University of Windsor

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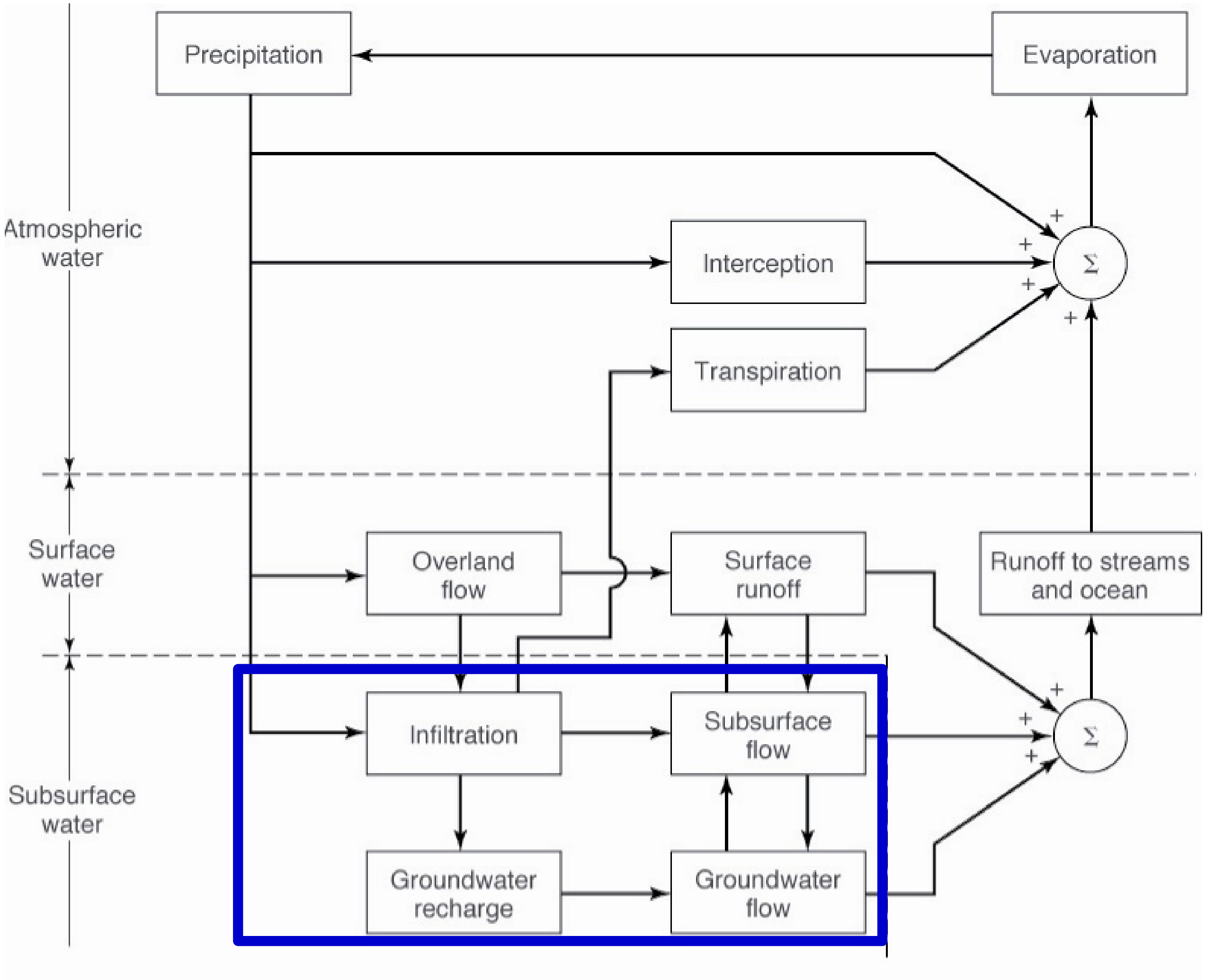
Advanced Hydrology and Water Resources Management

Groundwater Hydrology

Winter 2013

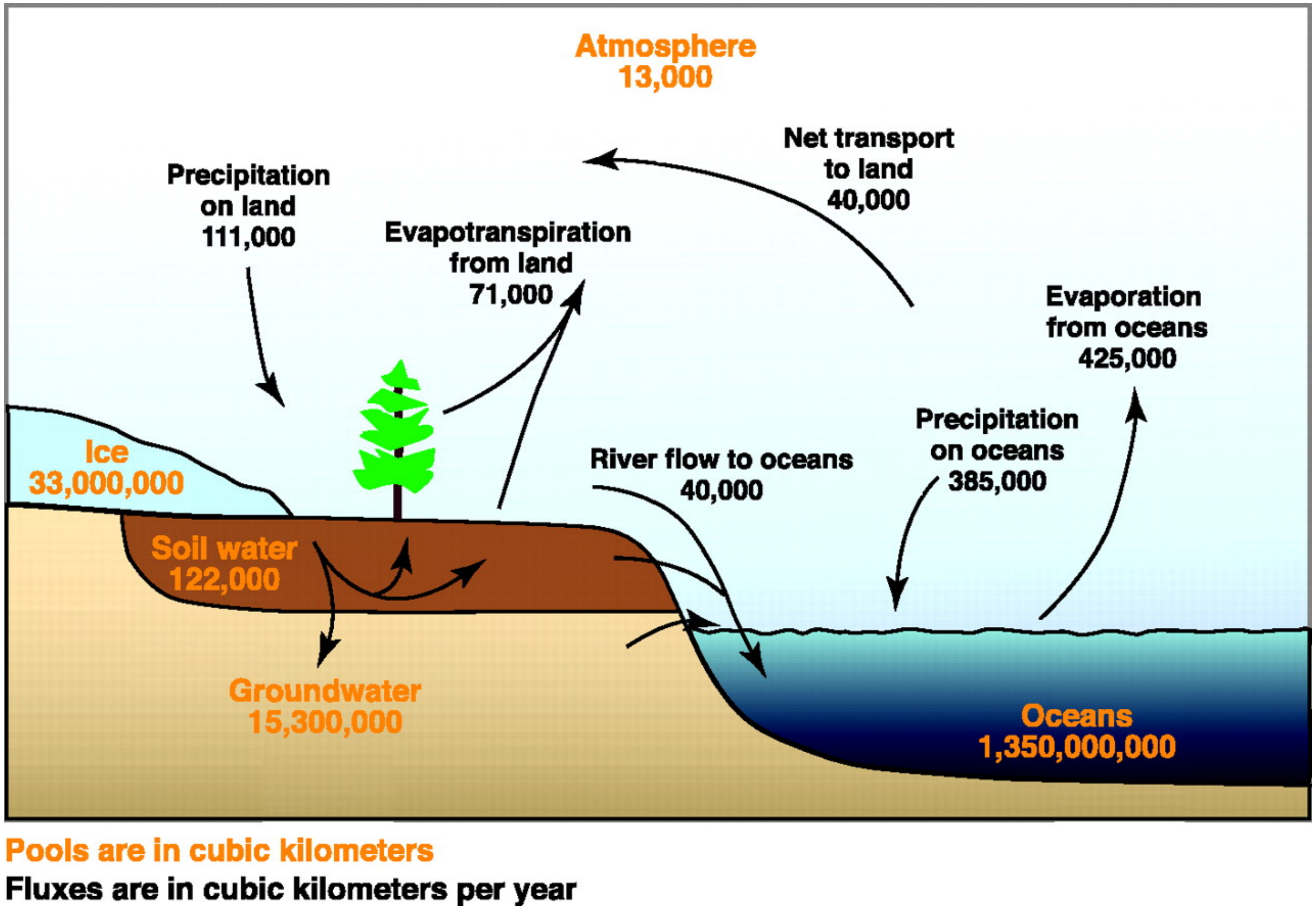
thinking forward

Hydrological Cycle



Todd and Mays (2005)

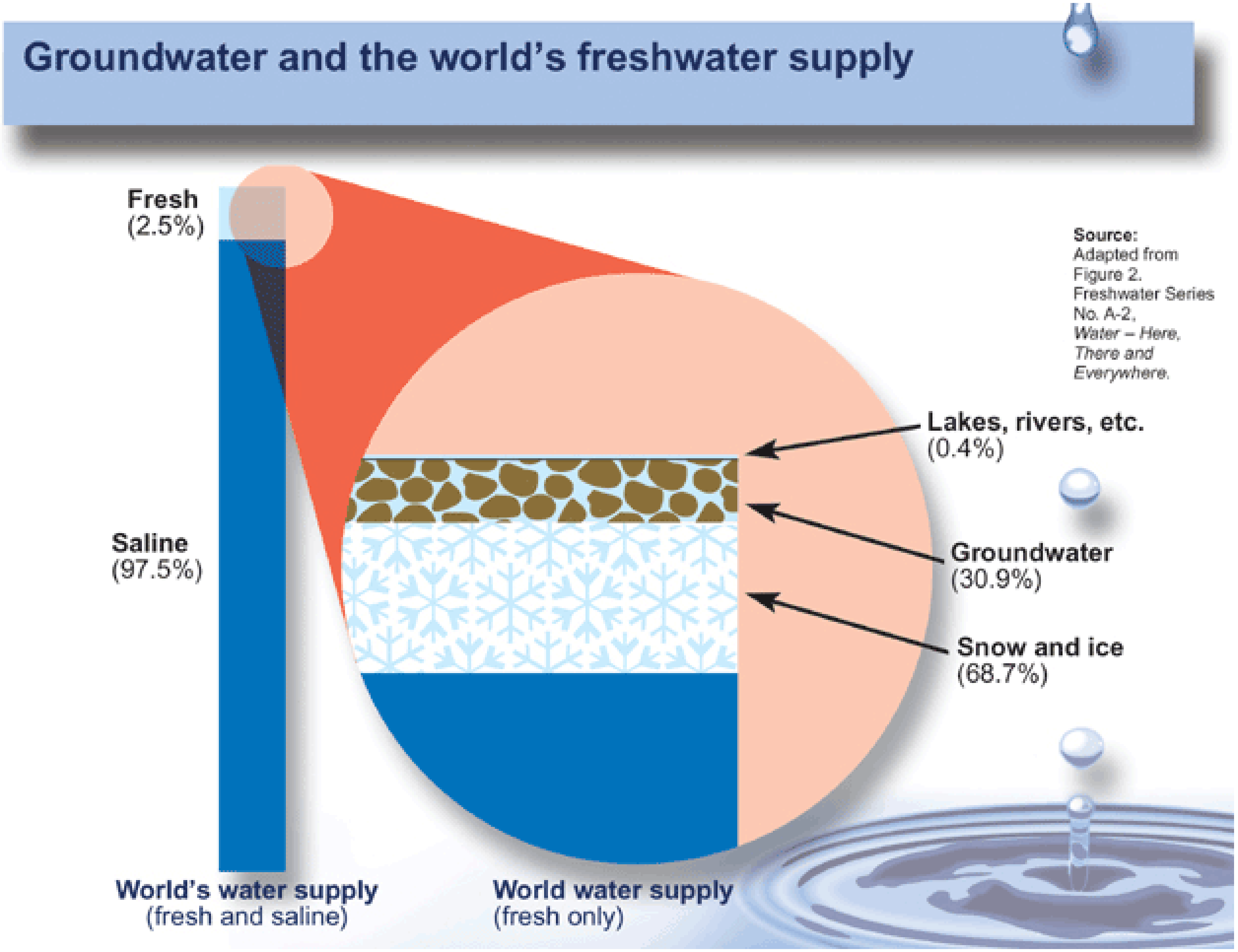
Hydrological Cycle - Water Fluxes



W. M. Alley et al., Science 296, 1985 -1990 (2002)

Published by AAAS

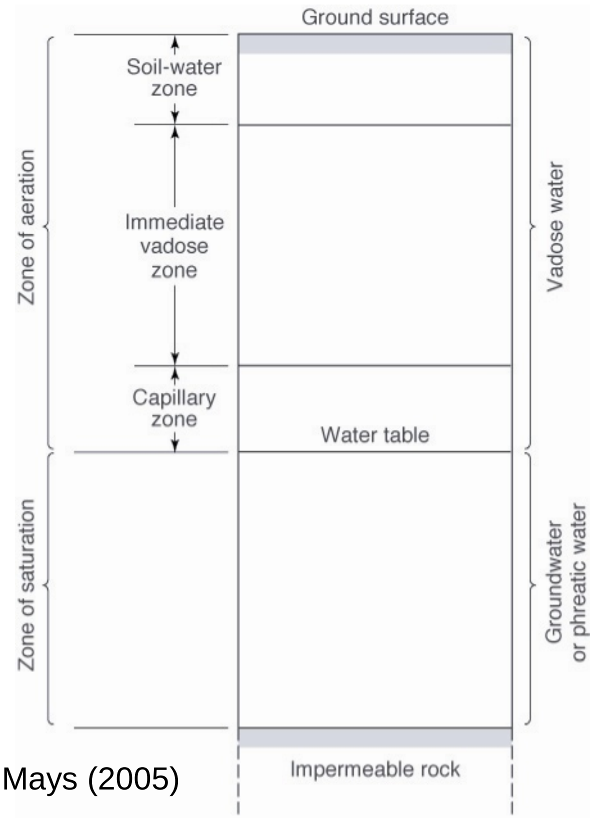
World Water Supply - Groundwater



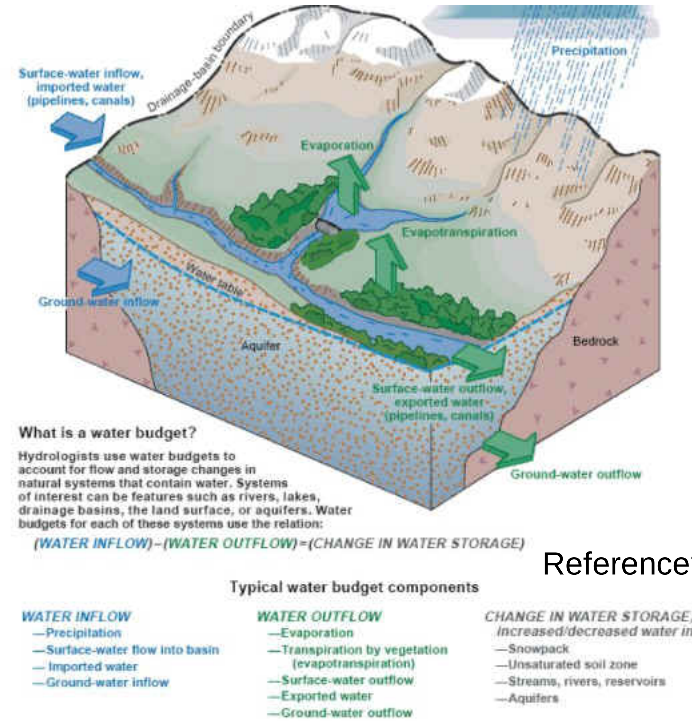
Questions to be Addressed?

- What is groundwater?
- Why is it important?
- Where does it come from?
- How does it move?
- How much can we take for water supplies?
- What is its role in transporting contaminants?

Groundwater



Todd and Mays (2005)



Reference???

- found underground in the spaces between particles of rock and soil, or in crevices and cracks in rock.
- flows slowly through water bearing formations (aquifers)

Hydrogeology

- study of the laws of occurrence and movement of subterranean water

What do Hydrogeologists do?

- Prepares plans for development of a groundwater supply
  - Locates and develops a source of groundwater
  - Determines if there is enough water of acceptable quality available
- Groundwater Control
  - To lower water levels, prepares dewater plan (where, how much etc)
  - Evaluates impact of a mine dewatering plan
- Aquifer protection and water conservation
  - Determines capture zones to protect the wells
  - Delineates plume of contaminated groundwater

Why is it important?

Groundwater is a major link in the hydrologic cycle

Areas of interest

1. Fluid Motion

   Flow rates, direction and amounts

   Important for transport of chemical substances/ contamination studies (ADVECTION & DISPERSION)

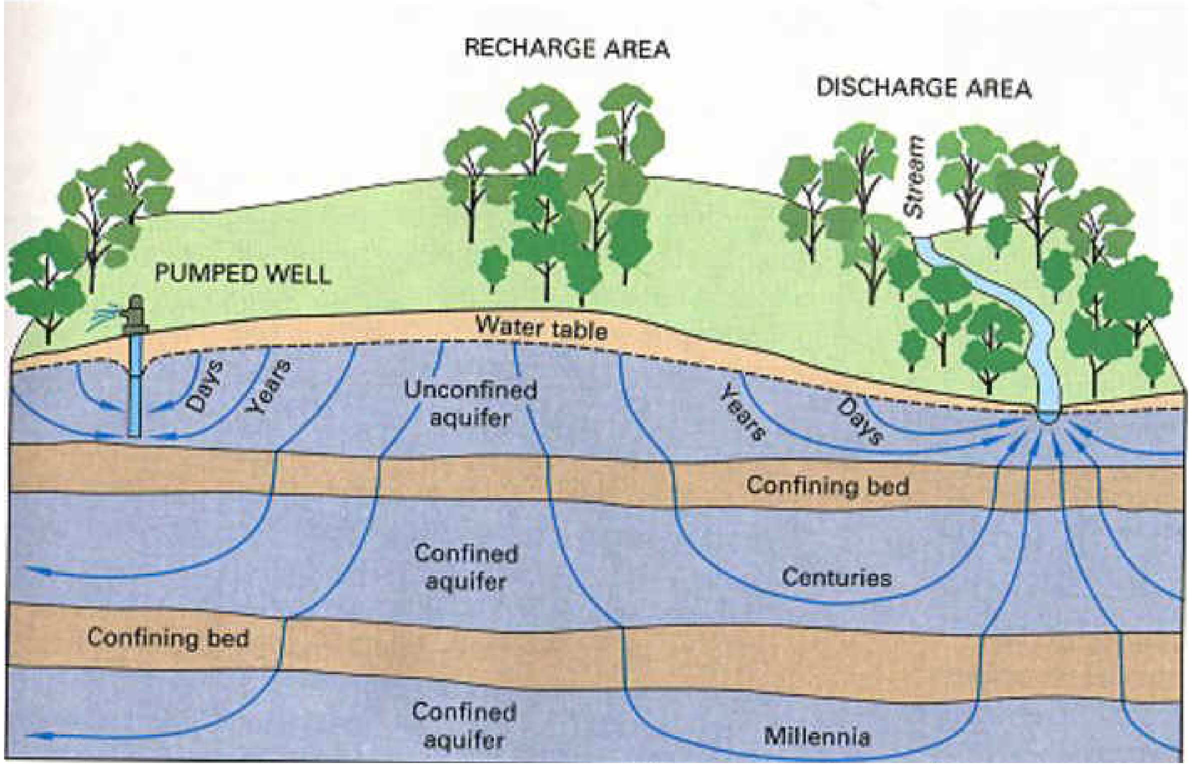
2. Storage

   Amount of fluid available in pore/fractures to exploit.

   Involves porosity and compressibility

   Important for water resources evaluation, land subsidence

How Old is Groundwater?



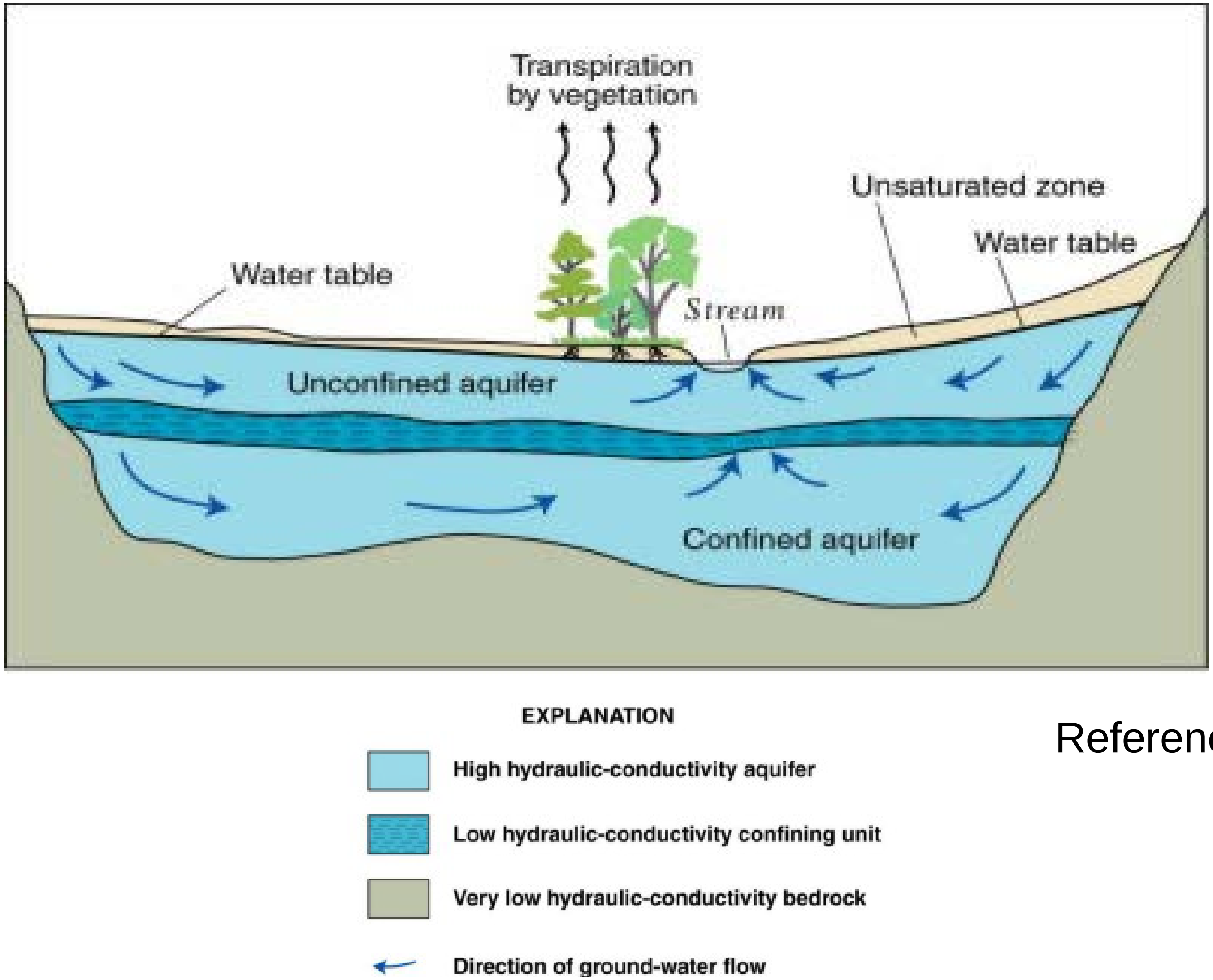
Reference??

- Residence time varies from as little as days or weeks to as much as 10,000 or more years
- By comparison, average turnover time of river water is about two weeks

Definitions

- Aquifer
  - Saturated permeable geologic unit that can transmit significant quantities of water under ordinary hydraulic gradients
    - Confined, Unconfined or Semi-Confined Aquifer
- Aquitard
  - Beds of lower permeability in the stratigraphic sequence that contain water but do not yield water to pumping wells
  - Aquifer and aquitard separation is ambiguous
- Aquiclude
  - Saturated geologic unit that is incapable of transmitting significant quantities of water under ordinary hydraulic gradients
  - e.g., Clays

Confined-Unconfined Aquifers



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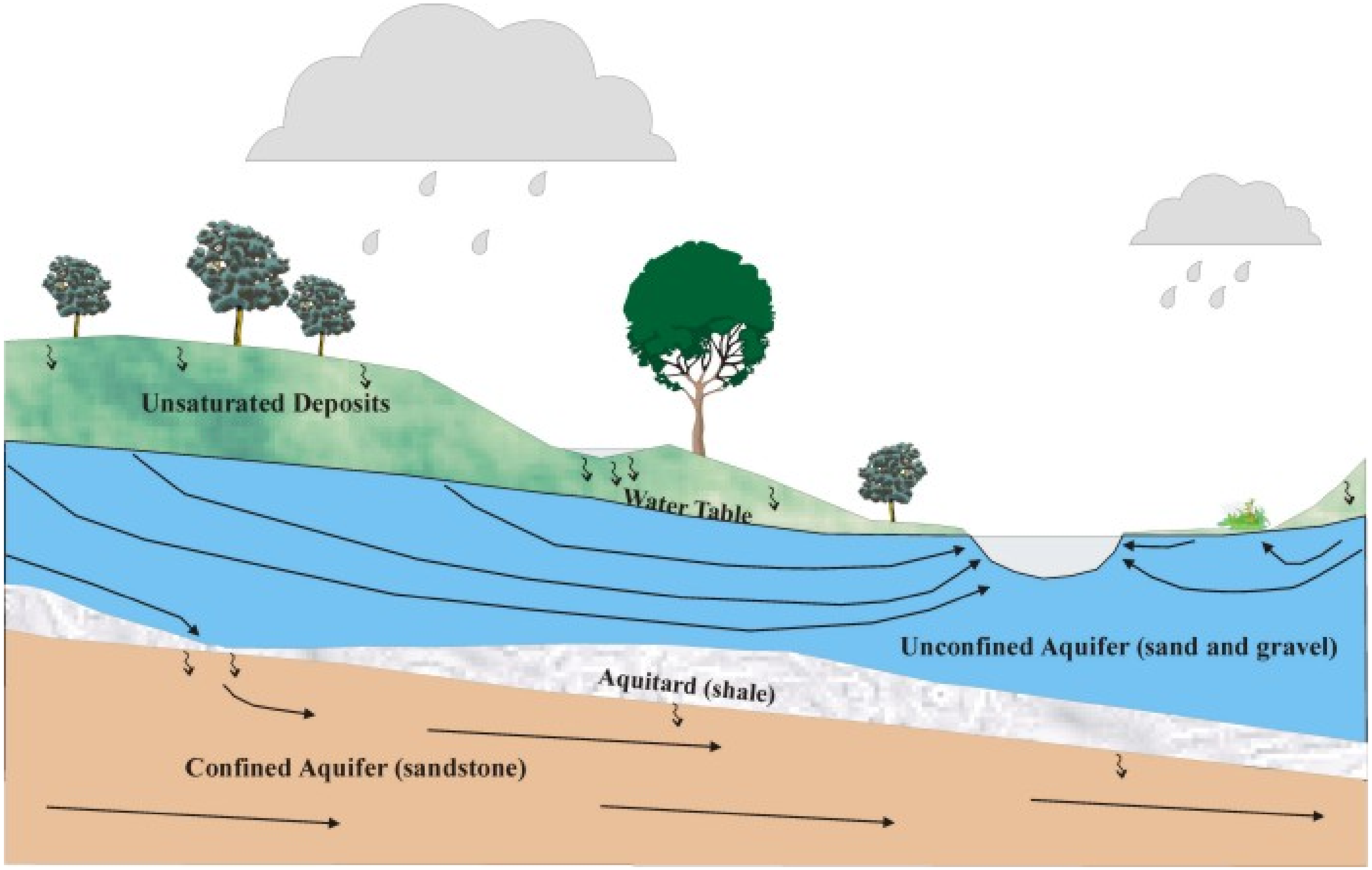
Confined-Unconfined Aquifers

- Unconfined Aquifers –Also water table aquifer an aquifer in which water table forms the upper boundary
  - Water level – water table

- Confined aquifers – confined between two aquitards
  - Potentiometric surface
  - Concept of potentiometric surface is valid in horizontal flow in horizontal aquifers

Confined-Unconfined Aquifers



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Groundwater Contamination

Any addition of undesirable substances to groundwater caused by human activities is considered to be **contamination**.

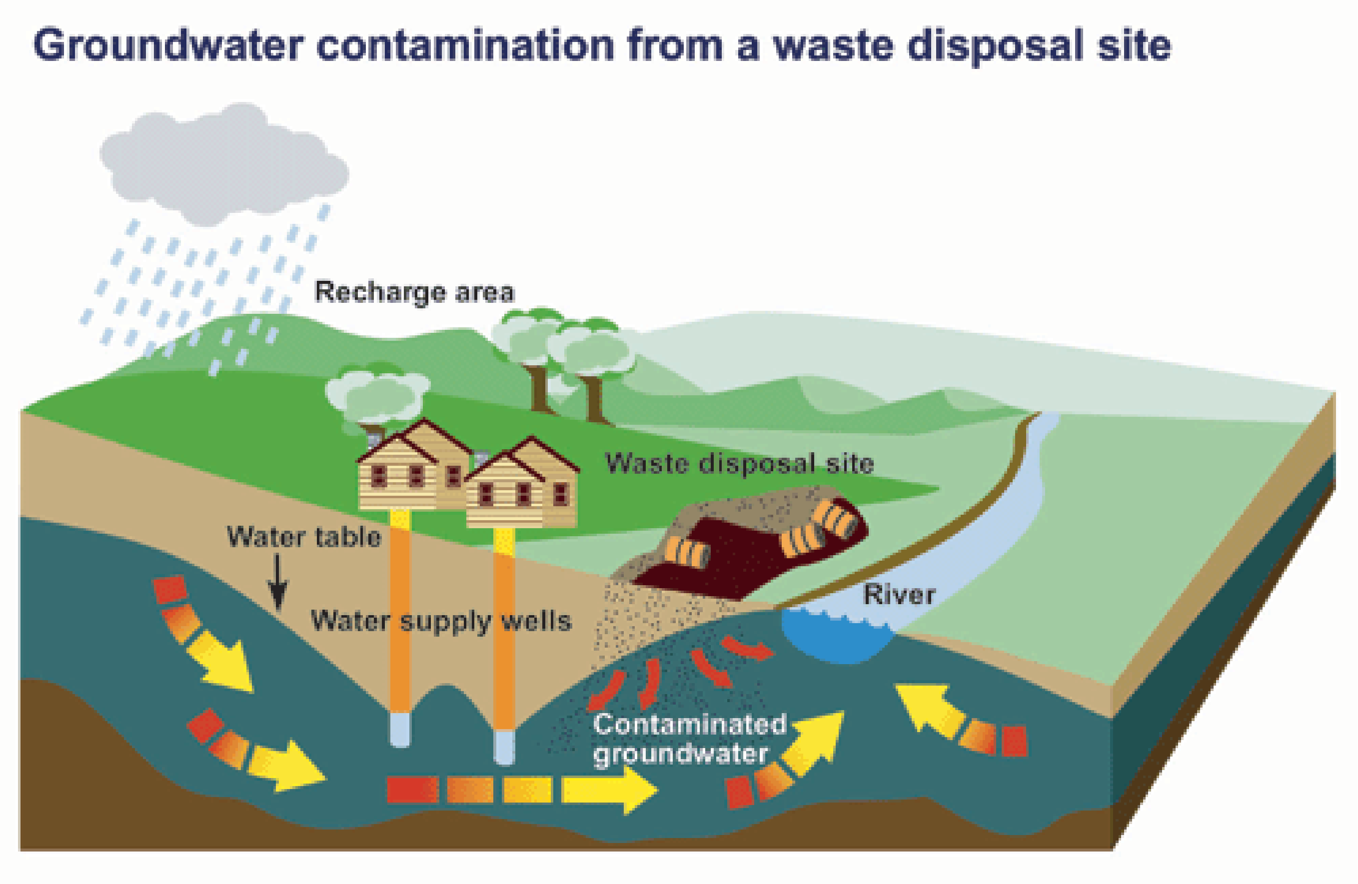
Pollution if the undesirable substances exceed the limits

Groundwater contaminants come from two categories of sources: point sources and distributed, or non-point sources

Groundwater contamination is recognized only after groundwater users have been exposed to potential health risks.

The cost of cleaning up contaminated water supplies is usually extremely high.

Groundwater Contamination

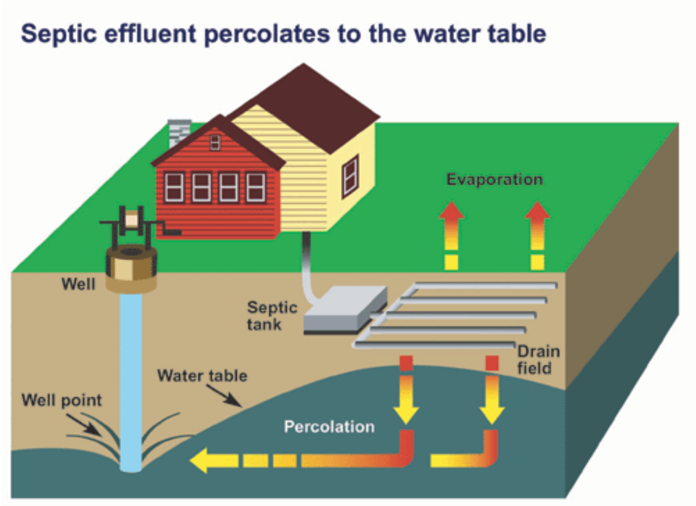


http://www.ec.gc.ca/eau-water/default.asp?lang=En&n=6A7FB7B2-1

Point Sources

Landfills, leaking gasoline storage tanks, leaking septic tanks, and accidental spills are examples of point sources

<u>municipal landfills and industrial waste disposal sites</u>



http://www.ec.gc.ca/eau-water/default.asp?lang=En&n=6A7FB7B2-1

Non-point Sources

Infiltration from farm land treated with pesticides and fertilizers is an example of a non-point source

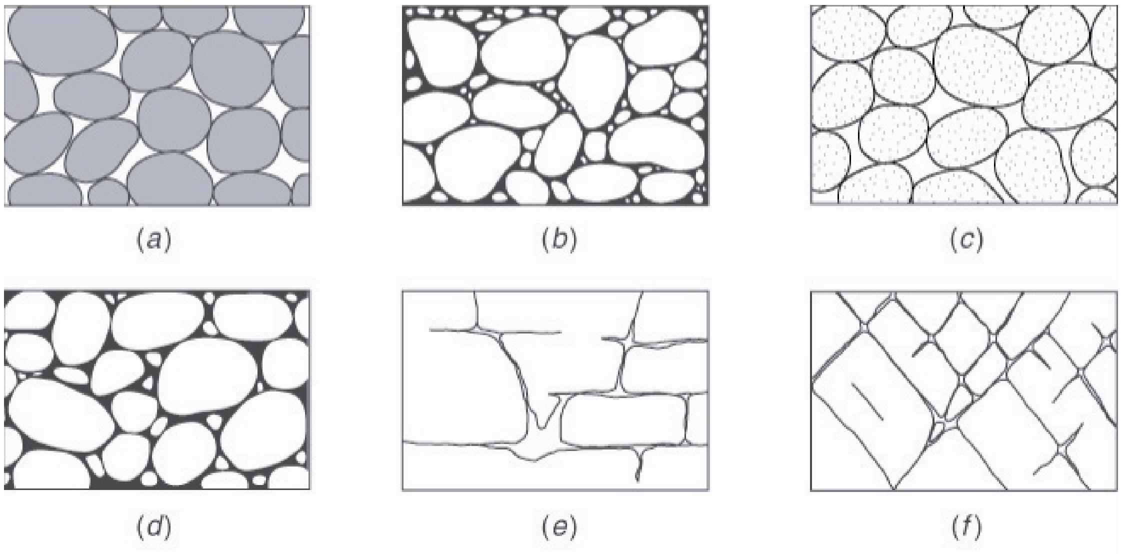
- Fertilizers and pesticides on agricultural land
- Contaminants in rain, snow, and dry atmospheric fallout

Basic Properties of Media and Fluid

- Media – Porosity (n), permeability (k) and compressibility (α)
- Fluid – Density (ρ), dynamic viscosity (μ) and Compressibility (β_w)
- Others are derived….
  - Hydraulic Conductivity (K), Specific Storage (S_s); Transmissivity (T) and Storativity (S) in confined aquifers; Hydraulic Conductivity (K) and specific yield (S_y) in unconfined aquifers etc.

Physical Properties and Principles

- Porosity – void volume/total volume
- Permeability – Ease with which fluid can move through a porous rock



Types of Pore Spaces

Todd and Mays (2005)

Total Potential and Hydraulic Head

$$\Phi = \Phi_g + \Phi_p + \Phi_k = gz + \left[\frac{p - p_o}{\rho}\right] + \frac{v^2}{2}$$

Bernoulli's Equation – Flow along a stream line

for groundwater, *v – is very small so the kinetic term will be ~ zero*

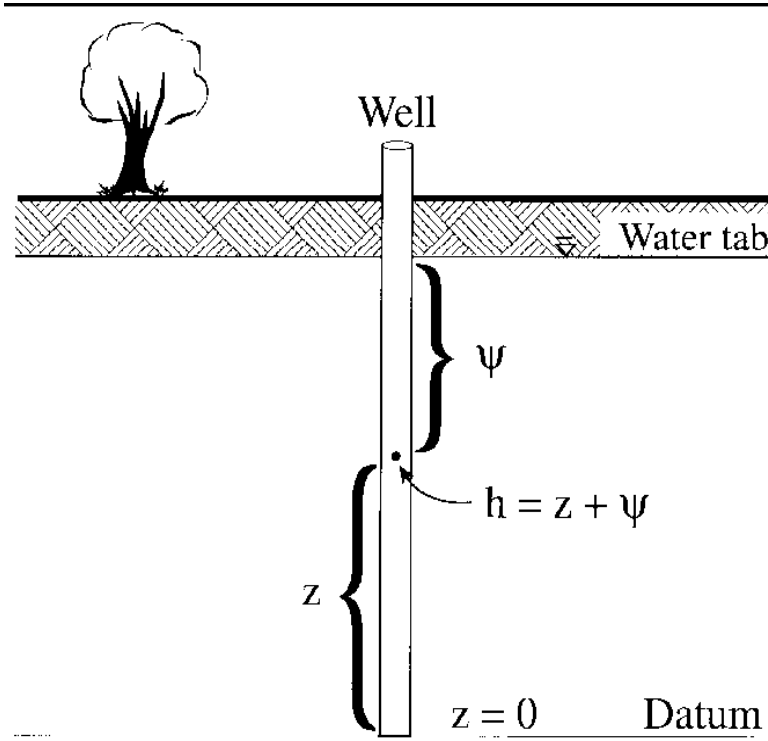
$$\Phi = gz + \left[\frac{p - p_o}{\rho}\right]$$

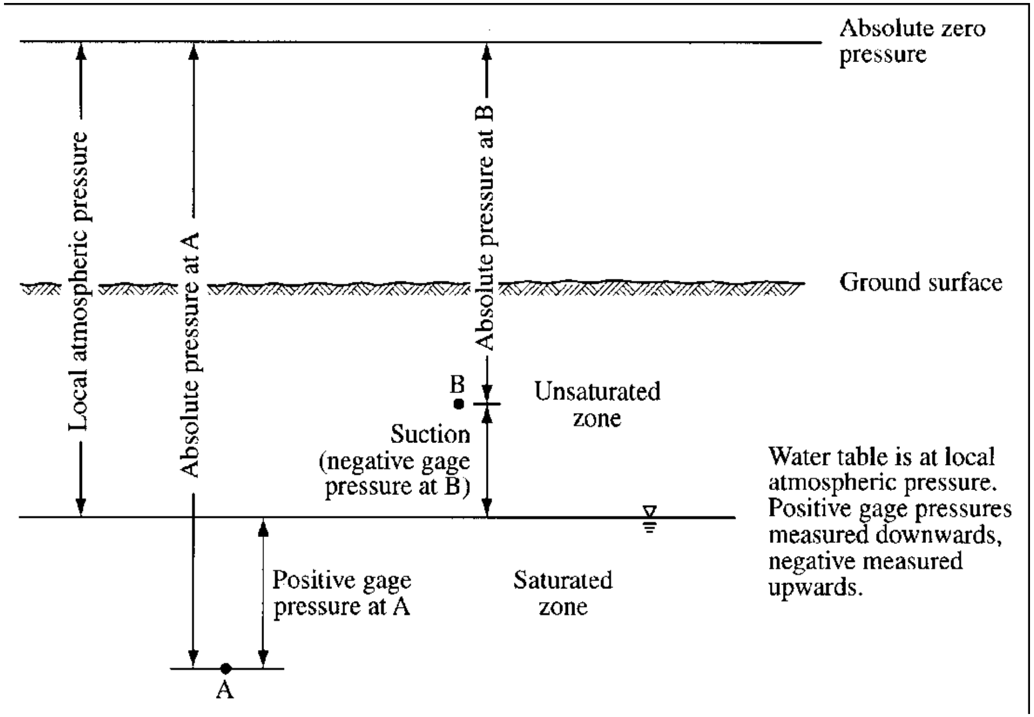
Total (or Hydraulic) head = Datum head + pressure head

h = z + ψ

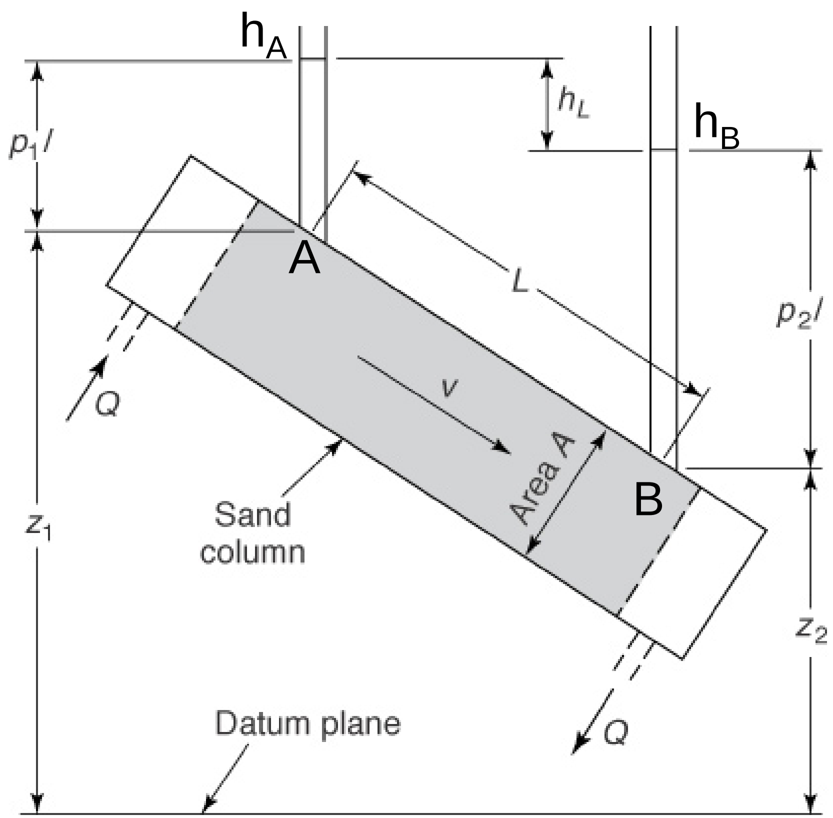
Hydraulic Head (h) – the driving force for groundwater flow

Concept of Head and Pressure





Fluid Motion and Darcy's Law



Henri Darcy (1856) – beginning of science of groundwater

illustrated the controls on water movement through a column of sand

$$Q \propto h_A - h_B \text{ and } Q \propto -(1/L)$$

$$Q = -KA\frac{h_L}{l} = -KA\frac{h_A - h_B}{L}$$

$$Q = -KA\frac{dh}{dl}$$

← Hydraulic Gradient

Darcy's Law

$$Q = -KA\frac{h_L}{l} = -KA\frac{h_A - h_B}{L} \qquad q = \frac{Q}{A} = -K\frac{\Delta h}{\Delta l} = -Ki$$

q = specific discharge (Darcy's flux); units : $(L^3/T)/L^2 = L/T$

Do Not Confuse with Velocity

q is the volume of water flowing through a unit time

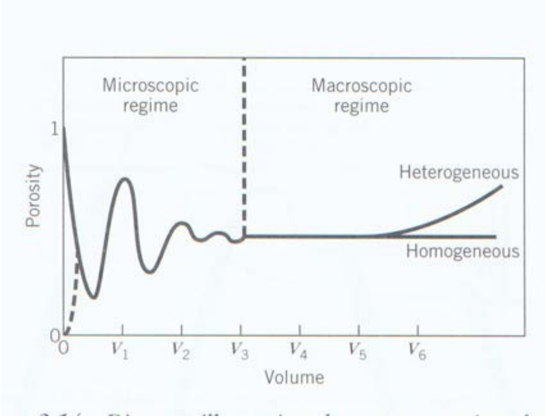
is the volume of averaged "flux." Hence, historically referred to as Darcy Flux

It makes an attempt to describe microscopic behaviour with macroscopic parameters

Validity of Darcy's Law

Limits:

- Macroscopic representation of flow
- Upper and lower limits of flow rates



<u>Macroscopic Behaviour</u>

It is assumed that a porous medium can be sampled to obtain measurements on a Representative Elementary Volume (REV)

<u>Limits</u>

- Darcy's law is valid only for laminar flow in porous media
- $R_e < 1$ (sometimes range is 1 to 10)

Hydraulic Conductivity

$$K = \frac{-q}{\frac{\Delta h}{\Delta l}} = \frac{L/T}{L/L} = L/T$$

- a measure of the ease with which a specific fluid (H_2O) will pass through a particular porous medium
- Depends on both (i) fluid and (ii) medium
- An empirical factor which is the average of the microscopic effects to describe macroscopic behaviour
- Assumes that there is a representative continuum for the porous medium

Note: Darcy's law is EMPIRICAL. This assumption may not always hold. But most real world situations it holds good.

Physical interpretation of K

Darcy's proportionality coefficient or hydraulic conductivity is

$K \propto \rho_w$

$K \propto 1/\mu$

$K \propto d^2$

$$K = K^* \frac{\rho_w d^2}{\mu}$$

$$q = \frac{-K^* \rho_w d^2}{\mu} \, grad\, h \qquad q = \frac{-N \rho_w g R^2}{\mu} \, grad\, h$$

$$K = \frac{N \rho_w g d^2}{\mu} = \frac{k \rho_w g}{\mu}$$

k = intrinsic permeability (Darcy)

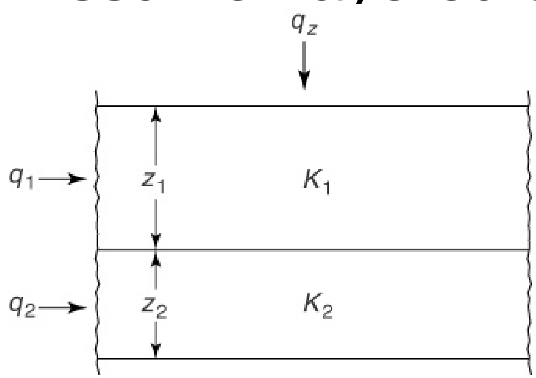
Table 3.2.1 Representative Values of Hydraulic Conductivity (after Morris and Johnson[75])

Material	Hydraulic conductivity (m/day)	Type of measurement[a]
Gravel, coarse	150	R
Gravel, medium	270	R
Gravel, fine	450	R
Sand, coarse	45	R
Sand, medium	12	R
Sand, fine	2.5	R
Silt	0.08	H
Clay	0.0002	H
Sandstone, fine-grained	0.2	V
Sandstone, medium-grained	3.1	V
Limestone	0.94	V
Dolomite	0.001	V
Dune sand	20	V
Loess	0.08	V
Peat	5.7	V
Schist	0.2	V
Slate	0.00008	V
Till, predominantly sand	0.49	R
Till, predominantly gravel	30	R
Tuff	0.2	V
Basalt	0.01	V
Gabbro, weathered	0.2	V
Granite, weathered	1.4	V

[a]H is horizontal hydraulic conductivity, R is a repacked sample, and V is vertical hydraulic conductivity.

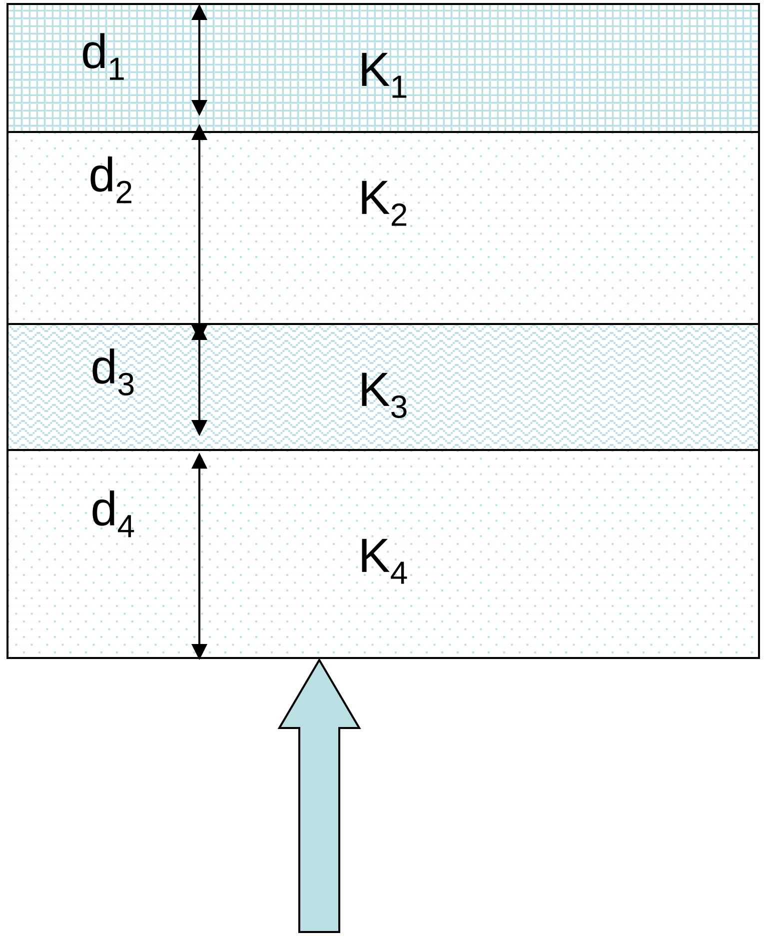
Equivalent Hydraulic Conductivity

- Assume Layered system

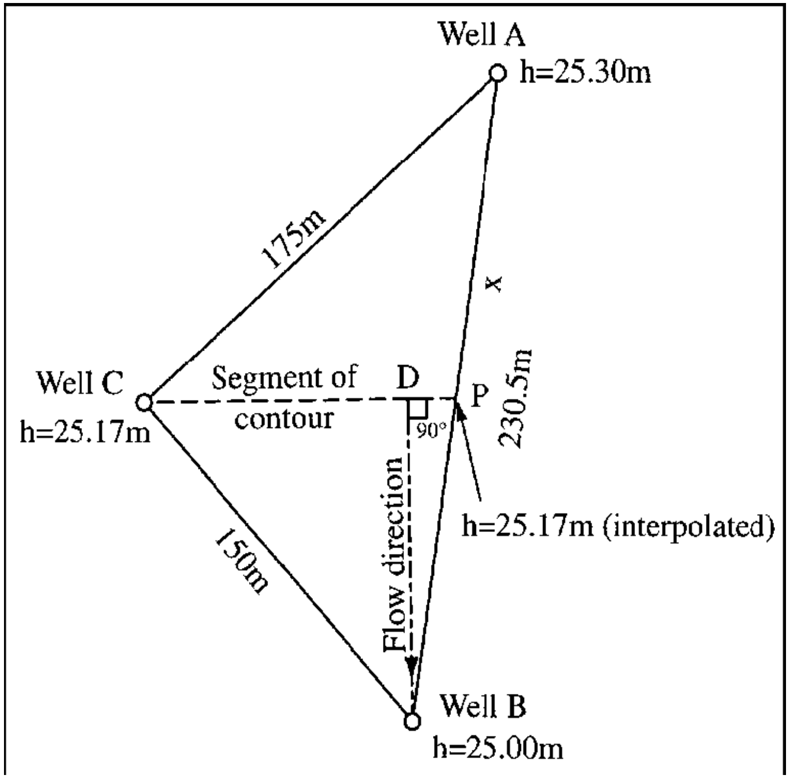


$$K_x = \frac{\sum d_i K_i}{\sum d_i}$$

$$K_z = \frac{\sum d_i}{\sum \frac{d_i}{K_i}}$$



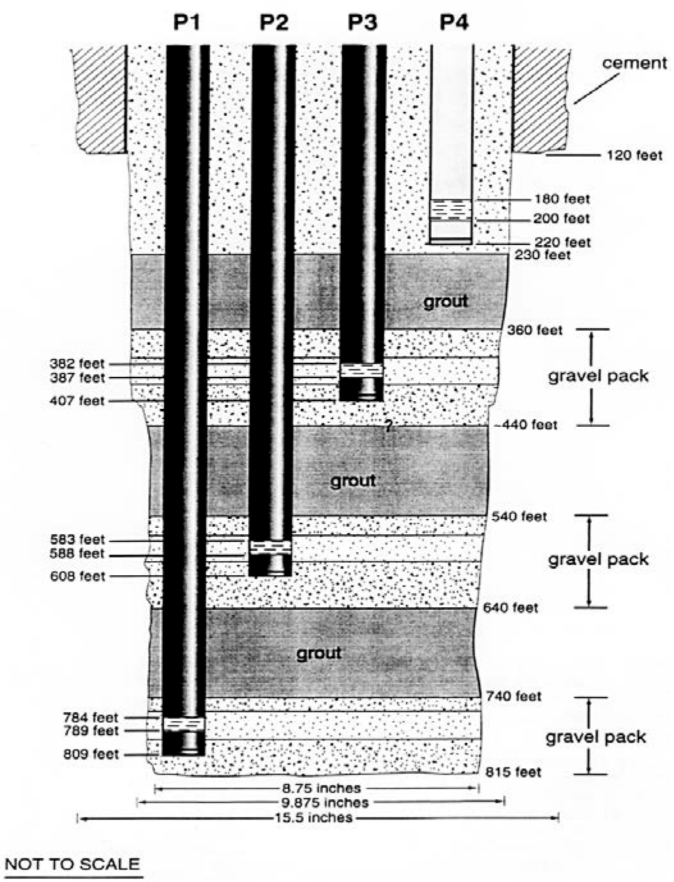
Flow gradients and directions



Water Table and Potentiometric Maps

2D representation of 3D surfaces

- **Unconfined aquifers**
  - Water table surface
- **Confined aquifers**
  - Potentiometric surface
  - Need water level readings made in a number of wells, each of which is open only in the aquifer of interest



Piezometers

Aquifer Characteristics

Specific Storage (S_s) - Also called elastic storage coefficient

- *proportionality constant relating the volumetric changes in fluid volume per unit volume to the time rate of change in hydraulic head*

$$S_s = \rho_w g (\alpha + n \beta)$$

← Expansion of water

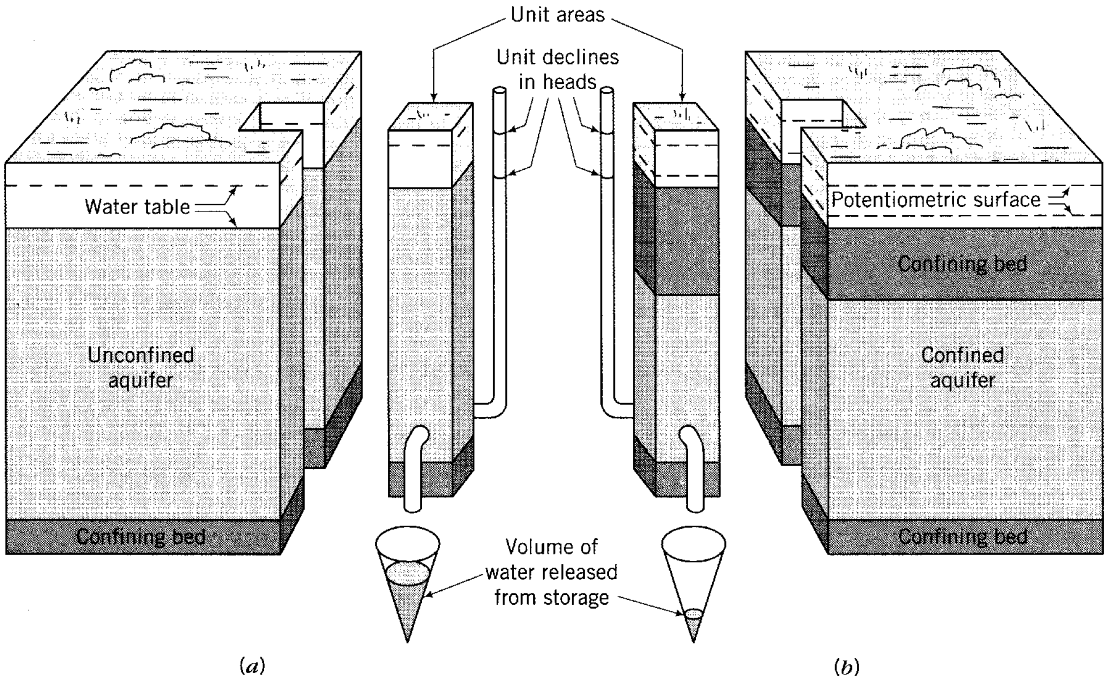
→ compression of porous medium

α and β are compressibility of pore structure and water

- **Unconfined Aquifer:** The amount of water obtained per unit volume drained is substantial and is equal to the volume of pore space actually drained.

- **Confined Aquifer:** a drop in head is not accompanied by drainage from storage as the aquifer remains fully saturated at all times
- Amount of water obtained in response to unit head drop is small fraction of that obtained in case of unconfined aquifer

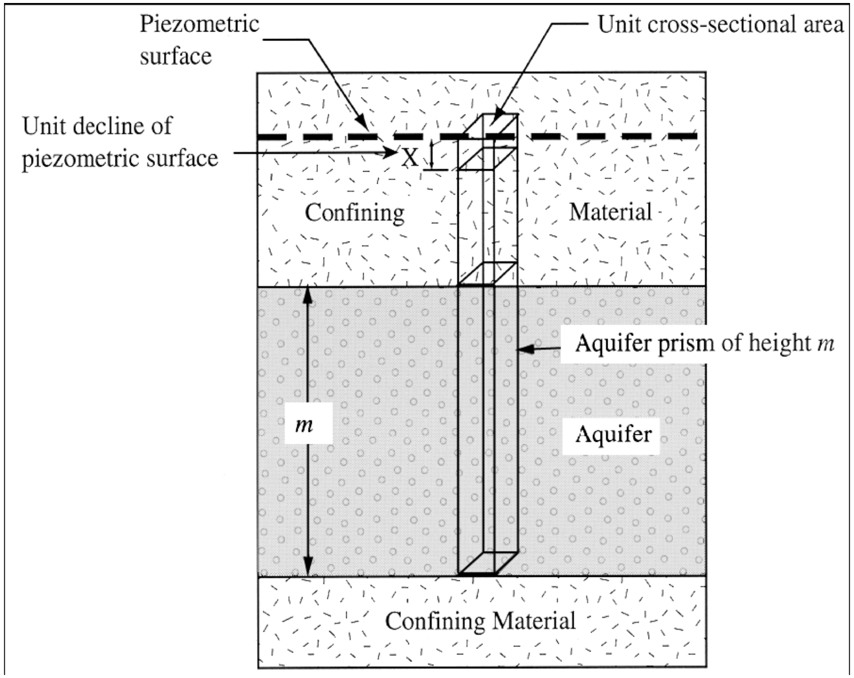
Aquifer Characteristics



Concept of storativity in unconfined and confined aquifers (Heath, 1982)

Storage Properties

- How confined aquifers take additional water in response to increase in head?
  - Water and porous structure are elastically compressible. Changes in head leads to changes in both water and pore volume
  - The interstitial pore space of the sandstone was reduced to the extent of the unaccountable volumetric withdrawals from storage.



Storativity or Storage Coefficient

- For confined aquifers only
- Volume of water that an aquifer releases from or takes into storage per unit surface area of aquifer per unit change in the component of head normal to that surface

$$0.00005 < S < 0.005$$

Specific Yield

- Storativity in case of unconfined aquifer is Specific Yield
- Specific Yield (S_y) : Ratio of the volume of water that drains by gravity to the total volume of rock
- Specific Retention (S_r): Ratio of the volume of water the rock retains against force of gravity to the total volume of rock

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

Material	Specific yield (percent)
Gravel, coarse	23
Gravel, medium	24
Gravel, fine	25
Sand, coarse	27
Sand, medium	28
Sand, fine	23
Silt	8
Clay	3
Sandstone, fine grained	21
Sandstone, medium grained	27
Limestone	14
Dune sand	38
Loess	18
Peat	44
Schist	26
Siltstone	12
Till, predominantly silt	6
Till, predominantly sand	16
Till, predominantly gravel	16
Tuff	21

Total porosity = S_y+ S_r+ ratio of volume of water contained in the unconnected pore space to the total volume

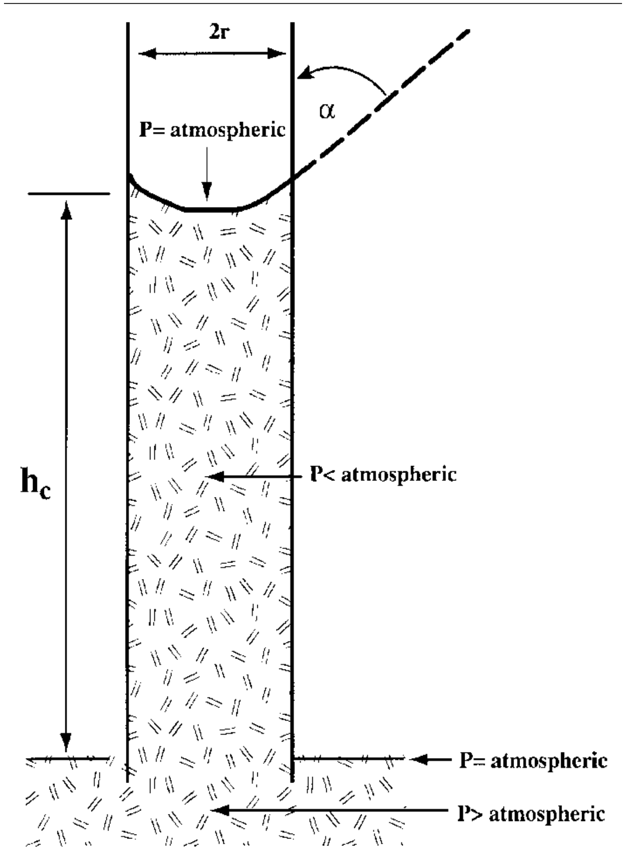
Transmissivity

- Rate at which water is transmitted through a unit width of aquifer under a unit hydraulic gradient
- T = K b where b= saturated thickness of the aquifer

- The concept is applicable only in case of Confined aquifer

- where as in unconfined aquifers, “b” changes as the pumping starts. Hence, the working parameter is ‘K’

Capillary Rise



$$h_c = \frac{2\sigma \cos\alpha}{\gamma_w r}$$

σ =surface tension = 0.0756 N/m at 0^0 C

γ_w = specific weight of water = 9.805 kN/m^3

Table 2.4.1 Capillary Rise in Samples of Unconsolidated Materials (after Lohman[34])

Material	Grain size (mm)	Capillary rise (cm)
Fine gravel	5–2	2.5
Very coarse sand	2–1	6.5
Coarse sand	1–0.5	13.5
Medium sand	0.5–0.2	24.6
Fine sand	0.2–0.1	42.8
Silt	0.1–0.05	105.5
Silt	0.05–0.02	200[a]

Note: Capillary rise measured after 72 days; all samples have virtually the same porosity of 41 percent.

[a]Still rising after 72 days.

Todd and Mays, 2005

Topics Covered Today

- What hydrogeology is and why it is of interest to you
- Basic Material Properties of Media and Fluid
- Fluid Potential and Hydraulic Head
- Darcy's Law
- Hydraulic Conductivity
- Equivalent K in case of layered soils
- Water Table and Potentiometric surfaces, flow gradients
- Aquifer Properties
- Specific Storage, Specific Yield, Storativity,transmissivity