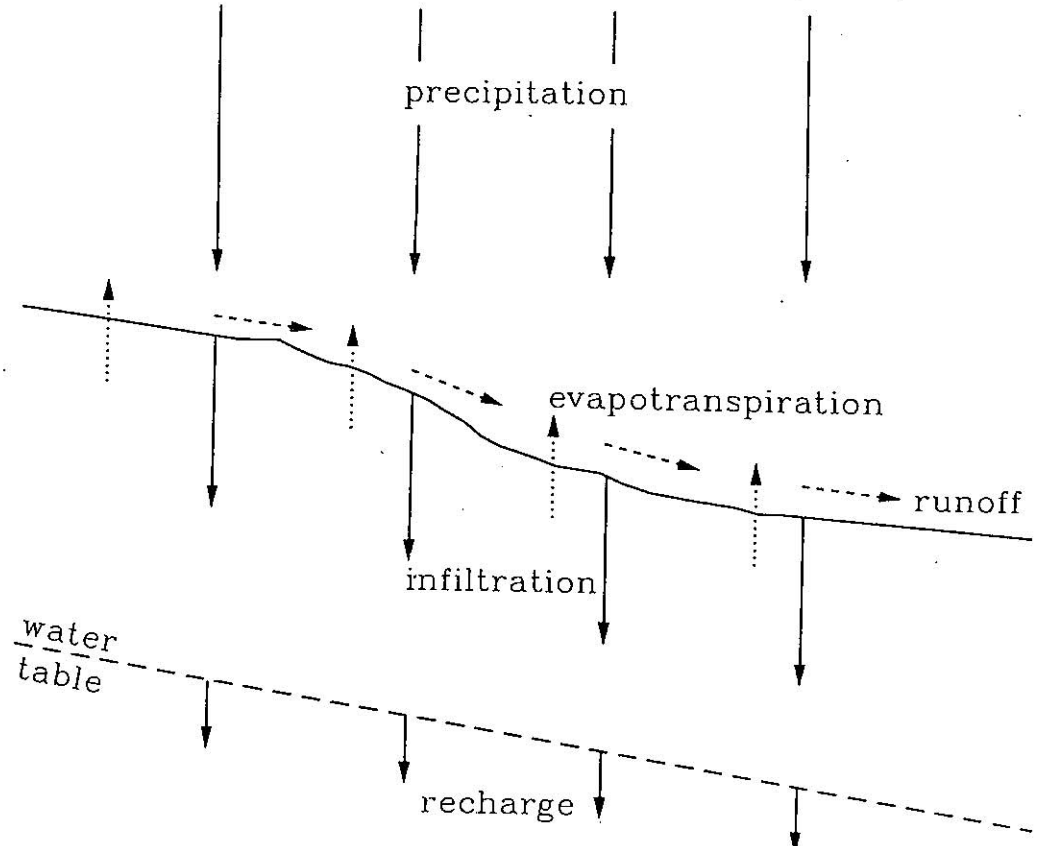


Fig. 4.3 Infiltration and recharge. Infiltration is water that percolates into the ground. Recharge is water that reaches and flows downward from the water table. Only that portion of infiltrating water that is not used to replenish soil-moisture deficits and is not discharged back to the atmosphere through evapotranspiration is available for recharge.

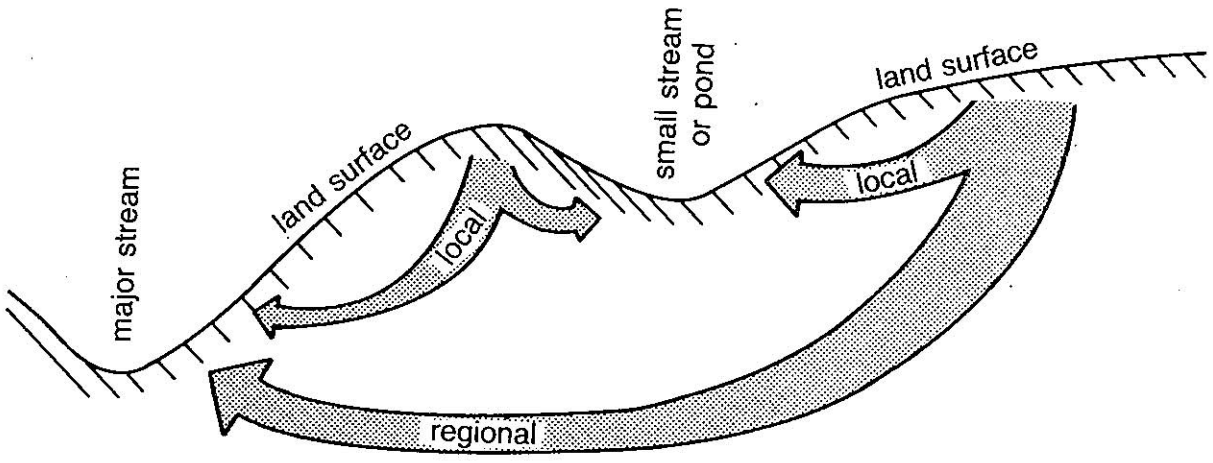


Fig. 4.7 Local and regional flow systems and relationship to recharge and discharge areas (from Cartwright and Sherman, 1969).

"Geotechnical Practice for Waste Disposal"
(Daniel, 1993)

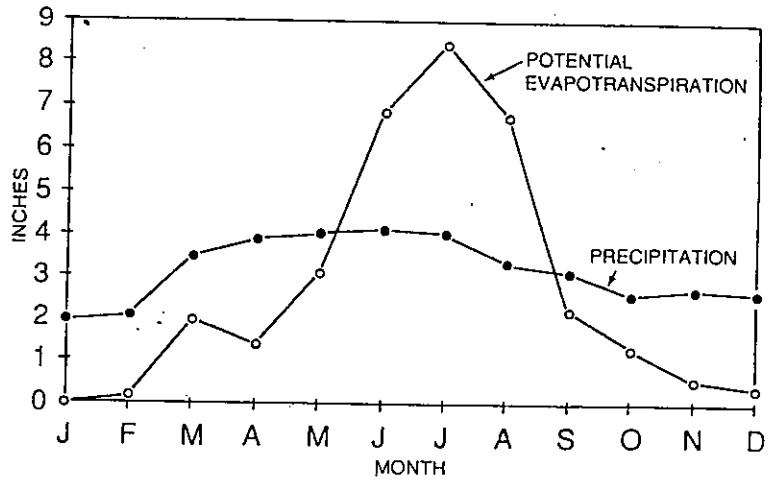
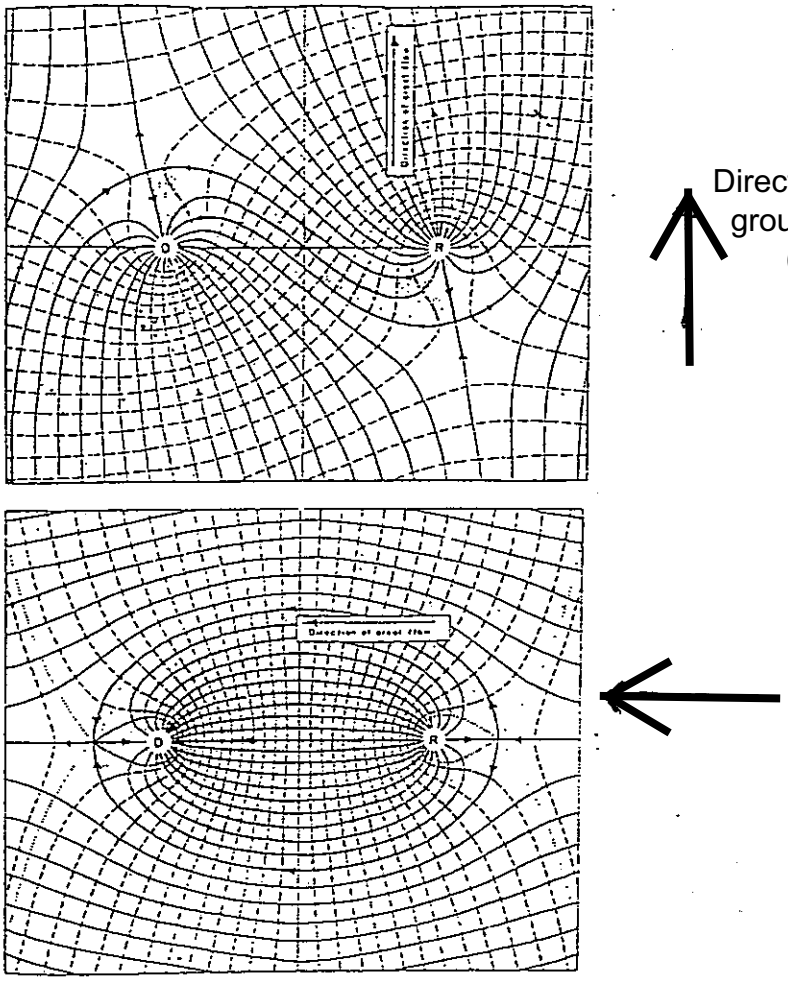


Fig. 4.4 Precipitation vs. evapotranspiration in the midwestern US from Bowman and Collins (1987).

"Geotechnical Practice for Waste Disposal"
(Daniel, 1993)



Diagrams, called flow nets, that illustrate the effect of well placement on the direction and quantity of ground water flow in a homogeneous aquifer with recharge (R) and discharge (D) wells that are at the same depth and are pumping the same amount of water. The solid lines are flow lines, which indicate the pattern of ground water movement. A flow net, by definition, has an equal quantity of water flowing between each pair of flow lines. The dashed lines are lines of equal hydraulic head. Only the water in the stippled areas moves from the recharge well to the discharge well. In the top diagram, the wells are placed in a line perpendicular to the direction of ground water flow, and little recharge water reaches the discharge well. In the bottom diagram, the line from the recharge well to the discharge well is parallel to the direction of ground water flow, and nearly all of the water from the recharge well reaches the discharge well. SOURCE: Da Costa and Bennett, 1960.

(NRC 1994)

TABLE 2-2 Geochemical Processes in Subsurface Environments

Process	Definition	Significance in Aquifers	Effect on Contaminants
Dissolution-precipitation	Reactions that dissolve or precipitate solids such as natural minerals	Primary control on the chemical composition of ground water	Can increase or decrease the concentrations of dissolved constituents, including some types of contaminants
Oxidation-reduction	Reactions that add electrons to (reduce) or remove electrons from (oxidize) chemicals, altering their chemical form	Determines the speciation of metals with more than one oxidation state and the possible chemical and biological degradation pathways of organic matter	Can alter contaminant concentration either by direct chemical reactions or by increasing microbial degradation of the contaminant; can dissolve or precipitate metals
Sorption-desorption	Reactions that transfer a substance from the fluid phase (solvent) to the solid phase (sorbent), or vice versa	Affects dissolved concentrations by the attachment and release of constituents on surfaces of aquifer sediment	Sorption can slow the movement of contaminants
Ion exchange	Exchange of ions in clays for ions in solution, with charge balance maintained	Reduces the concentration of one ion and increases the concentration of another	Can remove contaminant ions from solution, particularly when clay is present, and thus slow their removal by pumping
Complexation	Interactions between chemicals in solution that generate combined chemical species, such as ion pairs, complex ions, or chelates	Affects the availability of substances in ground water to participate in reactions	Can alter the concentrations, reactivities, and mobilities of contaminants (especially metals)

(NRC 1994)

TABLE 2-3 Characteristics of Toxic Inorganics in Ground Water

Metal	Oxidation State(s)	Principal Dissolved Forms[a]
Lead	Pb(II), Pb(IV)	Pb^{2+} ion Hydroxide complexes[b] Carbonate or sulfate ion pairs[c] Organic (e.g., tetraethyl lead)
Arsenic	As(III), As(V)	Arsenate (As^{5+}) oxyanions Arsenite (As^{3+}) oxyanions Organic (e.g., dimethyl arsenic acid)
Cadmium	Cd(II)	Cd^{2+} ion Carbonate ion pairs Chloride, hydroxide complexes
Chromium	Cr(III), Cr(VI)	Cr^{3+} ion Hydroxide complexes (Cr^{3+}) Chromate, dichromate (Cr^{6+}) oxyanions

[a]From Hem, 1985.

[b]Complex ions are species composed of two or more single ions that are combined (e.g., $Pb(OH)_3^-$).

[c]Ion pairs are ions of opposite charge that are adjacent in solution, temporarily forming a pair (e.g., $PbCO_{3(aq)}$). They are weakly bonded relative to complexes.

Table 3.6 Dissociation Reactions, Equilibrium Constants, and Solubilities of Some Minerals That Dissolve Congruently in Water at 25°C and 1 Bar Total Pressure

Mineral	Dissociation reaction	Equilibrium constant, K_{eq}	Solubility at pH 7 (mg/ℓ or g/m³)
Gibbsite	$Al_2O_3 \cdot 2H_2O + H_2O = 2Al^{3+} + 6OH^-$	10^{-34}	0.001
Quartz	$SiO_2 + 2H_2O = Si(OH)_4$	$10^{-3.7}$	12
Hydroxylapatite	$Ca_5OH(PO_4)_3 = 5Ca^{2+} + 3PO_4^{3-} + OH^-$	$10^{-55.6}$	30
Amorphous silica	$SiO_2 + 2H_2O = Si(OH)_4$	$10^{-2.7}$	120
Fluorite	$CaF_2 = Ca^{2+} + 2F^-$	$10^{-9.8}$	160
Dolomite	$CaMg(CO_3)_2 = Ca^{2+} + Mg^{2+} + 2CO_3^{2-}$	$10^{-17.0}$	90,* 480†
Calcite	$CaCO_3 = Ca^{2+} + CO_3^{2-}$	$10^{-8.4}$	100,* 500†
Gypsum	$CaSO_4 \cdot 2H_2O = Ca^{2+} + SO_4^{2-} + 2H_2O$	$10^{-4.5}$	2100
Sylvite	$KCl = K^+ + Cl^-$	$10^{+0.9}$	264,000
Epsomite	$MgSO_4 \cdot 7H_2O = Mg^{2+} + SO_4^{2-} + 7H_2O$	—	267,000
Mirabillite	$Na_2SO_4 \cdot 10H_2O = 2Na^+ + SO_4^{2-} + 10H_2O$	$10^{-1.6}$	280,000
Halite	$NaCl = Na^+ + Cl^-$	$10^{+1.6}$	360,000

*Partial pressure of $CO_2 = 10^{-3}$ bar.

†Partial pressure of $CO_2 = 10^{-1}$ bar.

SOURCE: Solubility data from Seidell, 1958.

Composition of Rain and Snow (mg/ℓ)*

Constituent	1	2	3	4	5	6	7
SiO_2	0.0	0.1	—	0.29	0.6	—	0.9
Ca	0.0	0.9	1.20	0.77	0.53	1.42	0.42
Mg	0.2	0.0	0.50	0.43	0.15	0.39	0.09
Na	0.6	0.4	2.46	2.24	0.35	2.05	0.26
K	0.6	0.2	0.37	0.35	0.14	0.35	0.13
NH_4	0.0	—	—	—	0.6	0.41	0.48
HCO_3	3	2.0	—	1.95	—	—	—
SO_4	1.6	2.0	—	1.76	0.45	2.19	3.74
Cl	0.2	0.2	4.43	3.75	0.22	3.47	0.38
NO_3	0.1	—	—	0.15	0.41	0.27	1.96
TDS	4.8	5.1	—	12.4	—	—	—
pH	5.6	—	—	5.9	5.3	5.5	4.1

*(1) Snow, Sponer Summit, U.S. Highway 50, Nevada (east of Lake Tahoe), altitude 7100 ft., Nov. 20, 1958; (2) rain, at eight sites in western North Carolina, average of 33 events, 1962–1963; (3) rain in southeastern Australia, 28 sites over 36 months, 1956–1957; (4) rain at Menlo Park, Calif., winters of 1957–1958; (5) rain, near Lake of the Woods, NW Ontario, average of 40 rain events, 1972; (6) rain and snow, northern Europe, 60 sites over 30 months, 1955–1956; (7) rain and snow at a site 20 km north of Baltimore, Maryland, average for 1970–1971.

SOURCE: Feth et al., 1964 (1); Laney, 1965 (2); Carroll, 1962 (3); Whitehead and Feth, 1964 (4); Bottomley, 1974 (5); Carroll, 1962 (6); and Cleaves et al., 1974 (7).

(Freeze & Cherry, 1979)

Table 3.3 Classification of Dissolved Inorganic Constituents in Groundwater

Major constituents (greater than 5 mg/ℓ)	
Bicarbonate	Silicon
Calcium	Sodium
Chloride	Sulfate
Magnesium	Carbonic acid
Minor constituents (0.01–10.0 mg/ℓ)	
Boron	Nitrate
Carbonate	Potassium
Fluoride	Strontium
Iron	
Trace constituents (less than 0.1 mg/ℓ)	
Aluminum	Molybdenum
Antimony	Nickel
Arsenic	Niobium
Barium	Phosphate
Beryllium	Platinum
Bismuth	Radium
Bromide	Rubidium
Cadmium	Ruthenium
Cerium	Scandium
Cesium	Selenium
Chromium	Silver
Cobalt	Thallium
Copper	Thorium
Gallium	Tin
Germanium	Titanium
Gold	Tungsten
Indium	Uranium
Iodide	Vanadium
Lanthanum	Ytterbium
Lead	Yttrium
Lithium	Zinc
Manganese	Zirconium

SOURCE: Davis and De Wiest, 1966.

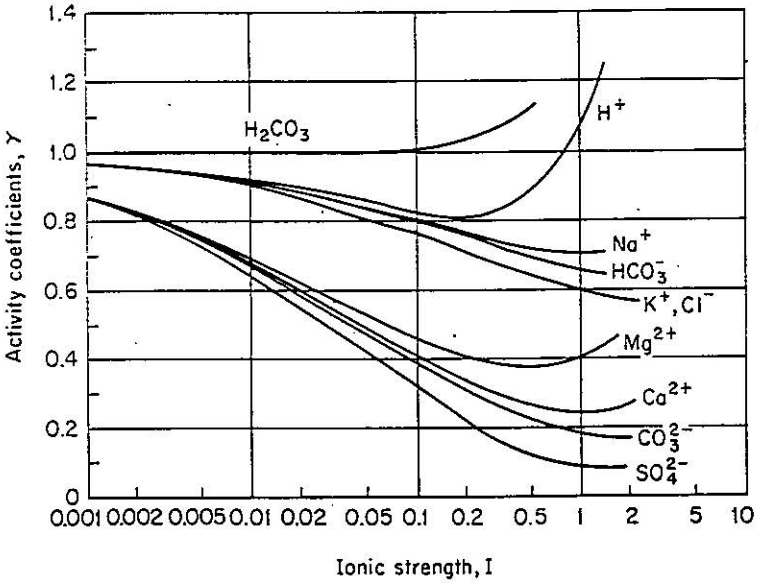


Figure 3.3 Activity coefficient versus ionic strength relations for common ionic constituents in groundwater.

Debye-Hückel expression for individual ion activities:

z:charge number

$$\log \gamma = \frac{-Az^2\sqrt{I}}{1 + \mathring{a}B\sqrt{I}}$$

Values of the Ion-Size Parameter $\mathring{a}$ for Common Ions Encountered in Natural Water:

$\mathring{a} \times 10^8$	Ion
2.5	NH_4^+
3.0	K^+, Cl^-, NO_3^-
3.5	OH^-, HS^-, MnO_4^-, F^-
4.0	SO_4^{2-}, PO_4^{3-}, HPO_4^{2-}
4.0–4.5	Na^+, HCO_3^-, $H_2PO_4^-$, HSO_3^-
4.5	CO_3^{2-}, SO_3^{2-}
5	Sr^{2+}, Ba^{2+}, S^{2-}
6	Ca^{2+}, Fe^{2+}, Mn^{2+}
8	Mg^{2+}
9	H^+, Al^{3+}, Fe^{3+}

Parameters A and B at 1 Bar

Temperature (°C)	A	B (× 10^{-8})
0	0.4883	0.3241
5	0.4921	0.3249
10	0.4960	0.3258
15	0.5000	0.3262
20	0.5042	0.3273
25	0.5085	0.3281
30	0.5130	0.3290
35	0.5175	0.3297
40	0.5221	0.3305
50	0.5319	0.3321
60	0.5425	0.3338

(Freeze & Cherry, 1979)