Overview of Groundwater and Aquifer Properties

I. Introduction to Groundwater

A. Introduction

1. Water contained within cracks, fractures and pore spaces of soil, sediment and rocks beneath the surface of the earth

2. Groundwater flow path: atmospheric precipitation percolates into soil/bedrock directly or from surface lakes and streams, and generally flows downward under the force of gravity until it reaches some sort of physical barrier or impermeable zone, which either severely impedes flow or stops it altogether.

II. Porosity of Earth Materials

1. Porosity: ratio, in per cent, of the volume of void space to the total volume of sediment or rock

$$P\ (\%) = \frac{\text{total volume - volume of solids}}{\text{total volume}} \times 100$$

a. Porosity is the primary governing factor influencing the ability of rock or sediment to store fluids (e.g. groundwater or hydrocarbons)

b. Types of Porous Openings

(a) Intergranular Porosity = primary pore spaces present between particles of a sediment or rock deposit

i) Intergranular Porosity influenced by:
a) sorting
b) grain packing
c) grain size

(b) Fractured Porosity
(c) Solution Cavities
(d) Vesicles

c. Effective porosity: considers the extent to which pore spaces are interconnected in a deposit, as well as the force of hydrostatic attraction that binds water molecules to the surfaces of grains/pore spaces

d. Secondary Porosity: can impart a secondary or "overprint" porosity on a rock unit via structural fracturing and chemical dissolution.

e. Lithologic Control on Porosity
(1) Porosity of Unconsolidated Sediments

(a) function of grain size and packing

i) uncompacted clay and silt = very high porosity (up to 50%)

**compacted clay and silt = decreased porosity to 15%

ii) sand and gravel: porosity of 20-30% typically

(2) Porosity of Crystalline Plutonic and Metamorphic Rocks

(a) Very low primary porosity

(b) Secondary "structural porosity"

i) joints, fractures, faults -----porous zones

a) may achieve 5-10% on avg, up to 50% porosity in some instances

(3) Porosity of Volcanic Rock

(a) Vesicles and columnar jointing may create relatively high porosities

(b) Inter-flow fluvial deposits

(c) brecciated horizons

III. Specific Yield

a. Specific Yield and Specific Retention

(1) Specific Yield of Aquifer

$$S.Y. = \frac{\text{Vol. of Water Drained Under Gravity}}{\text{Total Volume of Rock in Aquifer}}$$

(2) Specific Retention

$$S.R. = \frac{\text{Vol. of Water Retained as Water Film}}{\text{Total Volume of Rock in Aquifer}}$$

** Porosity = S.Y. + S.R. **

A. Ranges of Specific Yield and Earth Materials

1. Clay = 0-5%, sand = 10-35%, Gravel = 12-26%

IV. Hydraulic Conductivity of Earth Materials

1. <u>Permeability</u>: the degree of interconnectedness between pore spaces and fractures within a rock or sediment deposit. A measure of the capacity of a porous material to transmit fluids

a. Permeability (K) is largely a function of:

(1) grain size, size of pore space

(2) shape of grains/shape of pore space

(3) degree of interconnected pore space

b. Hydraulic Conductivity = permeability in a horizontal direction in aquifer

(1) Measure of rate of tranmission of fluids horizontally through aquifer, essentially another term for permeability (modification of Darcy's Law)

$$Q = -KIA$$

Where Q = discharge (L^3/T)
K = hydraulic conductivity (permeability) (L/T)
I = hydraulic gradient (vertical head distance between two points of observation) (decimal ratio)
A = cross-sectional area through which flow occurs (L^2)

(a) Vertical Conductivity = capacity to transmit fluids in vertical direction
(b) Horizontal Conductivity = capacity to transmit fluids in horizontal direction

c. Darcy's Law

$$Q = \frac{KA(P_2-P_1)}{uL}$$ where,

Q = Volume Discharge Rate (cm^3/sec)
K = Permeability (millidarcy = mD)
A = Cross-sectional area at perpendicular to flow (cm^2)
L = length along which press. diff. is measured (cm)
(P_2-P_1)= pressure difference (atm) between two points separated by distance L
u = viscosity of fluid (centipoises)

Generally, well sorted sand and gravel display high porosity and permeability, however, a poor sorted sand with much matrix material will have a low permeability.

Unpacked clay, may have a very high porosity but very low permeability.

Generally clay/shale make for good permeability barriers, while sand and gravel readily transmit fluids. However secondary overprints such as structural deformation and diagenetic alteration (post-depositional changes in mineralogy) can drastically influence permeabiltiy and porosity.

A. Hydraulic Conductivity

1. By rearranging Darcy's Law (above):

K = <u>   - Q   </u>

A (I)

where K = hydraulic conductivity
A = cross-sectional area
I = dh/dL = gradient ("rise over run")

B. Permeameters

1. Defined: lab device to measure hydraulic conductivity of earth materials (see figure included with the note set)

a. Involves a holding chamber for the seds/soil, and a head of water is established in the medium. The head is known, the length of the material medium is known, discharge is measured.

b. Equation for solution of constant head permeameter test:

$$K = QL/(Ah)$$

where K = hydraulic conductivity (cm/sec), L = length of sample (cm), A = cross-sectional area of sample (cm^2), h = hydraulic head (cm), Q = discharge (cm^3/sec)

c. Equation for solution of falling head permeameter test:
See attached equation sheet.

C. Permeability Vs. Lithology

(1) Permeability of Unconsolidated Sediments
(a) Relationships to Grain Size
i) Perm < with < Grain Size (and vice versa)
ii) Perm < with < sorting (and vice versa)
a) Hence well sorted coarse sediment (sand, gravel) display the highest permeability

b) Poorly sorted or very fine sediment (clayey sand, or clay) generally display lowest permeability
c) Permeability of Lithified Rocks

(b) Function of interconnected nature of pore spaces
i) Sandstone, Conglomerate = high primary permeability
ii) Limestone = low primary permeability

a) Dissolved Limestone ----- high secondary permeability

iii) Shale and Well-cemented Siltstone = low primary permeability
a) Fractured Shales and Siltstones = high

secondary permeability

b) Crystalline Igneous and Metamorphic Rocks = low primary permeabiltiy

c) Fractured Shales and Siltstones = high fractured (secondary permeability

iv) Volcanic Rocks = high primary permeability associated with columnar jointing

V. Aquifers

A. Subsurface Hydrologic Zones

1. Zone of Aeration or Vadose Zone:

a. the uppermost portion of the groundwater environment, extends from a few cm's to hundreds of meters.

(1) Zone contains mixture of moisture and air held in pore spaces by molecular attraction.

2. Zone of Saturation: or phreatic zone: zone below zone of aeration, in which all pore spaces, fractures and cracks are filled or saturated with water. (i.e. groundwater).

a. Water table: the top surface of the saturated zone, open to atmospheric pressure conditions via the vadose zone above.

b. Ground water flow: groundwater flows along permeable zones under the force of gravity, taking the path of least resistance. Ground water flows along porous paths from areas of higher water table elevation to areas of lower water table elevation.

c. Water table configuration: water table generally follows the surface topography of the land above, rising to higher elevations beneath hills, and lower elevations beneath valleys, generally water table deeper beneath hills, and coming closer to surface beneath valleys.

(1) intersection of water table with surface of the earth results in surface flow of water in form of springs or seeps, or perhaps manifested as a lake or swamp.

d. Pressure Relationships: the level of the water table is generally a surface of constant pressure or hydrologic head.

(1) A well dug to intersect the water table, will fill with water to the level of the water table, unless under some kind of hydrostatic pressure (artesian conditions)

(2) Groundwater Maps: elevations of top of water table can be mapped and contoured

i) Ground water elevations derived from measuring water levels in wells

ii) Hydraulic Gradient = rise/run or slope of water surface = (vertical difference/horizontal distance)

a) Groundwater flow generally parallel to lines of gradient (i.e. perpendicular to contour lines in downgradient direction under force of gravity)

(3) Cone of depression- if water is pumped from a well faster than it can be replaced, the level of the water table will be drawn down in the shape of an inverted cone.

B. Aquifer Types

1. Definitions

a. Aquifer: porous rock/sediment units that have a capacity to contain water, pores can be formed by openings between grains (primary porosity) or by cracks and fractures in the rocks (secondary porosity)

(1) Common Aquifers: unconsolidated sand and gravel, sandstone, dissolved/fractured limestone, lava flows, fractured crystalline rocks.

b. Aquiclude: Impermeable layers which will not transmit or store groundwater, tend to form the upper or lower boundaries of aquifers

c. Aquitard = "leaky" aquiclude: low permeability layers which transmit groundwater at very slow rates in both vertical and/or horizontal directions.

(1) More permeable than aquiclude

2. Unconfined Aquifers: aquifers in vertical and hydraulic continuity with land surface.

a. Water Table Aquifers = Unconfined Aquifers

(1) Water of saturated zone in open contact with atmopheric pressures

(2) Water percolates through vadose zone to phreatic zone

(3) Capillary Zone: layer immediately above water table where water moves upward under high surface tension and capillary forces

3. Confined Aquifers: aquifers that are separated from atmospheric pressures by impermeable zones or confing layers (water not referred to as "water table")

a. Confined aquifer and artesian conditions, relative to hydrostatic pressure

(1) Potentiometric surface: analogous to water table, but is elevation of water of confined aquifer that rises to equilibrium in open well penetrating confined aquifer

(a) may contour elevations to form potentiometric contour map
i) confined aquifer groundwater flow generally perpendicular to contour of potentiometric surface.

(b) confined aquifers commonly under hydrostatic pressure in response to rock compaction and pore fluid pressures

b. Artesian Aquifer: identified as water in a well that rises under pressure above the saturated confined aquifer horizon

(1) Conditions of formation:
(a) confined aquifer between two impermeable layers
(b) exposure of aquifer to allow recharge/infiltration
(c) hydraulic flux into the aquifer from water cycle

c. Free-flowing artesian aquifer
(1) Artesian aquifer in which pressures are such that water freely flows out onto the ground surface.

d. Perched Aquifers: localized zone of upper level groundwater occurrence "perched" above a laterally discontinous aquitard.
(1) forms a localized occurrence of groundwater above regional water table system (hybrid of confined and unconfined systems)

C. Water Table and Potentiometric Surface Maps

1. From well water level records, contour maps of the water table (unconfined aquifer) or potentiometric surface (confined aquifer) can be constructed.

a. Data
(1) Elevations of surface measuring points at wells
(2) Depth to water from surface measuring point
(3) Surface El. - DTW = Water Elevation
(4) Plot elevations according to location on map
(5) Contour at appropriate contour interval

b. Resultant Information of Water Level Maps
(1) Geometric orientation of water table/pot. surface
(2) Hydraulic gradient perpendicular to contours
(3) Groundwater flow directions along hydraulic grad.
(4) "upgradient" and "downgradient" relationships

VI. Aquifer Characteristics

A. Transmissivity- measure of the amount of water that can be transmitted horizontally through an aquifer unit by the full saturated thickness of the aquifer under a hydraulic gradient of 1

$T = Kb$ T = Transmissivity, K = hydraulic Conductivity, b = saturated thickness of aquifer

Units T = L sq./T, b = L, K = L/T

B. Storativity = storage coefficient

1. Volume of water that a permeable unit will or absorb or expel from storage per unit surface area per unit change in head
    a. a dimensionless ratio

V_L = volume loss, S = storativity, A = surface area of aquifer drained (m^2), ΔH = Head Decline = drop in head or water level (m)

VII. Groundwater and Environmental Concerns

A. Resource Development
1. Groundwater use for urban and domestic needs prevalent throughout North America
    a. Residential use in rural areas off "plumbing grid" of public water supplies
    b. Residential and Industrial use in arid and semi-arid portions of U.S.
        (1) Groundwater useage very prevalent throughout the Mid-west and far-west.

B. Environmental Hazards
1. Groundwater Contamination
    a. Industrial/Government Facilities
    b. Sewage/bacteria
        (1) Mining
        (2) Landfills
2. Ground Subsidence and Subsurface Fluid Withdrawal
    a. Extensive withdrawal of subsurface fluids
        (1) groundwater
        (2) Petroleum
    b. Fluid withdrawal results in decrease in pore pressure, leading to subsidence of land areas under lithostatic pressure

VIII. Hydraulic Head

A. Definition of Hydraulic Head

1. Hydraulic head = total mechanical energy operating on a fluid mass per unit weight

    a. h = hydraulic head, measured in terms of length (*see below)

B. Piezometer- device used to measure the total energy of fluid flowing through a pipe packed with sand.

1. open conduit at top and bottom
2. water rises into conduit in direction proportion to total fluid energy
3. Constructed of small-diameter well which measures hydraulic head at a point in the aquifer

C. Derivation of Hydraulic Head from Bernoulli Equation

** $h = z + h_p$ (units of measurement in L) **

here h = total hydraulic head, z = elevation of a reference point in water column above datum, h_p = point water pressure head = height of water column above reference point.

D. Derivation of Vertical Hydraulic Gradient

1. grad h = $(h_2 - h_1)/(L_2 - L_1)$

where grad h = hydraulic gradient (dimensionless ratio), h_2 = total head at point 2, h_1 = total head at point 1, $(L_2 - L_1)$ = horizontal distance between point 1 and 2.

2. Ground Water Flow
   a. Always directed from high force potential to low force potential

      (1) largely controlled by total hydraulic head (measured in L units)

   b. Potentiometric Surface: contouring of force potential
      (1) Ground Water Contour Maps

IX. Darcy's Law

A. Remember Darcy's Law ...

$$Q = KIA$$

Where Q = discharge (L^3/T)
K = hydraulic conductivity (permeability) (L/T)
I = hydraulic gradient (vertical head distance between two points of observation) (decimal ratio)
A = cross-sectional area through which flow occurs (L^2)

** This base equation was originally designed to solve for one dimensional flow through a sand filled pipe... Equation must be modified to solve for ground water flow through a porous media in three dimensions **

B. Specific Discharge and Average Linear Velocity

1. Specific Discharge

a. Discharge Defined (water flow through open conduit)

$Q = vA$

Where Q = discharge (L^3/T), v = velocity (L/T), and A = area (L^2)

Rearrange equation to $v = Q/A$

From Darcy's Law $Q/A = -K(dh/dl)$

Via Substitution **** $v = -K(dh/dl)$ = Darcy's Flux

** where v = specific discharge = velocity ground water would move through an aquifer if it were an ideal open, pipe-like conduit (which it is not)

b. Aquifer Conduit

(1) Flow openings/conduits of an aquifer comprise a much smaller cross-sectional area than the dimensions of the aquifer itself.

(2) Effective conduit area for a porous media

$Ae = n_e A$

where Ae = effective area of porous media for flow, n_e = effective porosity of media, and A = total cross-sectional area of media.

2. Seepage Velocity or Average Linear Velocity

a. Modification of specific discharge (modifying Darcy's Law to account for effective pore-throat area)

**** $Vs = Q/(n_e A) = \frac{K\,dh}{n_e\,dl}$

where Vs = seepage velocity = average linear velocity of ground water molecule moving through actual pore throat openings of aquifer

X. Flow Lines and Flow Nets

A. Flow Line:

1. Imaginary line that traces the path that a particle of ground water would follow as it flows through an aquifer

a. Flow lines allow visualization of ground water movement

2. Isotropic, homogeneous aquifers
    a. Flow lines drawn perpendicular to equipotential lines
    b. Flow lines parallel to grad h

B. Flow Nets
    1. Network of equipotential lines and flow lines

C. Construction of Flow Nets (Simple Case Scenario)
    1. Base Assumptions
        a. Aquifer is homogeneous with respect to composition
        b. Aquifer is fully saturated with water (all pores filled)
        c. Aquifer is isotropic with respect to hydraulic properties
        d. The potential field (head conditions) is "steady state" over time
        e. The soil and water are incompressible
        f. Flow is laminar, Reynolds No. low, Darcy's Law is valid
        g. All boundary Conditions are known
        h. Water Table Boundary (Unconfined aquifers only)
            (1) boundary represents a line where head is known
            (2) Recharge/discharge conditions across boundary
                (a) Flow lines at oblique angle to boundary

            (3) No recharge/discharge across boundary
                (a) Flow lines parallel to boundary

Well Hydraulics

XI. Introduction
    A. The Well
        1. hydraulic structure utilized to access water-bearing aquifers

        2. Well is in direct hydraulic communication with aquifer conditions
            a. Allows estimation of aquifer hydraulic properties
            b. Provides direct access to ground water conditions
                (1) Sampling
                (2) Testing
                (3) Resource Extraction
                (4) Environmental Restoration

XII. Well Hydraulics

    A. Process: ground water flow to well from aquifer system
        1. Controls
            a. Hydraulic Properties of Aquifer
                (1) Hydraulic Conductivity, Permeability
                (2) Transmissivity
                (3) Storativity
                (4) Hydraulic Gradient

b. Design and construction of well assembly
  (1) Materials
  (2) Screen Depth
  (3) Hydrogeologic Conditions

2. Well response a function of aquifer properties
  a. Character of well directly related to aquifer properties
  b. Aquifer testing and characterization conducted utilizing the "well"
    (1) Mathematical derivation of well/aquifer response models

3. Complicating Factors To Aquifer Characterization
  a. Complex mathematical models that are not applicable to actual conditions
    (1) False (but necessary) base assumptions

  b. Complex geologic and hydrologic conditions
    (1) Multiple variable systems,
    (2) Spatial and temporal differential processes

      (a) Unsolvable with simplified mathematical models
      (b) Analytical solutions virtually unobtainable for some complex and variable hydrogeologic conditions

        i) Necessity: simplification and assumption

B. Definition of Terms

1. Static Water Level (SWL)

  a. Equilibrium level of water in well (confined or unconfined aquifer) when no water is being removed from the aquifer via pumping or free flow

  b. Common expression: depth to water from surface measuring point
    (1) Artesian well: depth of water level above surface

  c. SWL in well at equilibrium with aquifer is a reflection of the total hydraulic head of the water table (unconfined) or potentiometric surface (confined)

2. Pumping Water Level (PWL)

  a. Level at which water stands in a well when pumping/removal is in progress
  b. aka "dynamic water level"

3. Cone of depression- if water is pumped from a well faster than it can be replaced, the level of the water table will be drawn down in the shape of an inverted cone.

4. Drawdown = (SWL - PWL) = s

  a. Length difference between the SWL (water table or potentiometric) and the

PWL

b. Head difference (drawdown) represents the force potential of aquifer that causes water to flow from the aquifer to the well at the rate of pumping/extraction

(1) s < as force potential > (and vice versa)

c. Unconfined/Water Table

(1) head = actual water level on water table along the drawdown curve
(2) Saturated thickness of aquifer decreases

d. Confined/Potentiometric

(1) Drawdown represents the pressure head at that point, as a sum of the aquifer force potential and the pumping interaction of the well
(2) Saturated thickness of aquifer is not affected, on the potentiometric surface

5. Drawdown Curve
a. Shape of depressed potentiometric surface/water table in 3-D

6. Residual Drawdown (Recovery Curve)
a. After pumping ceases, water levels will recover in well as well equilibrates with natural aquifer conditions

b. Residual Drawdown = (SWL - Recovery Level)

7. Falling Head Conditions
a. Active pumping and drawdown in well

8. Rising Head Conditions
a. Recovery of well and aquifer following cessation of pumping

9. Well Yield
a. Volume of water per unit time discharged from a well by pumping or free flow

(1) Units of discharge: Gallons/Minute or m^3/day

10. Specific Capacity
a. S.C. = (Yield/Drawdown)
b. Units: GPM/Ft or cu. m/day/m

11. Pumping Well
a. Active pumping of well/extraction of ground water
b. Active drawdown measuring point

12. Observation Well
    a. Well that is nearby pumping well, but is no actively undergoing pump/removal
    b. Passive drawdown measuring point

13. Unsteady Radial Flow = "Transient Flow Conditions"
    a. Flow to pumping well is unsteady, the head of the drawdown curve changes with time

    b. Flow to well assumed to be radial, equal flow from all directions, isotropic/homogeneous aquifer conditions

14. Steady Radial Flow = "Steady State Flow Conditions"
    a. Flow to pumping well is steady, the head and cone of depression are at equilibrium between pumping rate and aquifer properties

    b. Flow to well assumed to be radial, equal flow from all directions, isotropic/homogeneous aquifer conditions

C. Nature of Converging Flow (on a well)
1. Well Flow and Drawdown
    a. Pump removes water from well
    b. Zone of low pressure develops near well bore
    c. Water flow from higher pressure aquifer to lower pressure well zone
    d. Force Potential = Head
        (1) Head difference outside well vs. inside well

    e. Zone of influence

        (1) Distance r away from well where pumping influence (drawdown) is negligible

        (2) controls on Zone of Influence
            (a) Pumping/Discharge Rate
            (b) Hydraulic Conductivity/Transmissivity of Aquifer
            (c) Storage Coefficient of Well

2. Unconfined vs. Confined Aquifers
    a. Unconfined Aquifers
        (1) Drawdown of water table and saturated zone of aquifer

    b. Confined Aquifers
        (1) Saturated zone of aquifer generally not affected
        (2) Potentiometric surface is lowered (reduced head)

3. Radial Converging Flow

a. Under isotropic, homogeneous aquifer conditions ...

(1) Ground water will flow radially towards the pumping well from all directions

b. Darcy's Law and Cone of Depression

(1) As grad h >, velocity of flow >

(2) Cone of depression: grad h > in close proximity to well

(a) r = radius of influence

i) horizontal distance from the center of a well to the limit of the cone of depression

c. Controls on Shape of Cone of Depression

(1) Pumping rate

(2) Pumping duration

(3) Hydraulic Gradient

(4) Recharge from aquifer to well

(5) Aquifer Properties (K, T, S)

(a) S - Coefficient of Storage

i) Volume of water released from storage or taken into storage, per unit of aquifer storage area, per unit change in head

ii) Range in S
Unconfined Aquifers: 0.01-0.3
Confined Aquifers: 10^{-5} to 10^{-3}

(b) T - Coefficient of Transmissivity

i) Rate of water flow through vertical strip of aquifer 1 ft wide, through the full saturated thickness of the aquifer, under a hydraulic gradient of 1

T = Kb

where K = horizontal hydraulic conductivity, b = saturated thickness

ii) Range in T

<1000 GPD/Ft = domestic wells, low-yield wells
>10,000 GPD/Ft = industrial/agricultural production wells

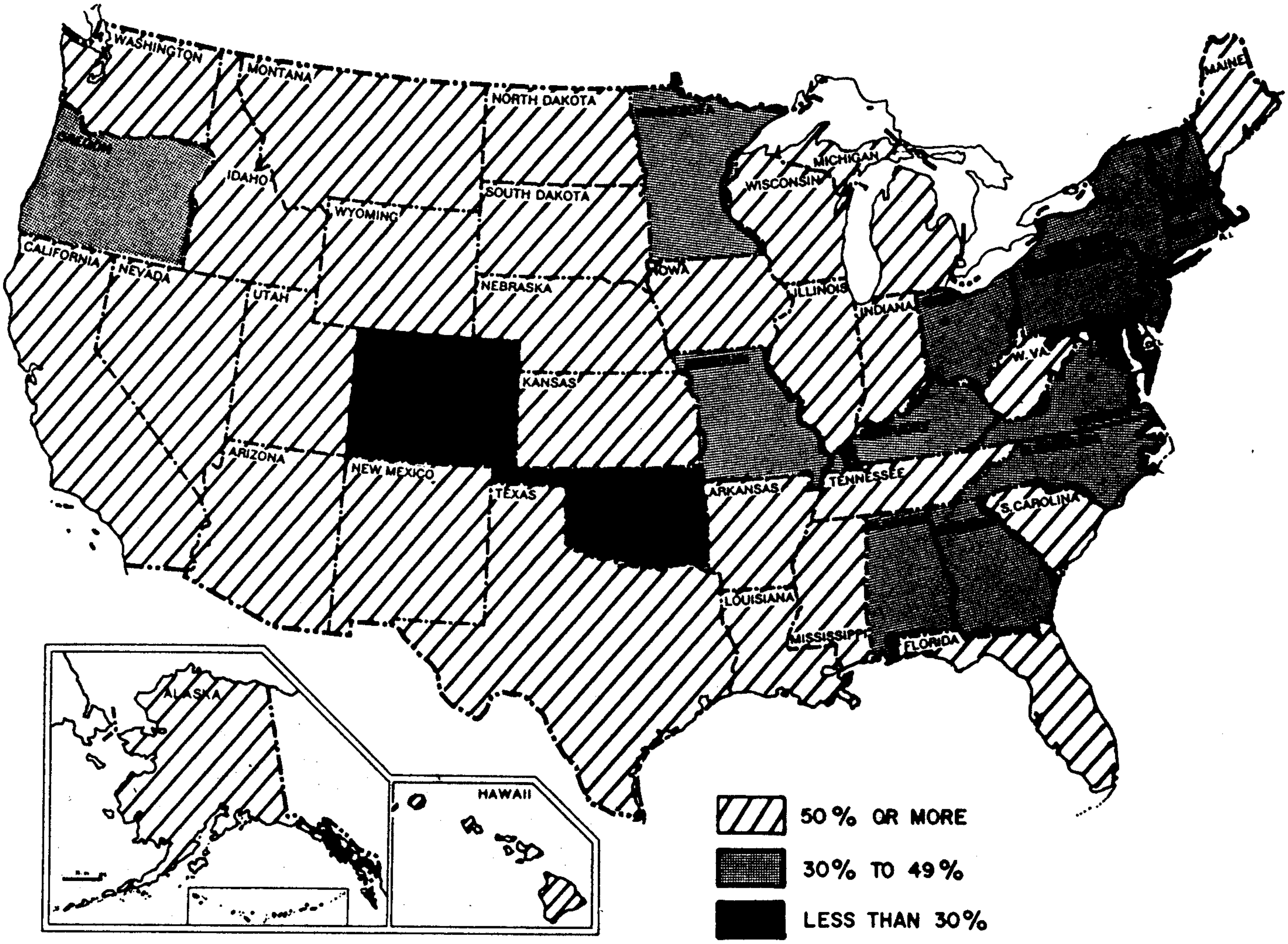
** T = how much water will move through the formation; S = how much water can be removed by pumping or draining of the aquifer

(6) Examples of Influence on Cone of Depression

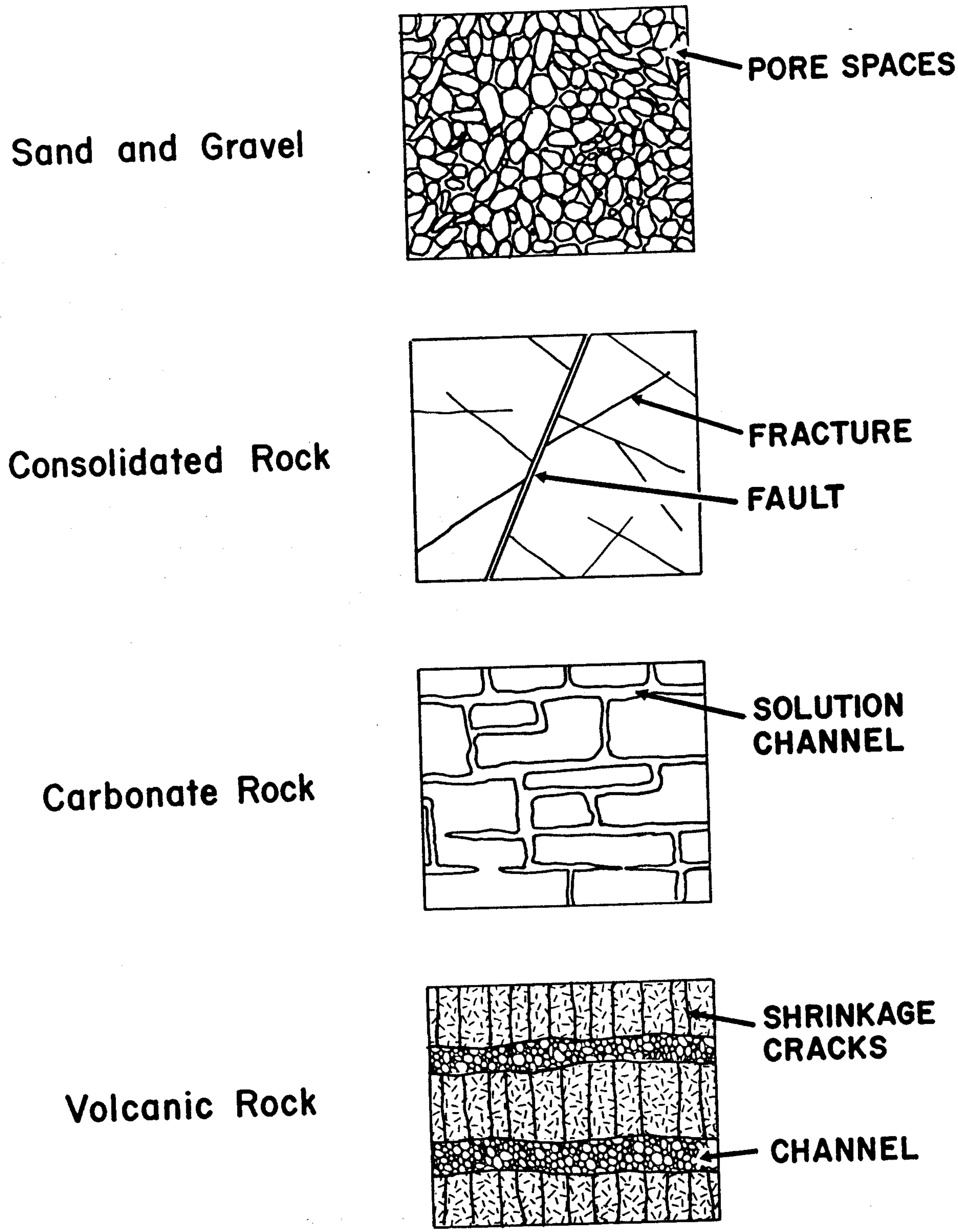
(a) High Transmissivity (High permeability)
- i) Flattened cone of depression
- ii) Drawdown at minimum

(b) Low Transmissivity (Low Permeability)
- i) Steepened cone of depression
- ii) Drawdown at a maximum at well

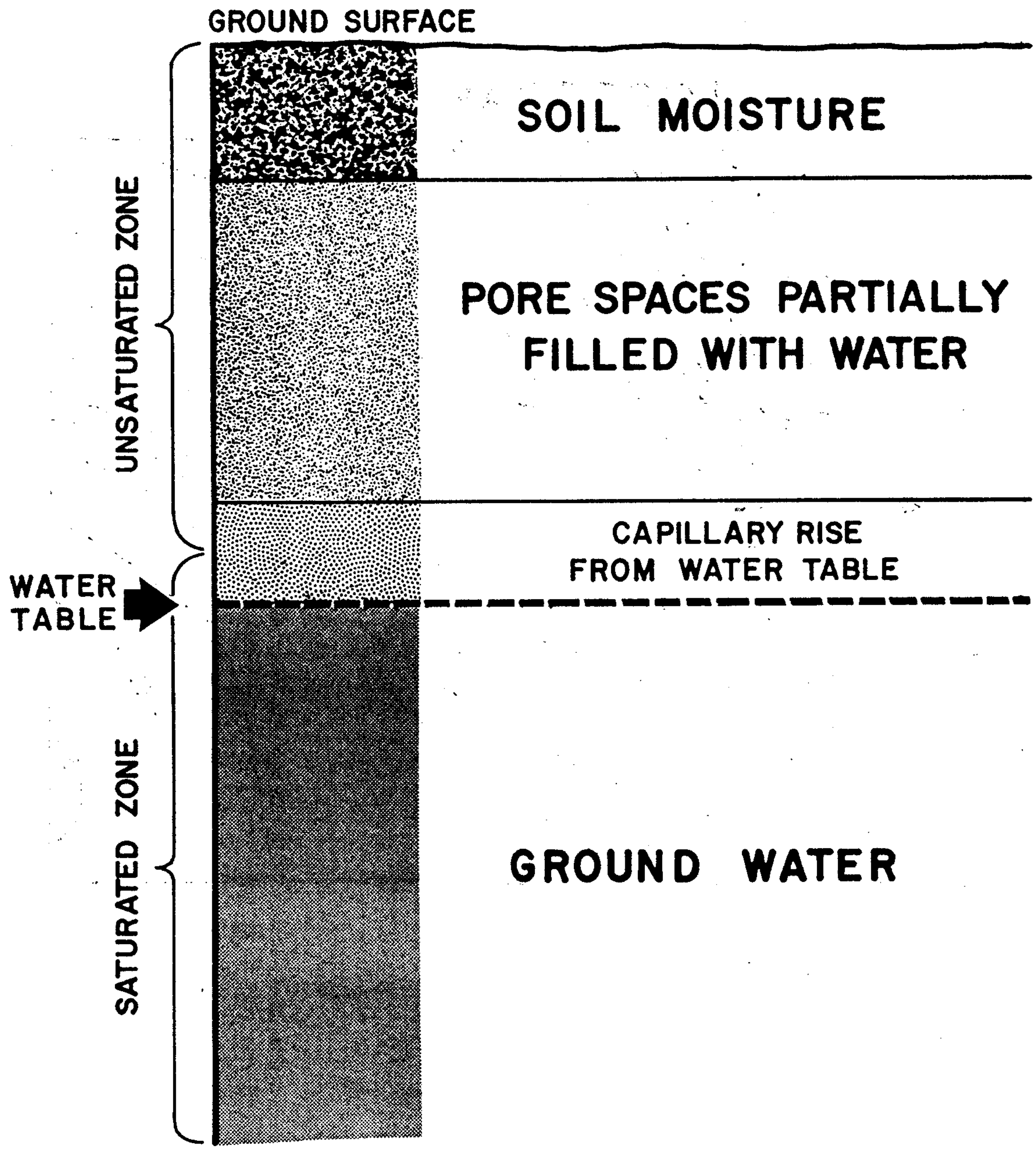
** moral of story: a steeper gradient is needed to move water at a given discharge through a less permeable aquifer relative to a more permeable aquifer (a la Darcy's Law)



Percentages of People Relying on Groundwater for Domestic Use



Rock texture in major aquifer types (Walton, 1970).



Relationship between unsaturated and saturated zones
(after Edward E. Johnson, Inc., 1966).

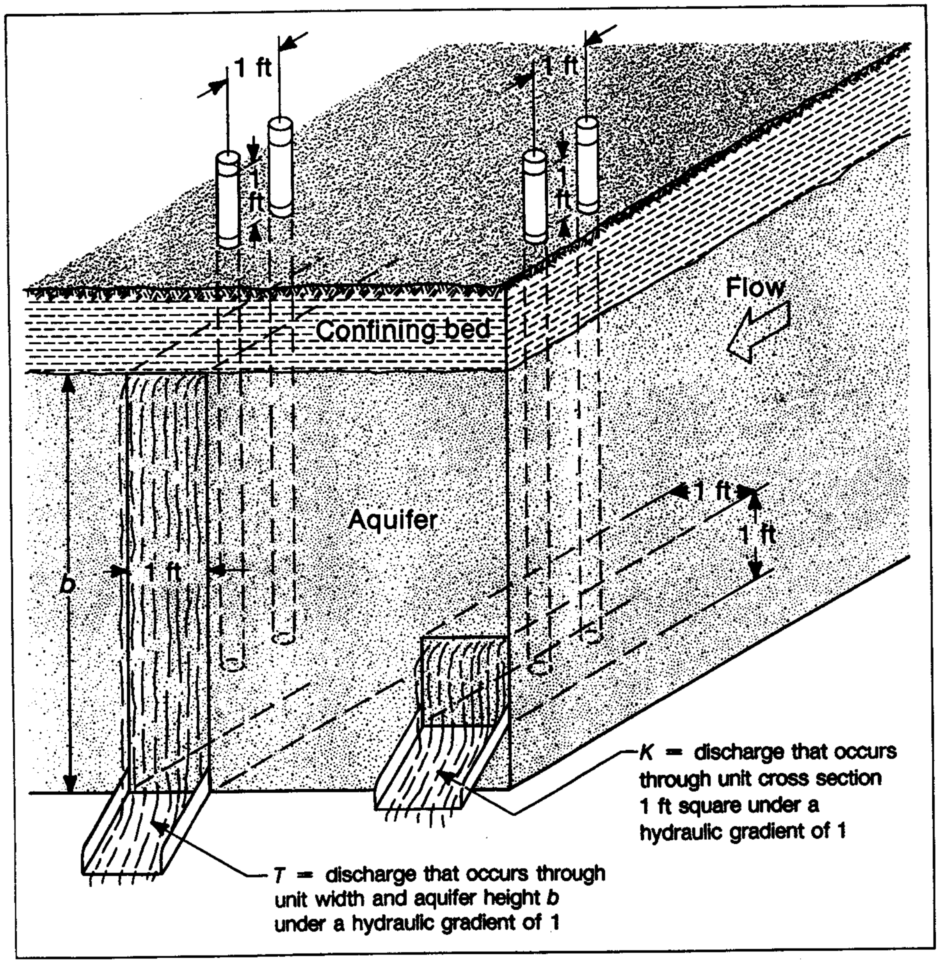


Figure 9.5. Illustration of the coefficients of hydraulic conductivity and transmissivity. Hydraulic conductivity multiplied by the aquifer thickness equals coefficient of transmissivity.

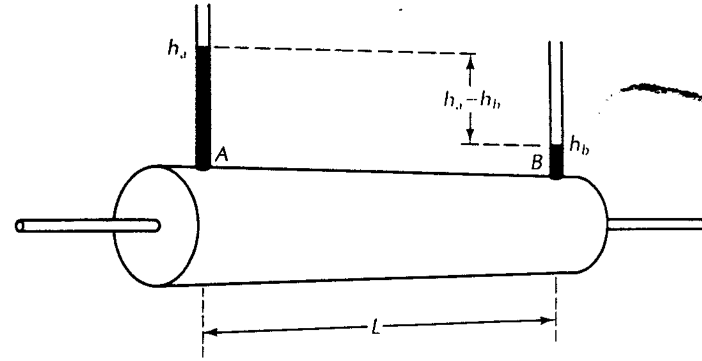


FIGURE 4.12 Horizontal pipe filled with sand to demonstrate Darcy's experiment. (Darcy's original equipment was actually vertically oriented.)

TABLE 4.5 Conversion values for hydraulic conductivity

1 gal/day/ft^2	= 0.0408 m/day
1 gal/day/ft^2	= 0.134 ft/day
1 gal/day/ft^2	= 4.72×10^{-5} cm/s
1 ft/day	= 0.305 m/day
1 ft/day	= 7.48 gal/day/ft^2
1 ft/day	= 3.53×10^{-4} cm/s
1 cm/s	= 864 m/day
1 cm/s	= 2835 ft/day
1 cm/s	= 21,200 gal/day/ft^2
1 m/day	= 24.5 gal/day/ft^2
1 m/day	= 3.28 ft/day
1 m/day	= 0.00116 cm/s

TABLE 4.6 Ranges of intrinsic permeabilities and hydraulic conductivities for unconsolidated sediments

Material	Intrinsic Permeability (darcys)	Hydraulic Conductivity (cm/s)
Clay	10^{-6}–10^{-3}	10^{-9}–10^{-6}
Silt, sandy silts, clayey sands, till	10^{-3}–10^{-1}	10^{-6}–10^{-4}
Silty sands, fine sands	10^{-2}–1	10^{-5}–10^{-3}
Well-sorted sands, glacial outwash	1–10^{2}	10^{-3}–10^{-1}
Well-sorted gravel	10–10^{3}	10^{-2}–1

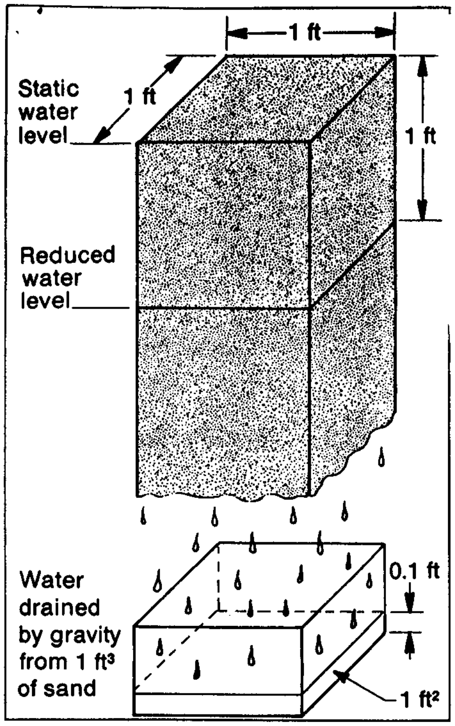


Figure 5.5. Specific yield of sand can be visualized from this diagram. Its value here is 0.1 ft³ per ft³ of aquifer material.

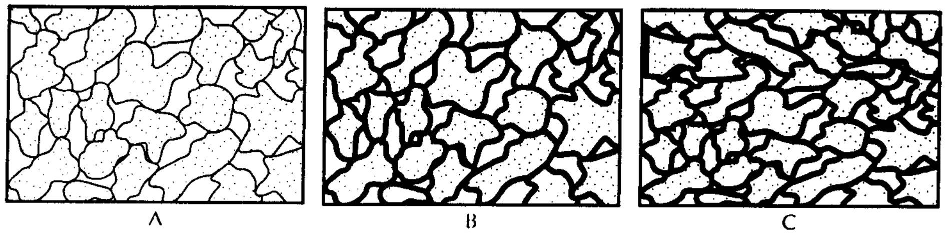
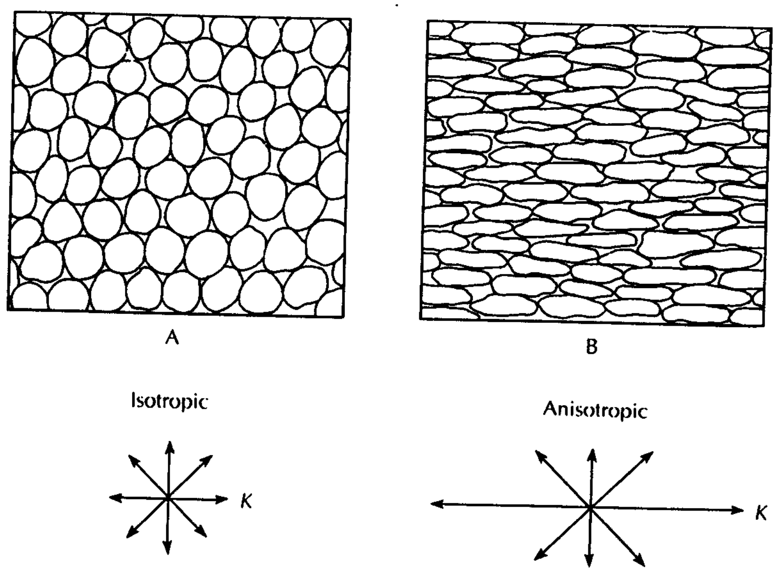


FIGURE 4.6 **A.** A clastic sediment with intergranular porosity. **B.** Reduction of porosity in the clastic sediment due to deposition of cementing material in the pore spaces. **C.** Further reduction in porosity due to compaction and cementation.

TABLE 4.3 Porosity ranges for sediments

Well-sorted sand or gravel	25–50%
Sand and gravel, mixed	20–35%
Glacial till	10–20%
Silt	35–50%
Clay	33–60%



AC

FIGURE 4.26 Grain shape and orientation can affect the isotropy or anisotropy of sediment.

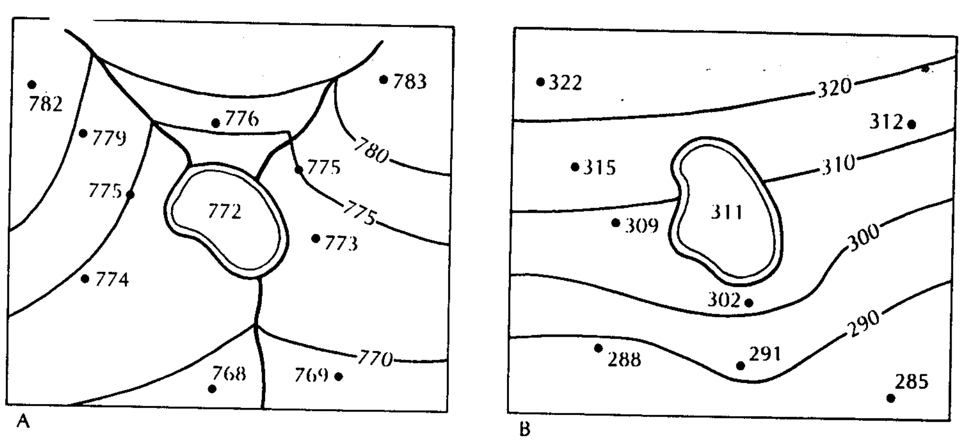


FIGURE 4.23 Maps showing construction of water-table maps in areas with surface-water bodies. **A.** A water-table lake with two gaining streams draining into it and one gaining stream draining from it. **B.** A perched lake that, through outseepage, is recharging the water table.

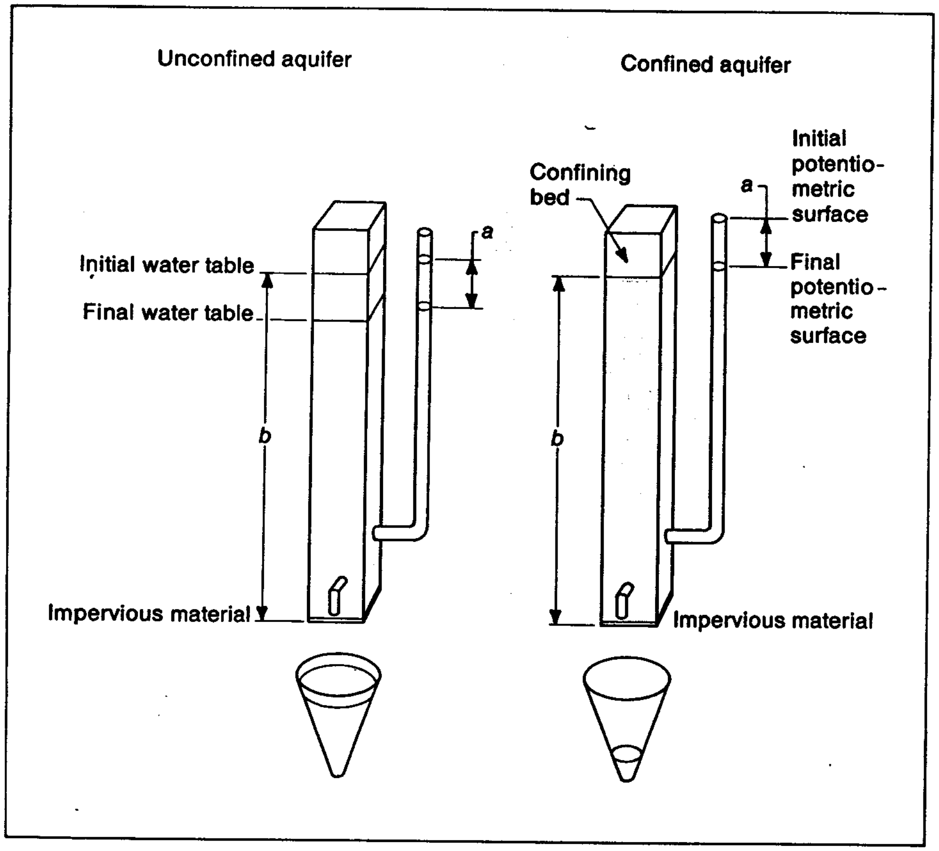


Figure 5.6. Unit prisms of unconfined and confined aquifers illustrating differences in storage coefficients. For equal declines in head, the yield from an unconfined aquifer is much greater than that from a confined aquifer. *(After Heath and Trainer, 1968)*

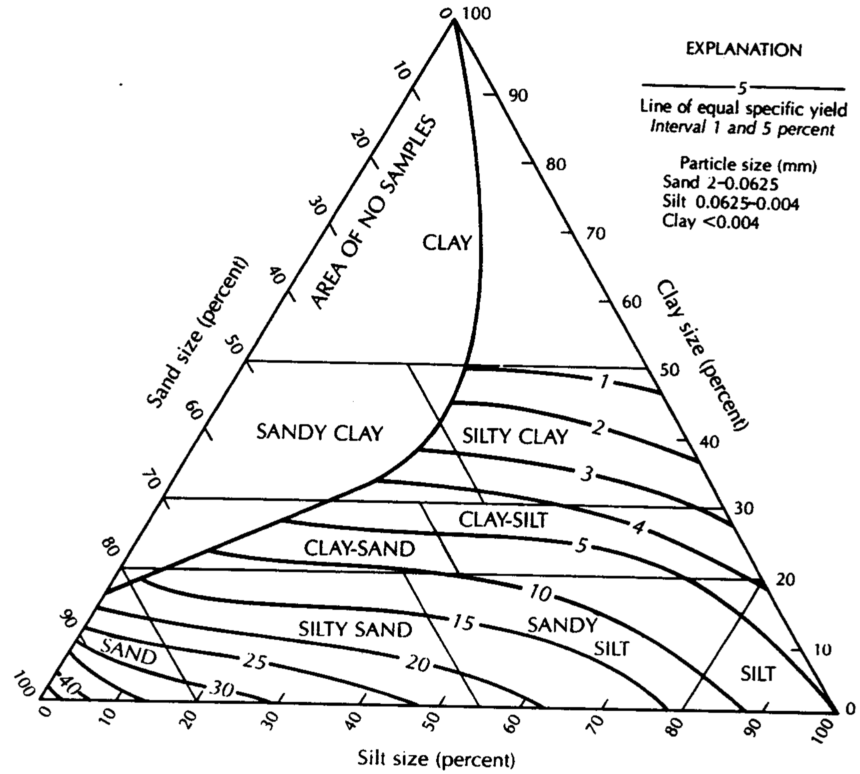


FIGURE 4.11 Textural classification triangle for unconsolidated materials showing the relation between particle size and specific yield. Source: A. I. Johnson, U.S. Geological Survey Water-Supply Paper 1662-D, 1967.

TABLE 4.4 Specific yields in percent

Material	Specific Yield Maximum	Minimum	Average
Clay	5	0	2
Sandy clay	12	3	7
Silt	19	3	18
Fine sand	28	10	21
Medium sand	32	15	26
Coarse sand	35	20	27
Gravelly sand	35	20	25
Fine gravel	35	21	25
Medium gravel	26	13	23
Coarse gravel	26	12	22

Source: Johnson (1967).

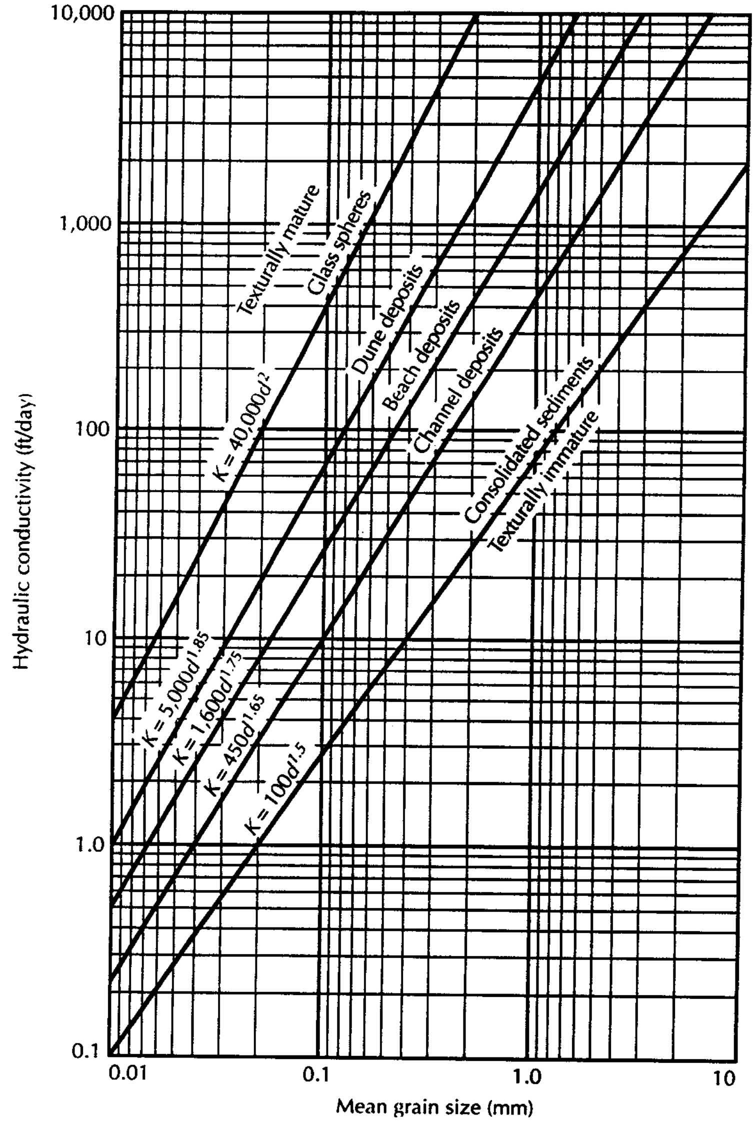


FIGURE 4.14 Graph showing the relationship of hydraulic conductivity to mean grain diameter for sediments of different textural maturity. Modified from R. G. Shepherd, *Ground Water* 27, no. 5 (1989): 633–638. Copyright © 1989 Ground Water Publishing Co.

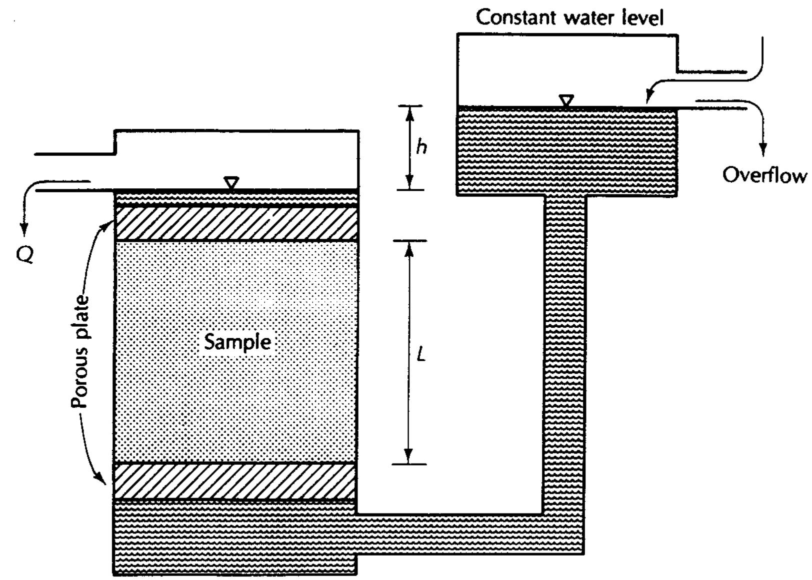


FIGURE 4.15 Constant-head permeameter apparatus.

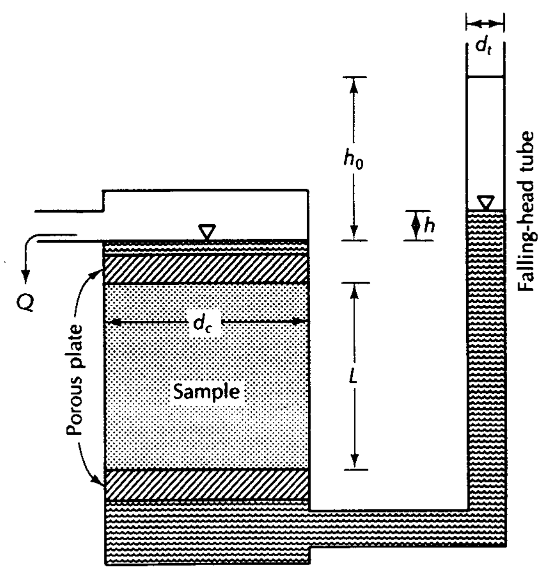


FIGURE 4.16 Falling-head permeameter apparatus.

Table 2.2 Range of Values of Hydraulic Conductivity and Permeability

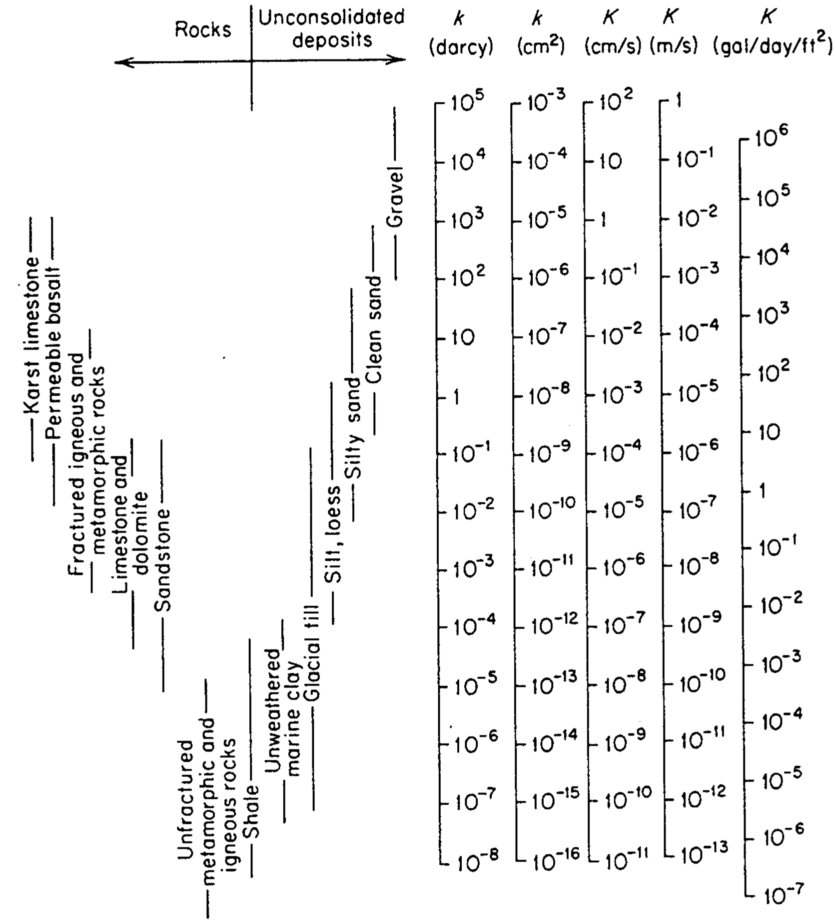
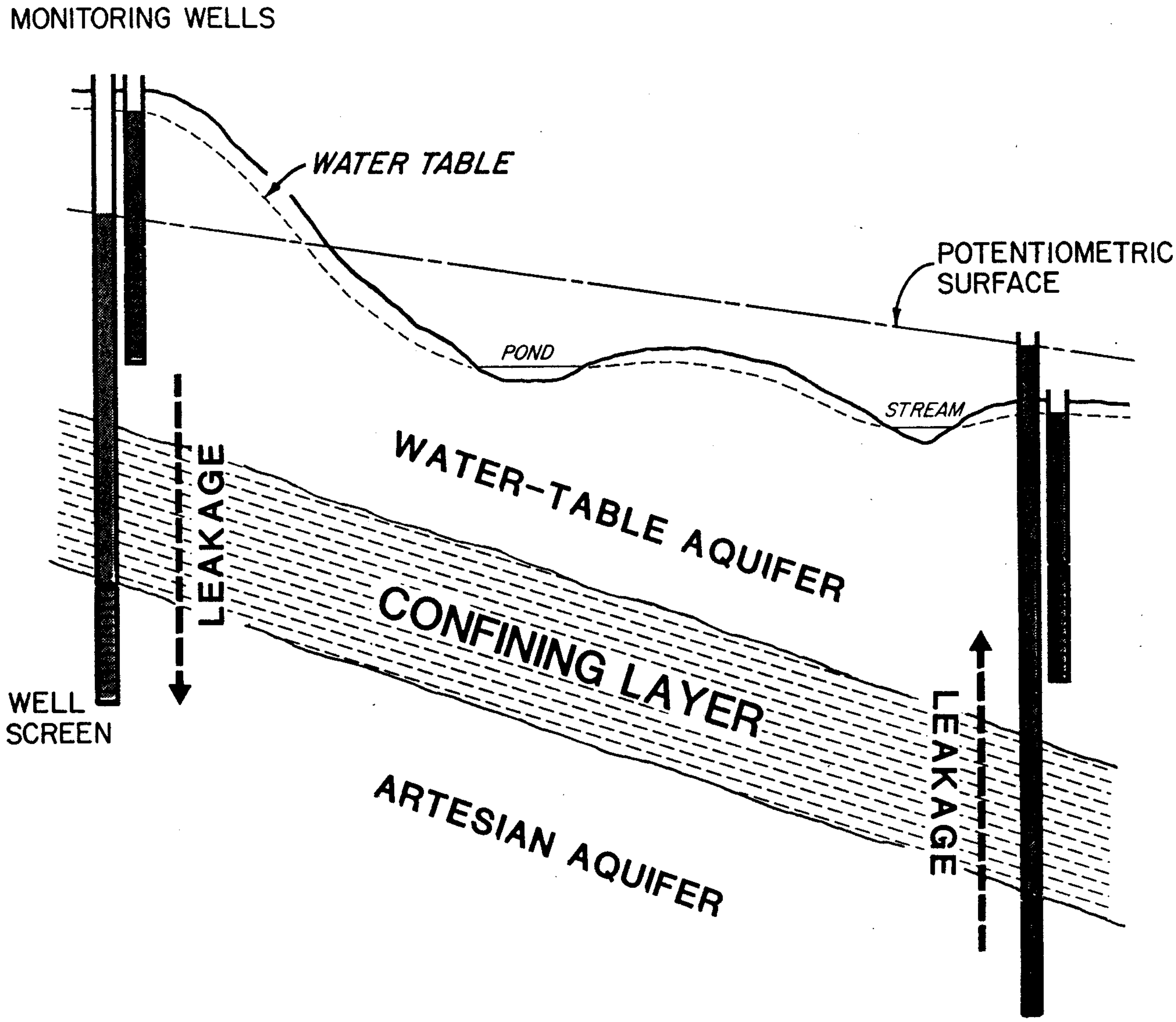


Table 2.3 Conversion Factors for Permeability and Hydraulic Conductivity Units

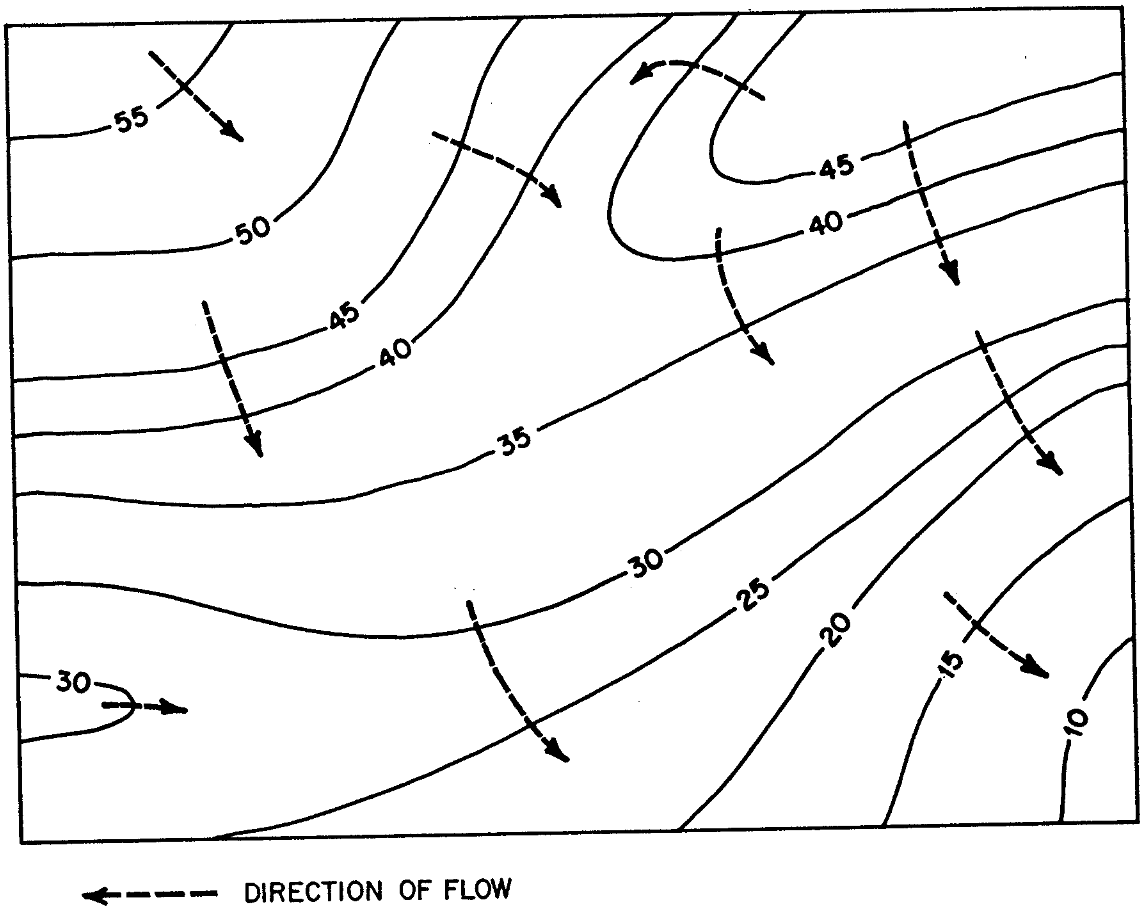
	Permeability, k*			Hydraulic conductivity, K		
	cm^2	ft^2	darcy	m/s	ft/s	U.S. gal/day/ft^2
cm^2	1	1.08×10^{-3}	1.01×10^{8}	9.80×10^{2}	3.22×10^{3}	1.85×10^{9}
ft^2	9.29×10^{2}	1	9.42×10^{10}	9.11×10^{5}	2.99×10^{6}	1.71×10^{12}
darcy	9.87×10^{-9}	1.06×10^{-11}	1	9.66×10^{-6}	3.17×10^{-5}	1.82×10^{1}
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

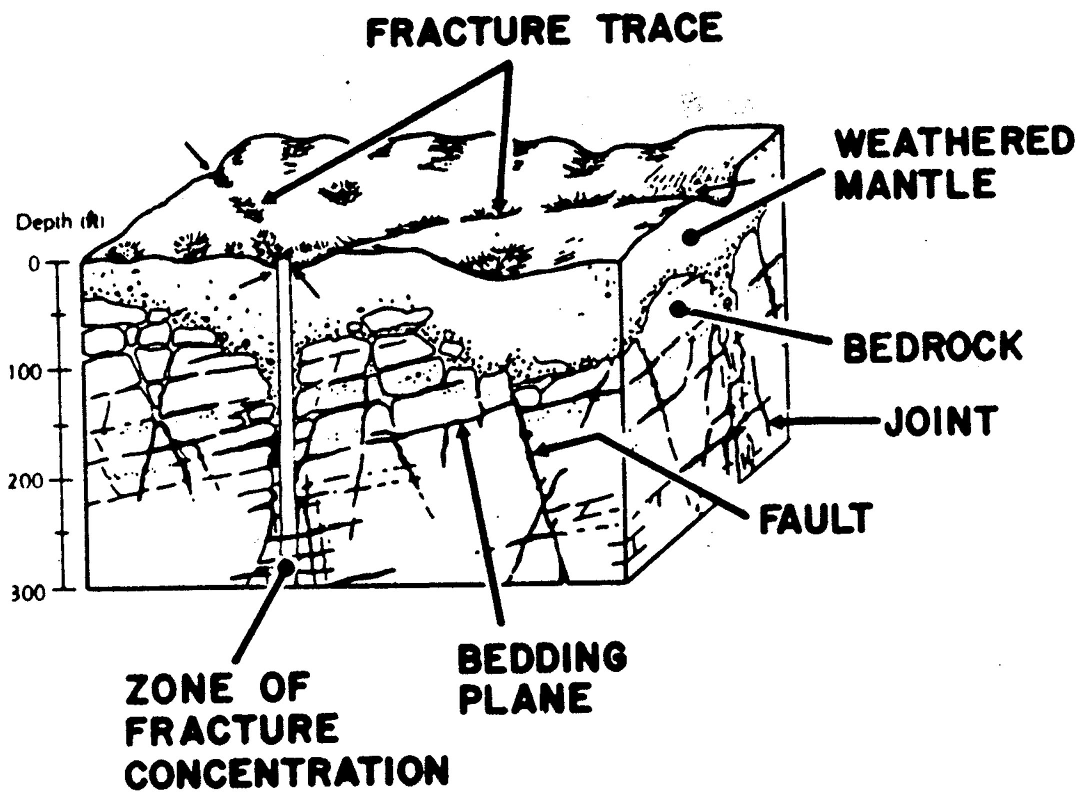
*To obtain k in ft^2, multiply k in cm^2 by 1.08×10^{-3}.



Relationships within the hydrologic system.

WATER TABLE





Principal flow paths in fractured rock (after Lattman and Parizek, 1964).

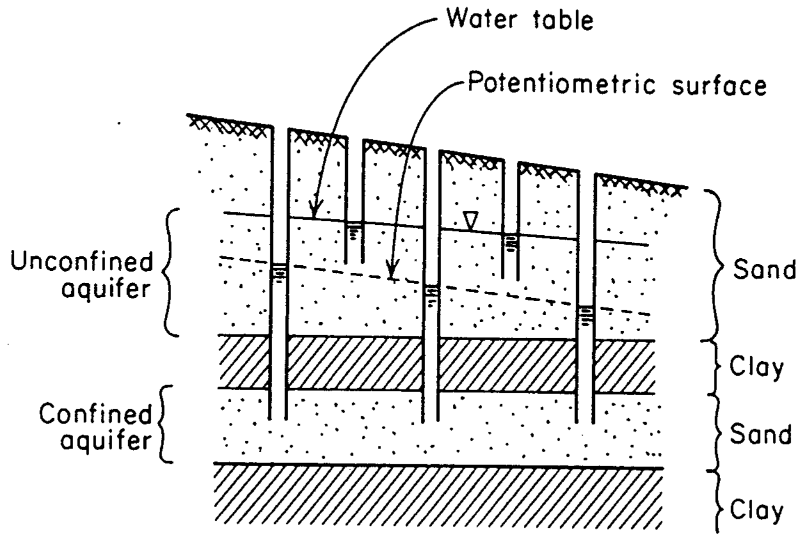


Figure 2.16 Unconfined aquifer and its water table; confined aquifer and its potentiometric surface.

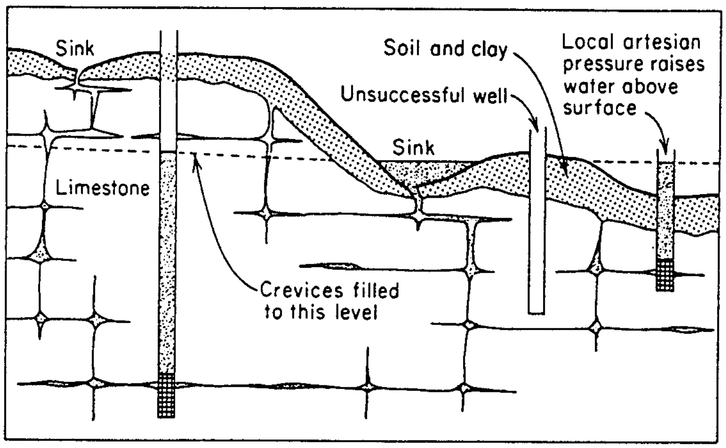


Figure 4.7 Schematic illustration of the occurrence of groundwater in carbonate rock in which secondary permeability occurs along enlarged fractures and bedding plane openings (after Walker, 1956; Davis and De Wiest, 1966).

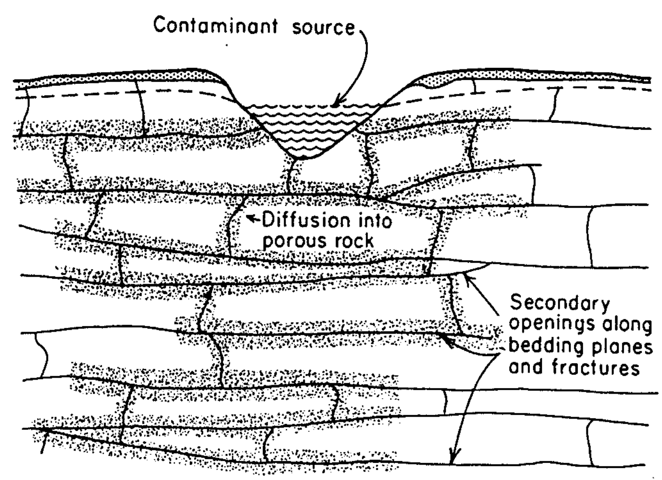
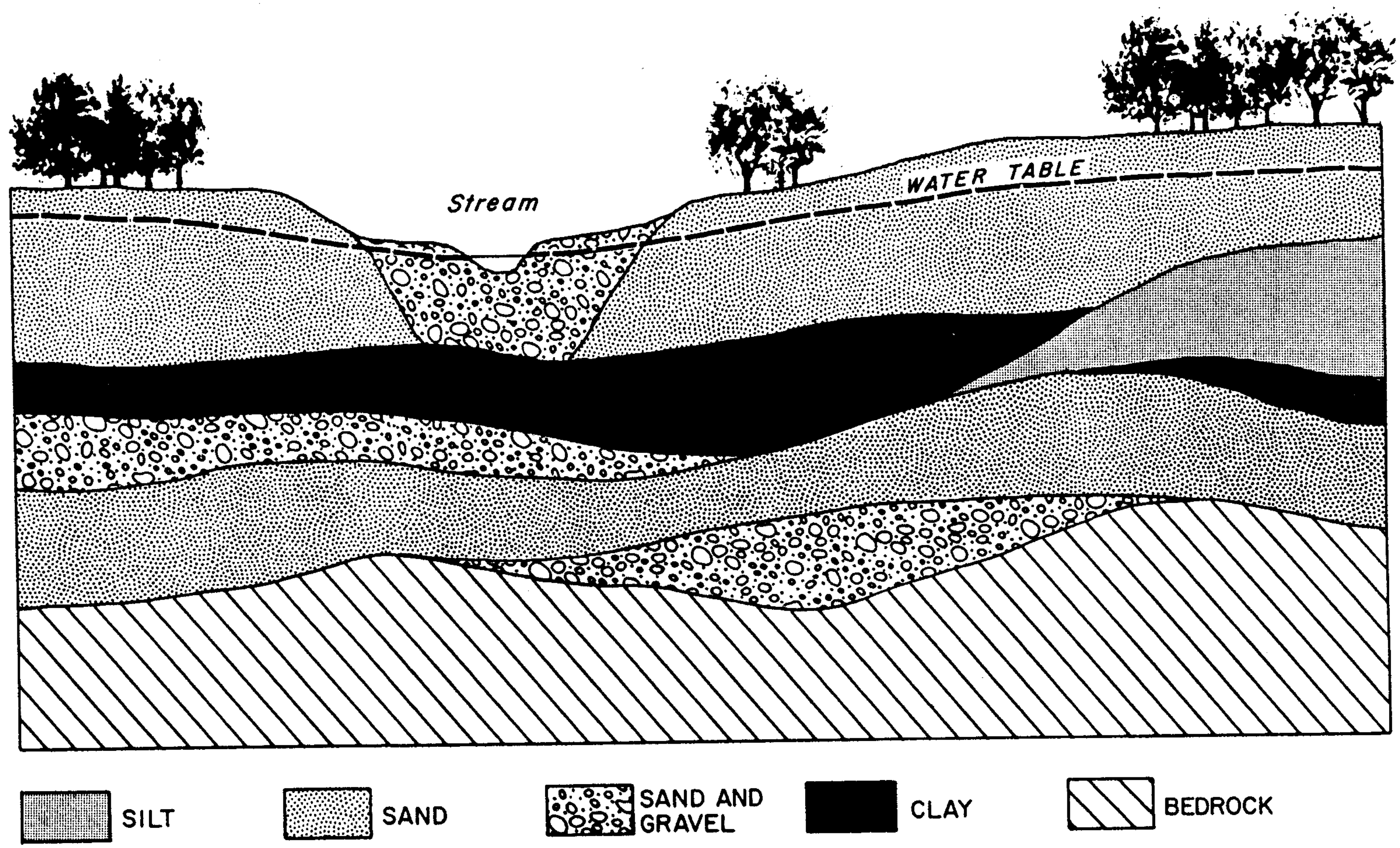


Figure 9.16 Schematic representation of contaminant migration from a surface source through fractured porous limestone.

15 m



Geologic Cross Section

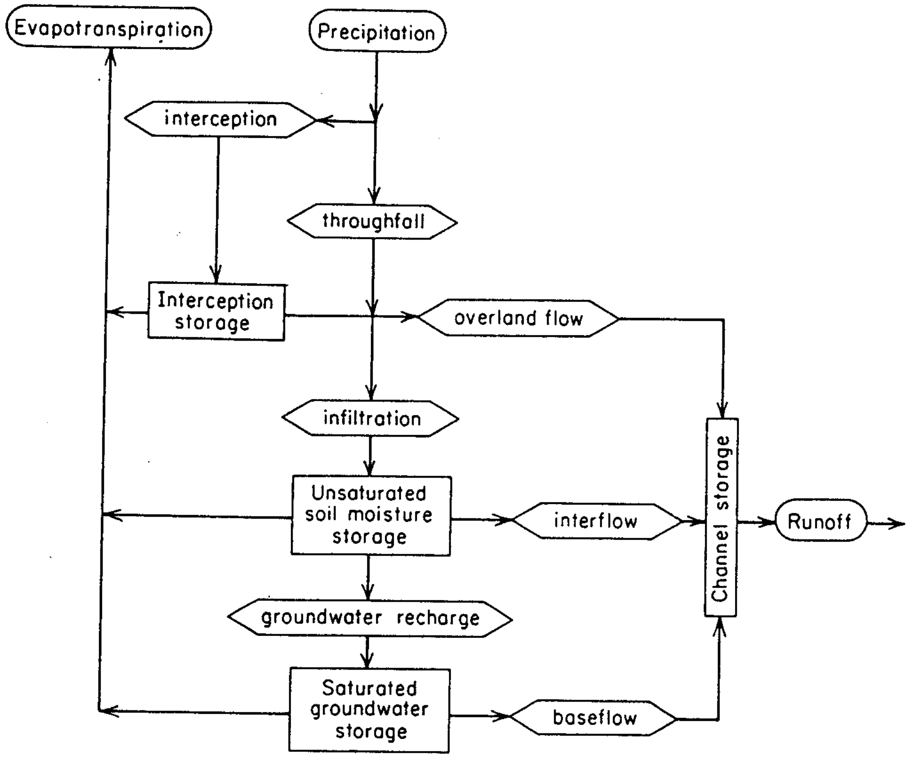


Figure 1.2 Systems representation of the hydrologic cycle.

Table 1.1 Estimate of the Water Balance of the World

Parameter	Surface area $(km^2) \times 10^6$	Volume $(km^3) \times 10^6$	Volume (%)	Equivalent depth (m)*	Residence time
Oceans and seas	361	1370	94	2500	~4000 years
Lakes and reservoirs	1.55	0.13	<0.01	0.25	~10 years
Swamps	<0.1	<0.01	<0.01	0.007	1–10 years
River channels	<0.1	<0.01	<0.01	0.003	~2 weeks
Soil moisture	130	0.07	<0.01	0.13	2 weeks–1 year
Groundwater	130	60	4	120	2 weeks–10,000 years
Icecaps and glaciers	17.8	30	2	60	10–1000 years
Atmospheric water	504	0.01	<0.01	0.025	~10 days
Biospheric water	<0.1	<0.01	<0.01	0.001	~1 week

SOURCE: Nace, 1971.

*Computed as though storage were uniformly distributed over the entire surface of the earth.

Table 1.2 Water Use in the United States, 1950–1970

	Cubic meters/day × 10^6*					Percent of 1970 use
	1950	1955	1960	1965	1970	
Total water withdrawals	758	910	1023	1175	1400	100
Use						
Public supplies	53	64	80	91	102	7
Rural supplies	14	14	14	15	17	1
Irrigation	420	420	420	455	495	35
Industrial	292	420	560	667	822	57
Source						
Groundwater	130	182	190	227	262	19
Surface water	644	750	838	960	1150	81

SOURCE: Murray, 1973.

*$1\ m^3 = 10^3\ \ell = 264$ U.S. gal.

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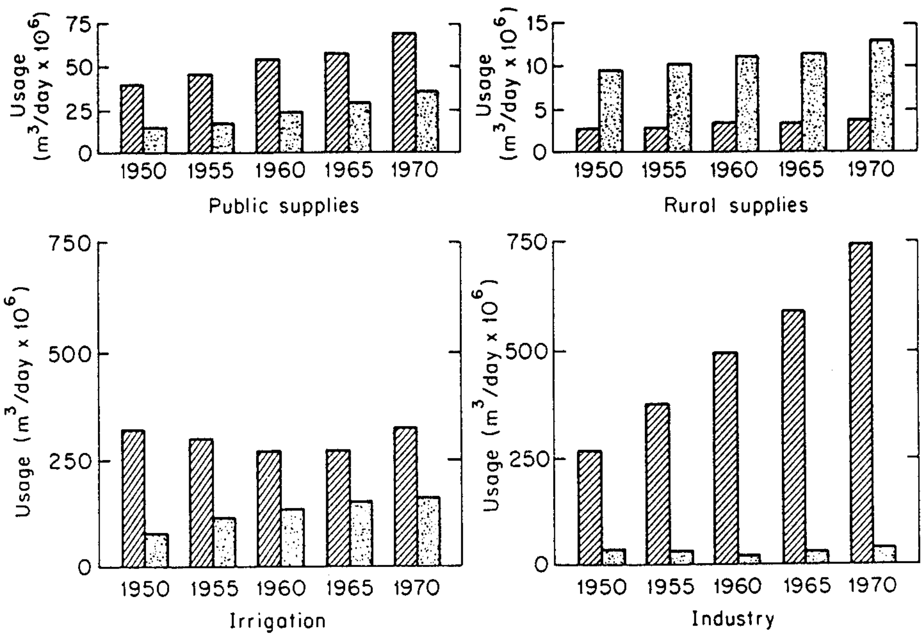


Figure 1.3 Surface water (hatched) and groundwater (stippled) use in the United States, 1950–1970 (after Murray, 1973).

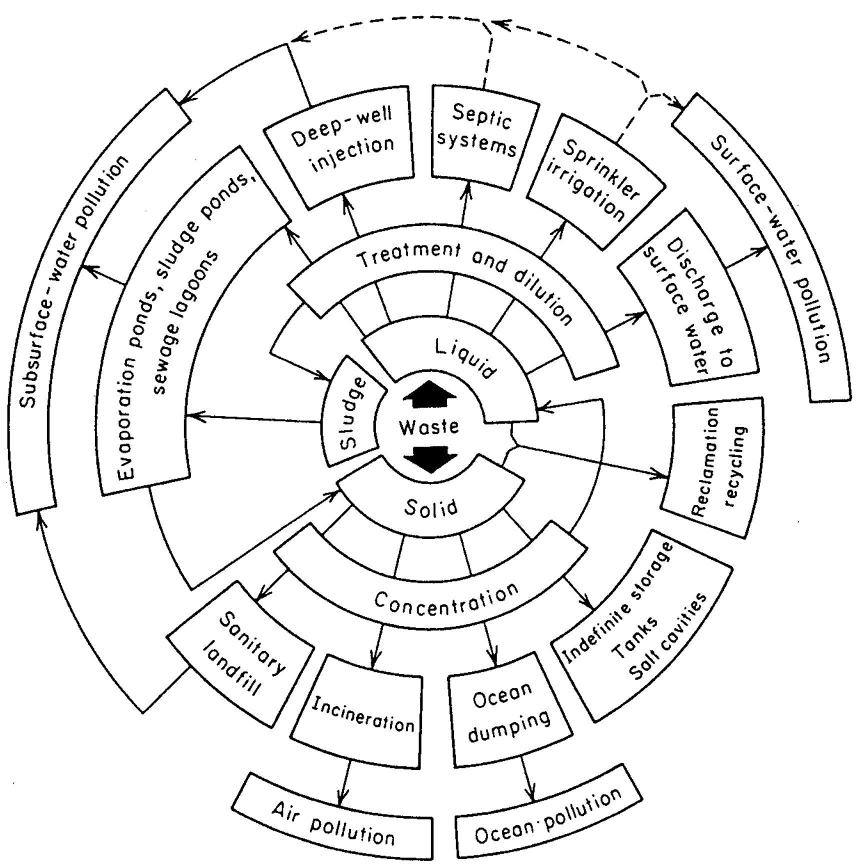
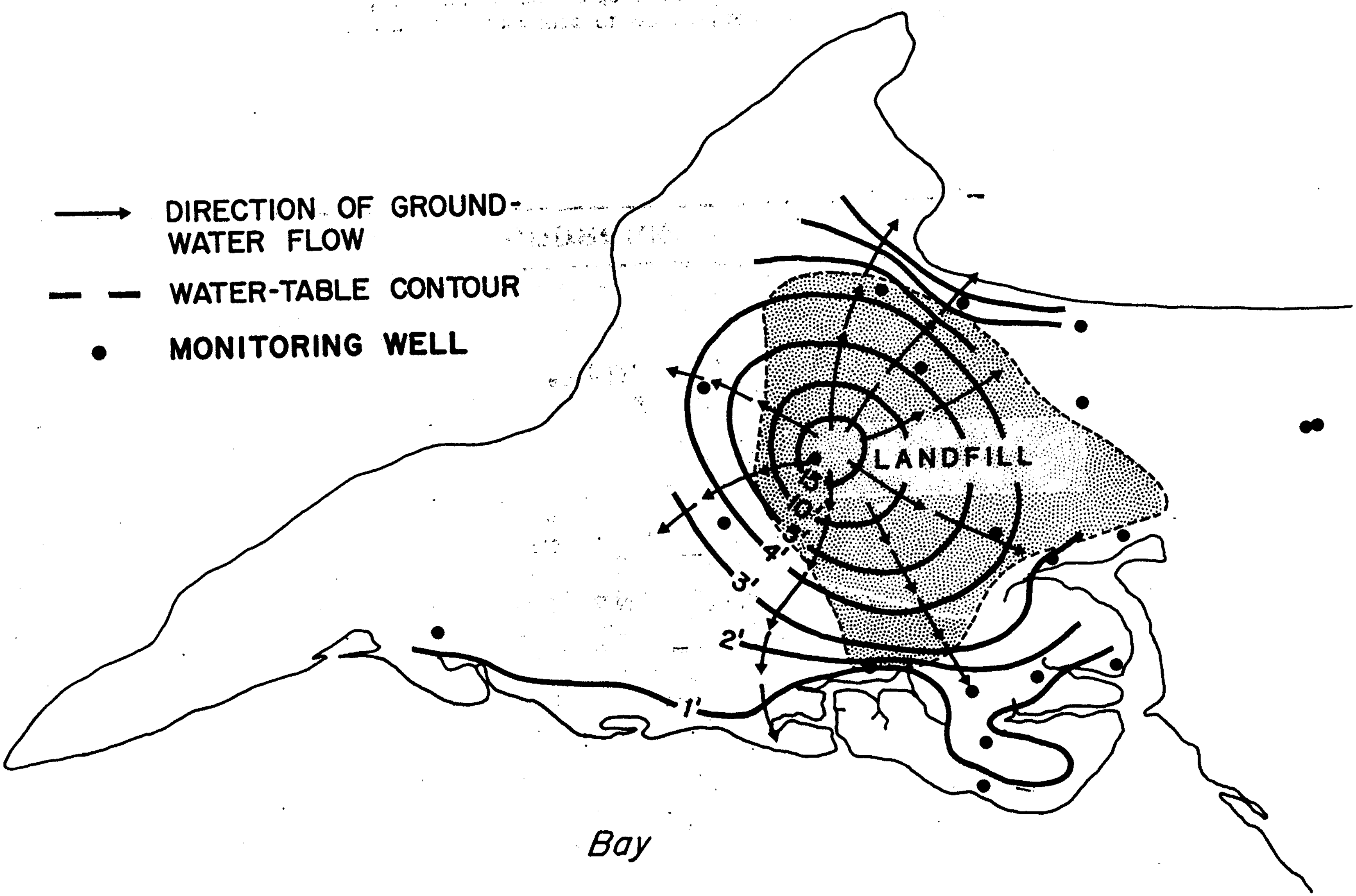
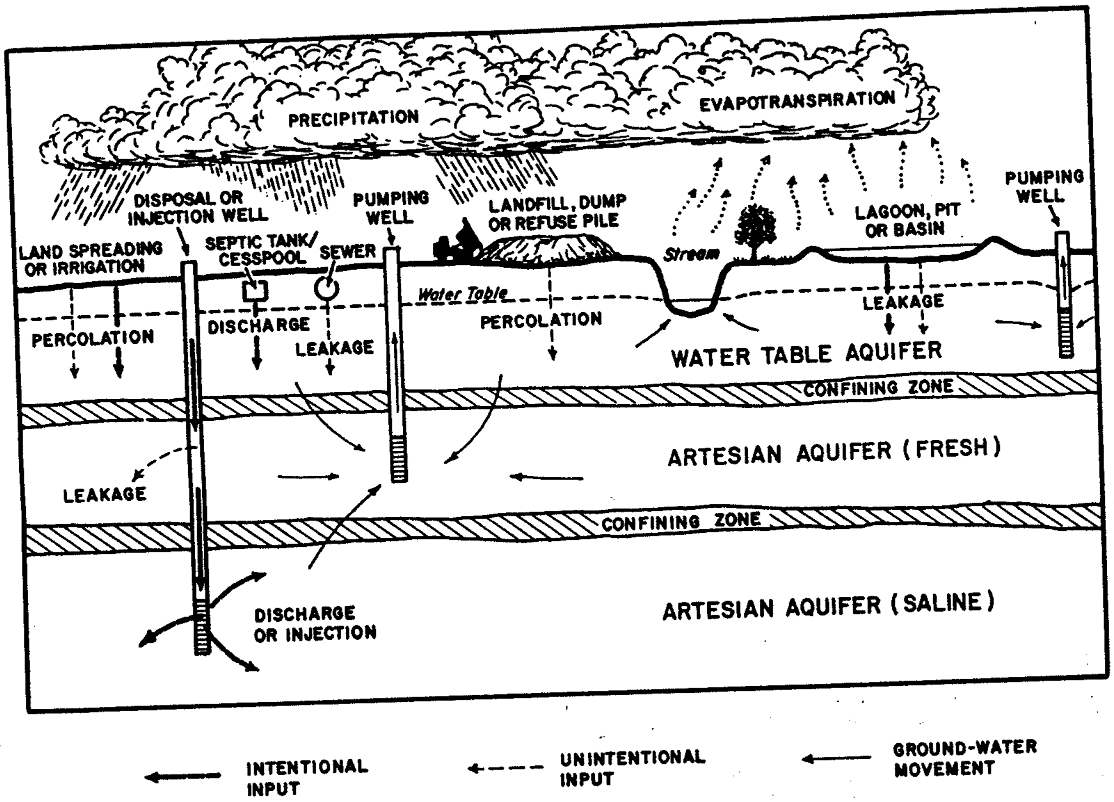


Figure 1.4 Spectrum of waste disposal alternatives.



Water-table configuration and directions of ground-water flow, Croton Point Landfill.



Sources of ground-water contamination.