

(2) Specific Retention

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

$$\text{** Porosity} = \text{S.Y.} + \text{S.R. **}$$

(3) Specific Retention > with < grain size

- i) Pendular Water- moisture that clings to soil particles because of surface tension.

A. Ranges of Specific Yield and Earth Materials

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

III. Hydraulic Conductivity of Earth Materials

1. Permeability: 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 transmission 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

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

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 permeability and porosity.

A. Hydraulic Conductivity

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

$$K = \frac{-Q}{A (I)}$$

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

2. Intrinsic Permeability (K_i)

- a. Modified K that considers the properties of the porous medium, shape of the pore openings

$$K_i = Cd^2 \quad \text{where } C = \text{shape constant, } d = \text{diameter of grains}$$

standard units in civil engineering = sq^2
 standard units in petroleum eng. = darcy

$$1 \text{ darcy} = 9.87 \times 10^{-9} \text{ cm}^2$$

3. Relationship of K to K_i

- a. Hydraulic conductivity then is a function of both pore throat geometry and physical nature of the fluid

$$K = K_i(\rho g / \mu) \text{ where}$$

K = hydraulic conductivity, K_i = intrinsic permeability, ρ = density of fluid, g = acceleration due to gravity, and μ = viscosity of the fluid.

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:

$$K = VL / (Ath)$$

where K = hydraulic conductivity, L = length of sample, A = cross-sectional area of sample, h = hydraulic head

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

IV. 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.
 - b. Much water flows downward through this zone into the underlying layer.
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

- d. Aquifuge: effectively impermeable body of rock or unconsolidated material
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 atmospheric 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 confining 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 discontinuous 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

V. 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

$$T = Kb \quad T = \text{Transmissivity, } K = \text{hydraulic Conductivity,} \\ b = \text{saturated thickness of aquifer}$$

Units $T = L \text{ sq./T}$, $b = L$, $K = L/T$

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

C. Specific Storage = amount of water per unit volume of a saturated formation that is stored or expelled from storage owing to compressibility of the mineral skeleton and the pore water per unit change in head.

** S.S. applied to both confined and unconfined aquifers**

** see equation sheet for details ***

$$S.S. = pg(\alpha + n\beta)$$

S.S. = specific storage

p = density of water

g = acceleration due to gravity (9.8 m/sec^2)

α = compressibility of aquifer skeleton

n = porosity (decimal fraction)

β = beta = compressibility of the water ($4.6 \times 10^{-10} \text{ sq. m/N}$)

D. Relationship of storativity to specific storage

1. Confined Aquifer

$$S = b(S.S.) \quad (\text{units L/L} = \text{dimensionless})$$

where S = storativity, b = aquifer thickness, $S.S.$ = specific storage

2. Unconfined Aquifer

$$S = S.Y. + h(S.S.)$$

where S = storativity, $S.Y.$ = specific yield, h = thickness of saturated zone, $S.S.$ = specific storage

** Since $S.Y.$ is several orders of magnitude $> h(S.S.)$ then for all practical purposes: $S = S.Y.$ in unconfined aquifers**

3. Determination of the volume of water drained from an aquifer as head is lowered:

$$V = SA \text{ (Head Decline)}$$

V = volume loss, S = storativity, A = surface area of aquifer drained, Head Decline = drop in head or water level

VI. Homogeneity and Heterogeneity of the Aquifer

A. Homogeneous Hydraulic Unit

1. A homogeneous porous medium with uniform hydraulic properties in 3-dimensions (X,Y,Z)
 - a. T, S, K of similar value vertically and horizontally in all directions
 - b. e.g. uniform, porous sandstone of constant thickness

B. Heterogeneous Hydraulic Unit

1. A heterogeneous porous medium with non-uniform hydraulic properties (vary according to X,Y,Z directions)
2. T, S, K vary vertically and horizontally according to direction
 - a. e.g. fractured granite (can be quite complicated)

C. Directional Permeability Control

1. Isotropic Medium: intrinsic permeability same in all directions (3-D)
 - (1) $K_v = K_h$
2. Anisotropic Medium: intrinsic permeability varies according to preferred orientations
 - (1) K_v not equal to K_h

- 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

PROPERTIES OF Aquifers BASIC EQUATIONS

I DIMENSION / UNITS

"L" = LENGTH UNITS (cm, mm, m etc)

"M" = MASS UNITS (gm, Kg)

"T" = TIME UNITS (SEC, MIN, DAYS)

II MATTER & ENERGY (BASIC PHYSICS)

1. $W = FD$

WORK = (FORCE) (DISTANCE)

$$\left(\frac{ML^2}{T^2}\right) = \left(\frac{ML}{T^2}\right) (L)$$

2. $F = ma$

F = FORCE (ML/T^2)

m = MASS (M)

a = acceleration (L/T^2)

3. $w = mg$

w = weight (ML/T^2)

g = acceleration due to gravity (M/T^2)

m = mass (M)

4. $\rho = m/V$

ρ = DENSITY (M/L^3)

m = mass (M)

V = VOLUME (L^3)

5. $\gamma = w/V$

γ = SPECIFIC WEIGHT (M/L^2T^2)

w = weight (ML/T^2)

V = VOLUME (L^3)

6. By SUBSTITUTION $w = mg$ & $m = \rho V$

$$\gamma = \frac{w}{V} = \frac{mg}{V} = \frac{\rho V g}{V} = \rho g \longrightarrow \boxed{\gamma = \rho g}$$

II. MATTER & ENERGY (CONT.)

7.
$$P = \frac{F}{A}$$

P = PRESSURE (M/LT²)

F = FORCE (ML/T²)

A = X-sectional area (L²)

III Porosity of EARTH MATERIALS

1.
$$n = \frac{100 V_v}{V_T}$$

n = porosity (%)

V_v = VOLUME OF VOID SPACE (L³)

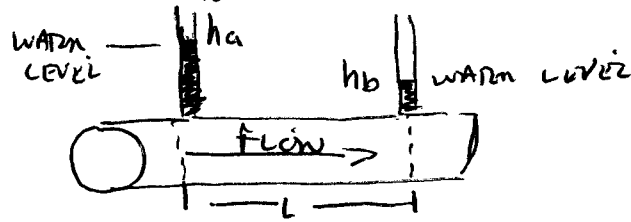
V_T = VOLUME TOTAL (L³)
(VOID + MATERIAL)

2. Specific Yield =
$$\frac{S_y}{S_y} = \frac{\text{VOL. H}_2\text{O GRAVITY DRAINED}}{\text{TOTAL VOLUME ROCK}}$$

2. Specific Retention =
$$\frac{S_r}{S_r} = \frac{\text{VOL. H}_2\text{O RETAINED UNDER CURVING}}{\text{TOTAL VOLUME ROCK}}$$

4.
$$n = S_y + S_r$$

⑤ DARCY'S LAW: CONSIDER A SAND-FILLED CONDUIT (LIKE AN AQUIFER)



h_a = head pressure at pt. A
 h_b = head pressure at pt. B

$$Q = -KA \left(\frac{h_A - h_B}{L} \right) = -KA \left(\frac{dh}{dL} \right)$$

Q = Discharge (L^3/T)

L = flow length (L) = dL

A = x-sectional area \perp to flow

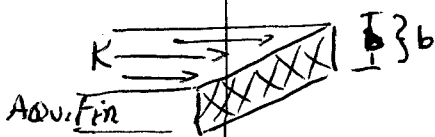
dh = head difference between a & b

K = hydraulic conductivity = coefficient of permeability

$$⑥ \quad K = \frac{-Q}{A(dh/dL)} = \frac{-(L^3/T)}{(L^2)(L/L)} = \frac{L}{T}$$

THUS K ESSENTIALLY EQUALS THE "HORIZONTAL" PERMEABILITY OF AN AQUIFER

⑦ TRANSMISSIVITY: ~~volume~~ ^{Amount} of water TRANSMITTED horizontally THROUGH THE UNIT WIDTH OF THE AQUIFER.



$$T = Kb$$

T = TRANSMISSIVITY (L^2/T)
 b = SATURATED THICKNESS (L)
 K = hydraulic conductivity (L/T)

STORATIVITY

IN RESPONSE TO HEAD CHANGE IN AN AQUIFER, WATER WILL EITHER: 1) BE EXPELLED OR STORED

STORATIVITY - VOL. OF H₂O ABSORBED OR EXPELLED FROM STORAGE PER UNIT SURFACE AREA PER UNIT HEAD CHANGE

$$\left(\frac{L^3/L^2}{L} = \frac{L^3}{L^2} \cdot \frac{1}{L} = \frac{L^3}{L^3} = \text{DIMENSIONLESS RATIO} \right)$$

(FOR CONFINED AQUIFER)

$$(8) S_s = \rho_w \cdot g \cdot (\alpha + nB)$$

S_s = Specific Storage

ρ_w = Density of Water (M/L^3)

g = acceleration due to gravity (L/T^2)

α = compressibility of Aquifer Skeleton ($1/M/LT^2$)

n = porosity (L^3/L^3)

B = compressibility of water ($1/M/LT^2$)

(FOR UNCONFINED AQUIFER) (GRAVITY DRAINAGE)

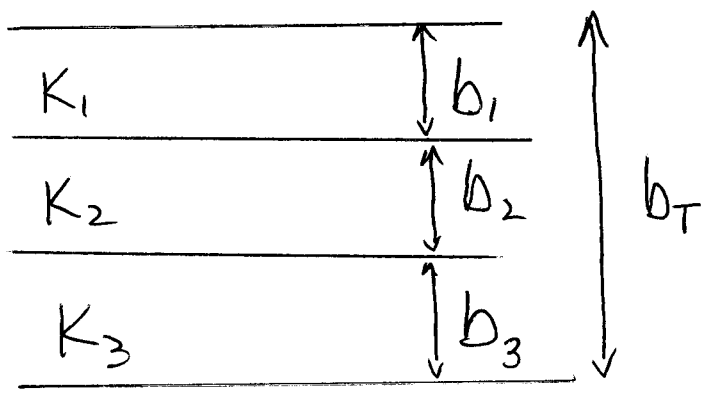
$$(9) S = S_y$$

S = storativity

S_y = Specific Yield

(SEE EQUATION III-2)

HYDRAULIC CONDUCTIVITY & MULTILAYER AQUIFERS



K_n = Hydraulic Conductivity of Layer 1, 2, 3
 b_n = Thickness of layer 1, 2, 3
 b_T = Total Aquifer Thickness

AVERAGE HORIZONTAL HYDRAULIC CONDUCTIVITY

$$K_{h(avg)} = \sum_{m=1}^n \frac{K_m b_m}{b_T} = \frac{K_1 b_1 + K_2 b_2 + K_3 b_3}{b_T}$$

AVERAGE VERTICAL HYDRAULIC CONDUCTIVITY

$$K_{v(avg)} = \frac{b_T}{\sum_{m=1}^n \frac{b_m}{K_{vm}}} = \frac{b_T}{\frac{b_1}{K_1} + \frac{b_2}{K_2} + \frac{b_3}{K_3}}$$

GRADIENT OF POTENTIOMETRIC SURFACE (GRADIENT DERIVED FROM GROUNDWATER ELEVATIONS)

$$GRAD = \frac{dh}{dx}$$

GRADIENT = Slope of potentiometric surface
 dh = change in elevation between 2 pts.
 dx = distance between 2 pts.

INTRINSIC PERMEABILITY

$$K_i = C d^2$$

K_i = intrinsic permeability (L^2)

C = dimensionless constant

d^2 = mean pore diameter

$$K = K_i \left(\frac{\rho g}{\mu} \right)$$

K = hydraulic conductivity (L/T)

ρ = density of fluid

g = gravity

μ = viscosity of fluid

PERMEAMETER EQUATIONS

① CONSTANT HEAD

$$K = \frac{V L}{A t h}$$

K = hydraulic conductivity (L/T)

V = vol. of H_2O discharge at time t (L^3)

L = length of sample (L)

A = cross-sectional area of sample (L^2)

h = hydraulic head (L)

t = time (T)

② FALLING HEAD

$$K = \frac{(d_t)^2 L}{(d_c)^2 t} \ln \left(\frac{h_0}{h} \right)$$

K = hydraulic conductivity (L/T)

L = length of sample (L)

h_0 = initial head (L)

h = final head (L)

t = time from $H_0 \rightarrow H$ (T)

d_t = diameter falling head tube (L)

d_c = diameter of sample chamber

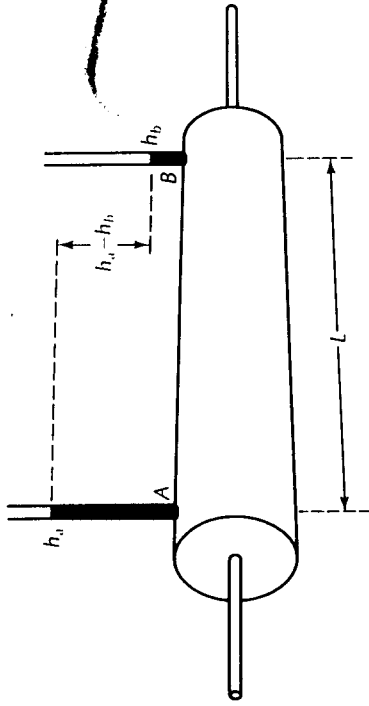


FIGURE 4.12 Horizontal pipe filled with sand to demonstrate Darcy's experiment. (Darcy's original equipment was actually vertically oriented.)

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

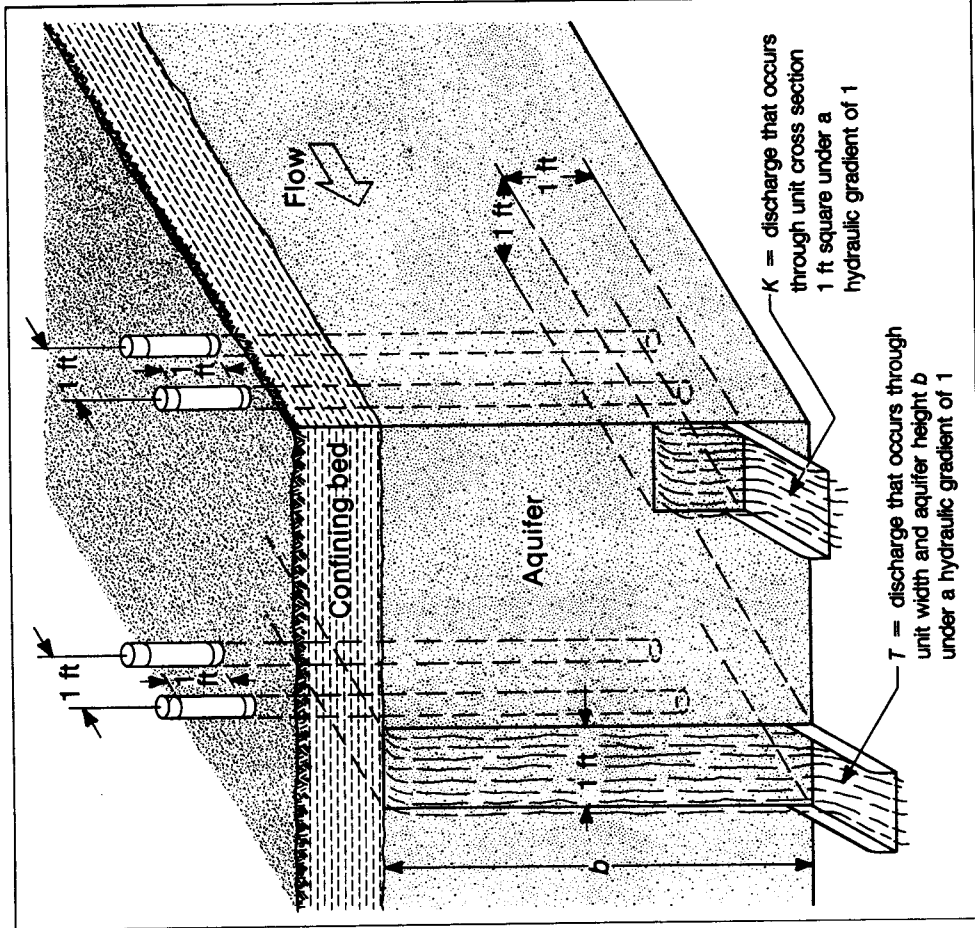


Figure 9.5. Illustration of the coefficients of hydraulic conductivity and transmissivity. Hydraulic conductivity multiplied by the aquifer thickness equals coefficient of transmissivity.

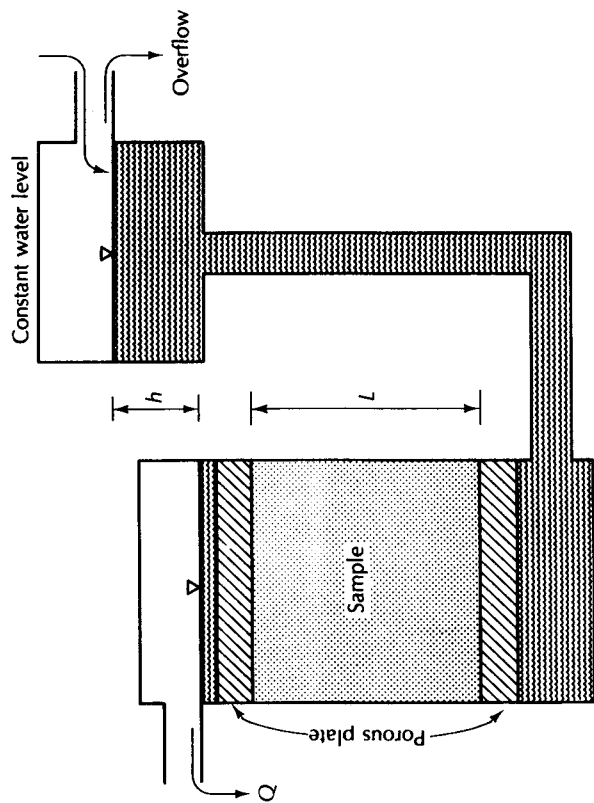


FIGURE 4.15 Constant-head permeameter apparatus.

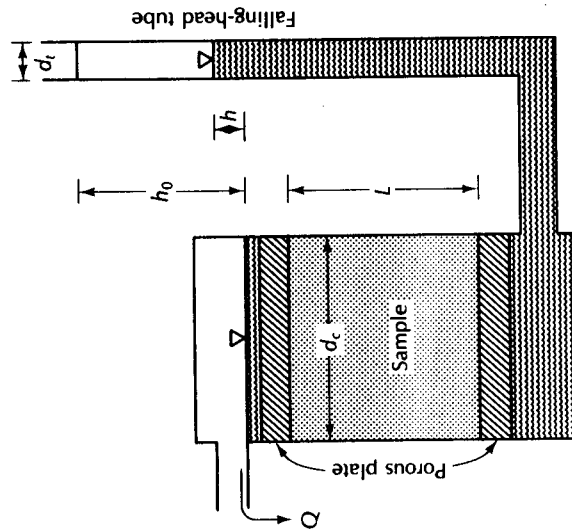


FIGURE 4.16 Falling-head permeameter apparatus.

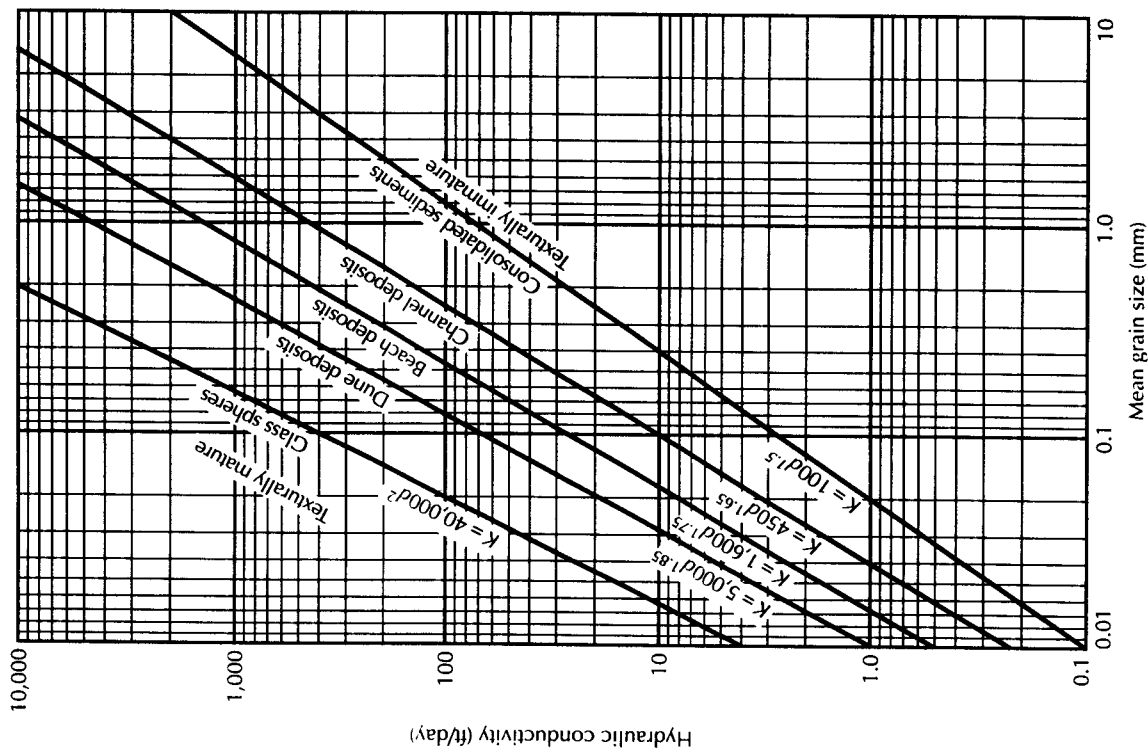


FIGURE 4.14 Graph showing the relationship of hydraulic conductivity to mean grain diameter for sediments of different textural maturity. Modified from R. G. Shepherd, *Ground Water* 27, no. 5 (1989): 633–638. Copyright © 1989 Ground Water Publishing Co.

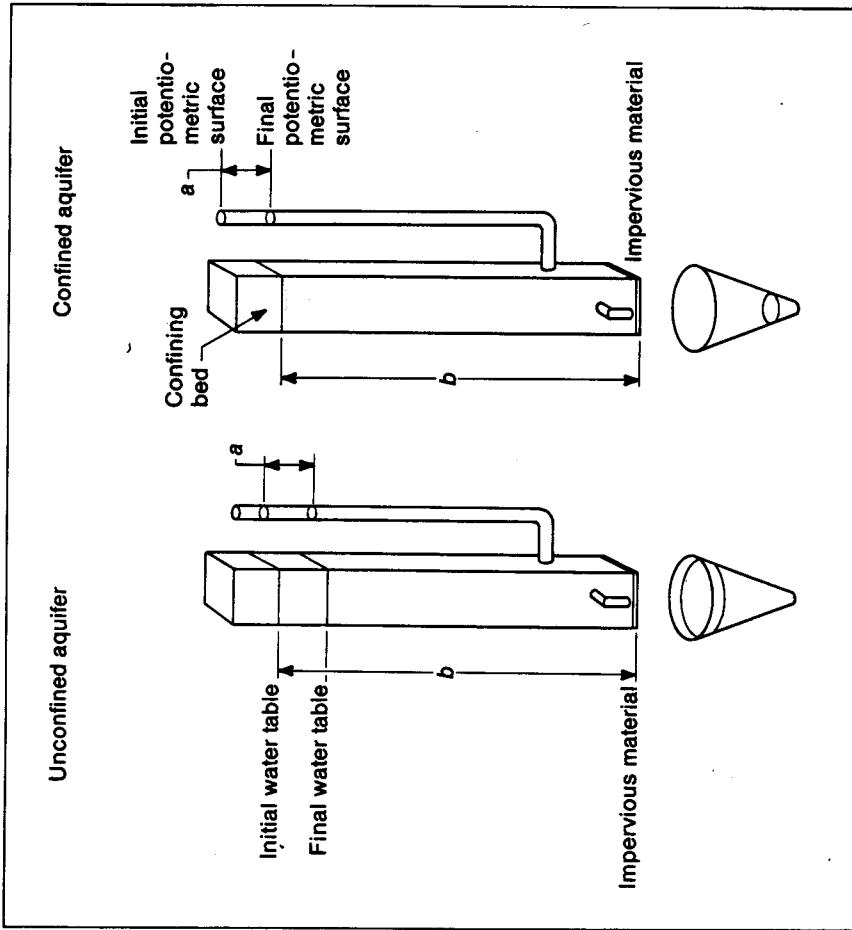


Figure 5.6. Unit prisms of unconfined and confined aquifers illustrating differences in storage coefficients. For equal declines in head, the yield from an unconfined aquifer is much greater than that from a confined aquifer. (After Heath and Trainer, 1968)

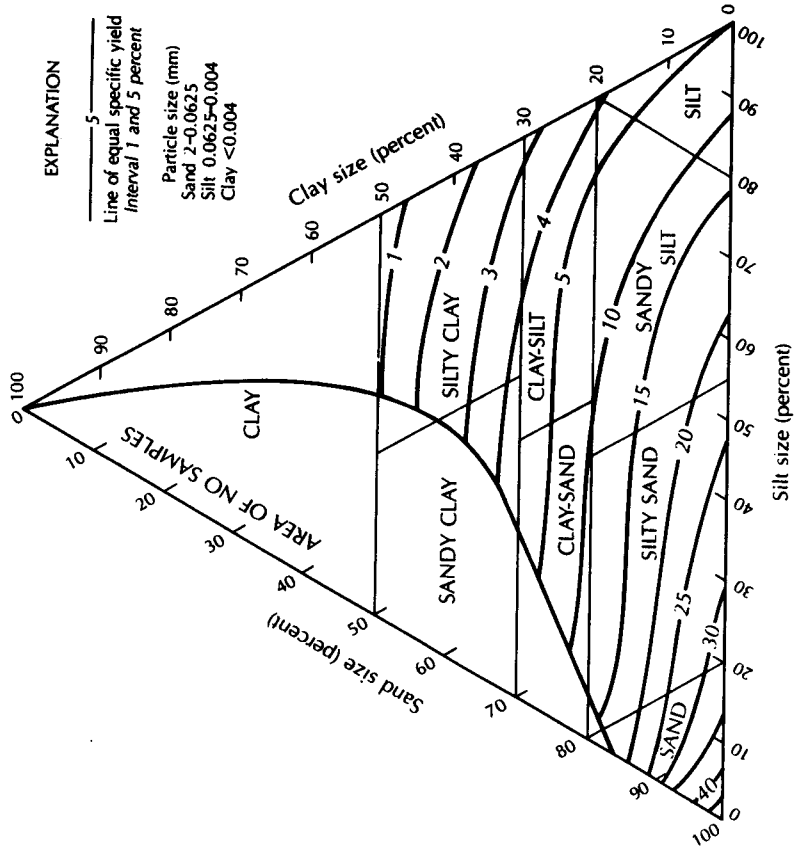


FIGURE 4.11 Textural classification triangle for unconsolidated materials showing the relation between particle size and specific yield. Source: A. I. Johnson, U.S. Geological Survey Water-Supply Paper 1662-D, 1967.

TABLE 4.4 Specific yields in percent

Material	Maximum	Specific Yield 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).

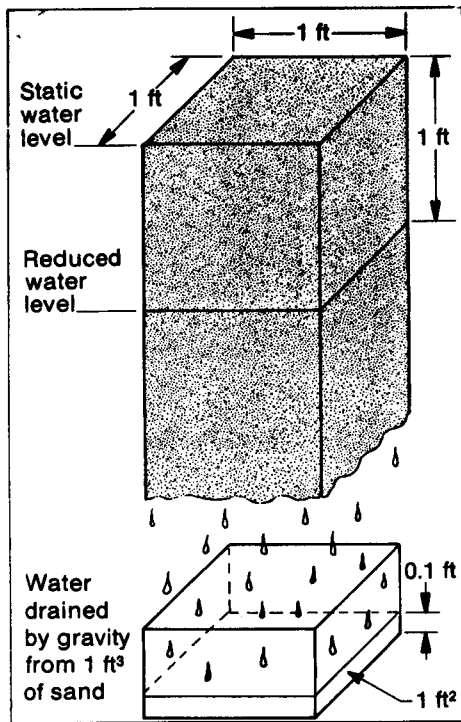


Figure 5.5. Specific yield of sand can be visualized from this diagram. Its value here is 0.1 ft³ per ft³ of aquifer material.

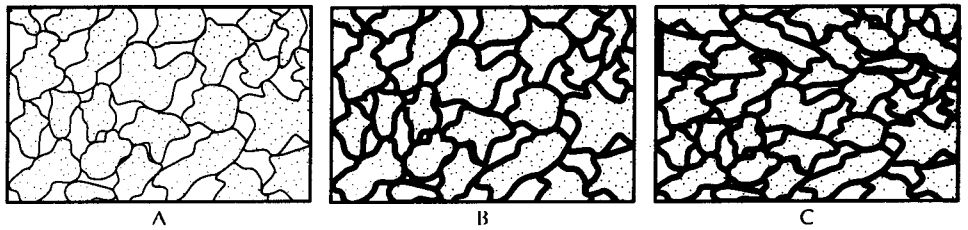
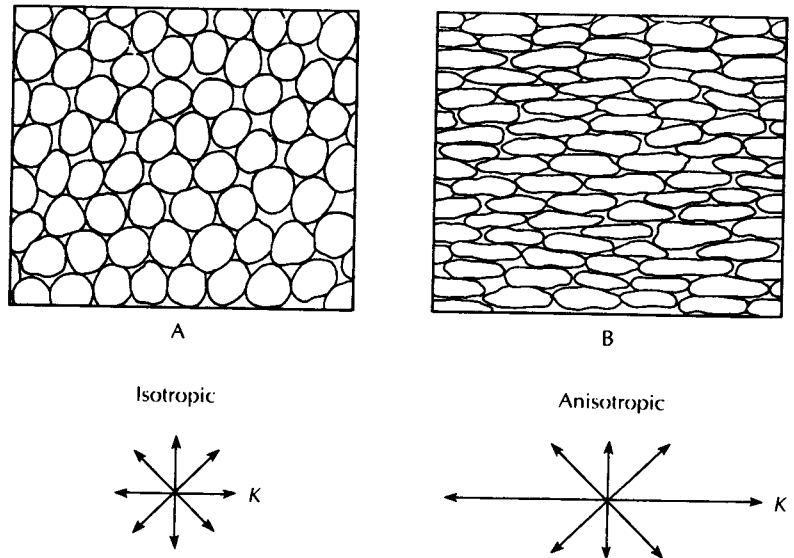


FIGURE 4.6 A. A clastic sediment with intergranular porosity. B. Reduction of porosity in the clastic sediment due to deposition of cementing material in the pore spaces. C. Further reduction in porosity due to compaction and cementation.

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.

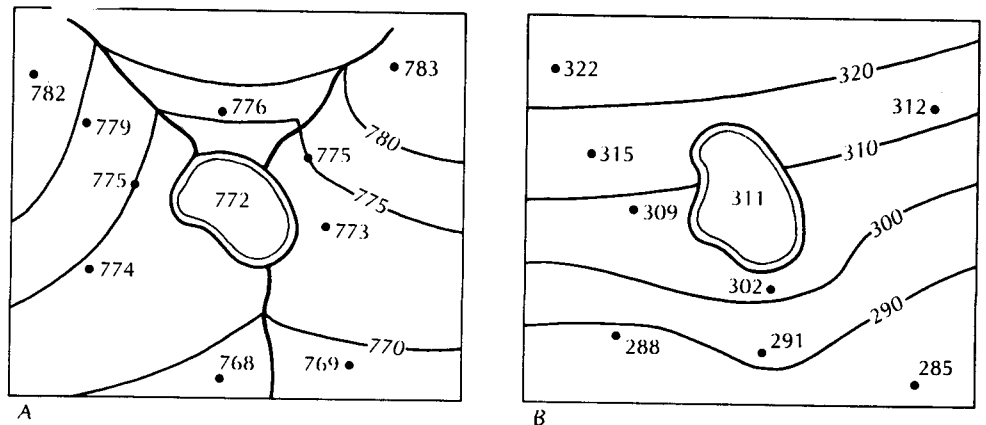


FIGURE 4.23 Maps showing construction of water-table maps in areas with surface-water bodies. A. A water-table lake with two gaining streams draining into it and one gaining stream draining from it. B. A perched lake that, through outseepage, is recharging the water table.