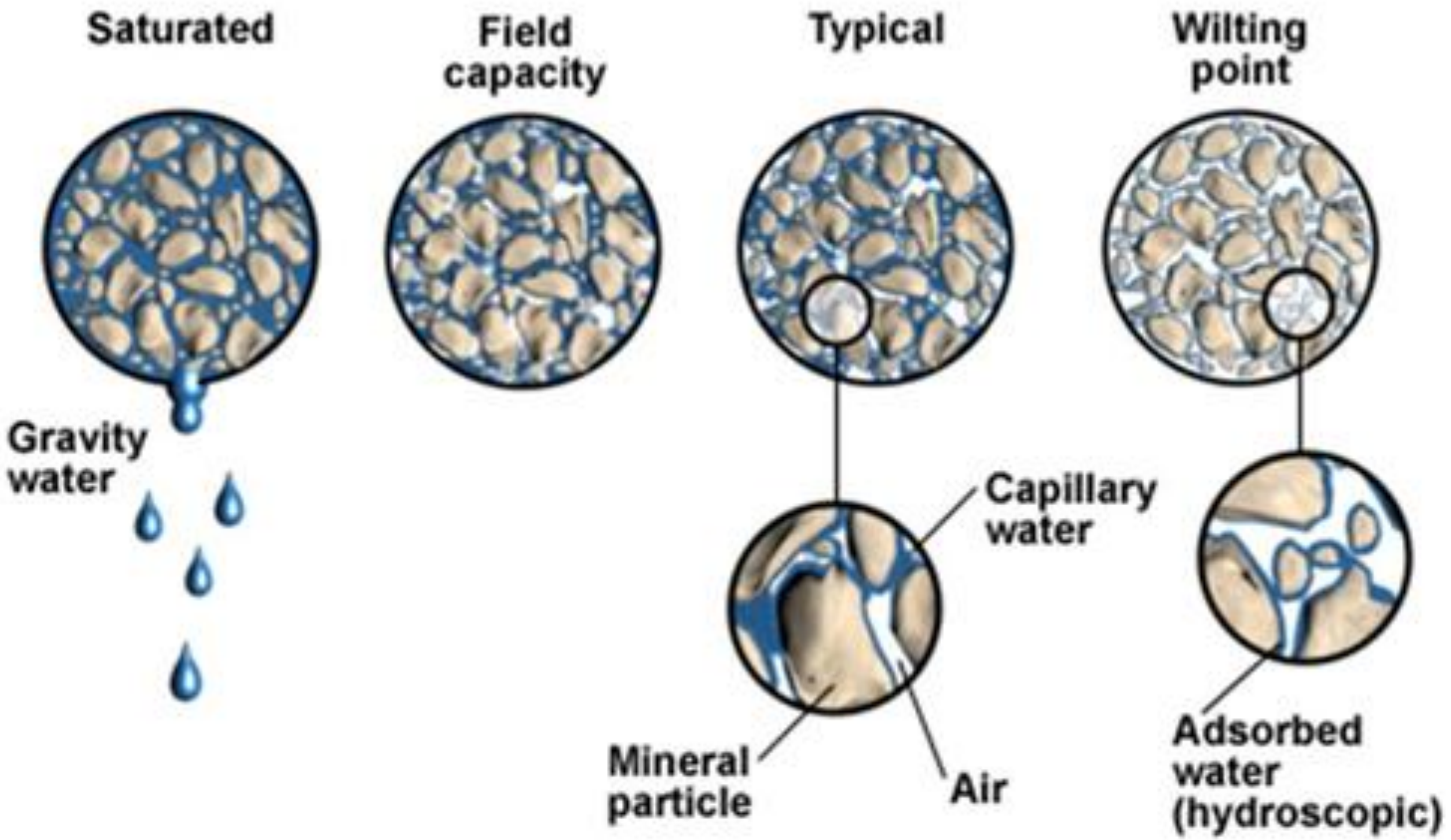
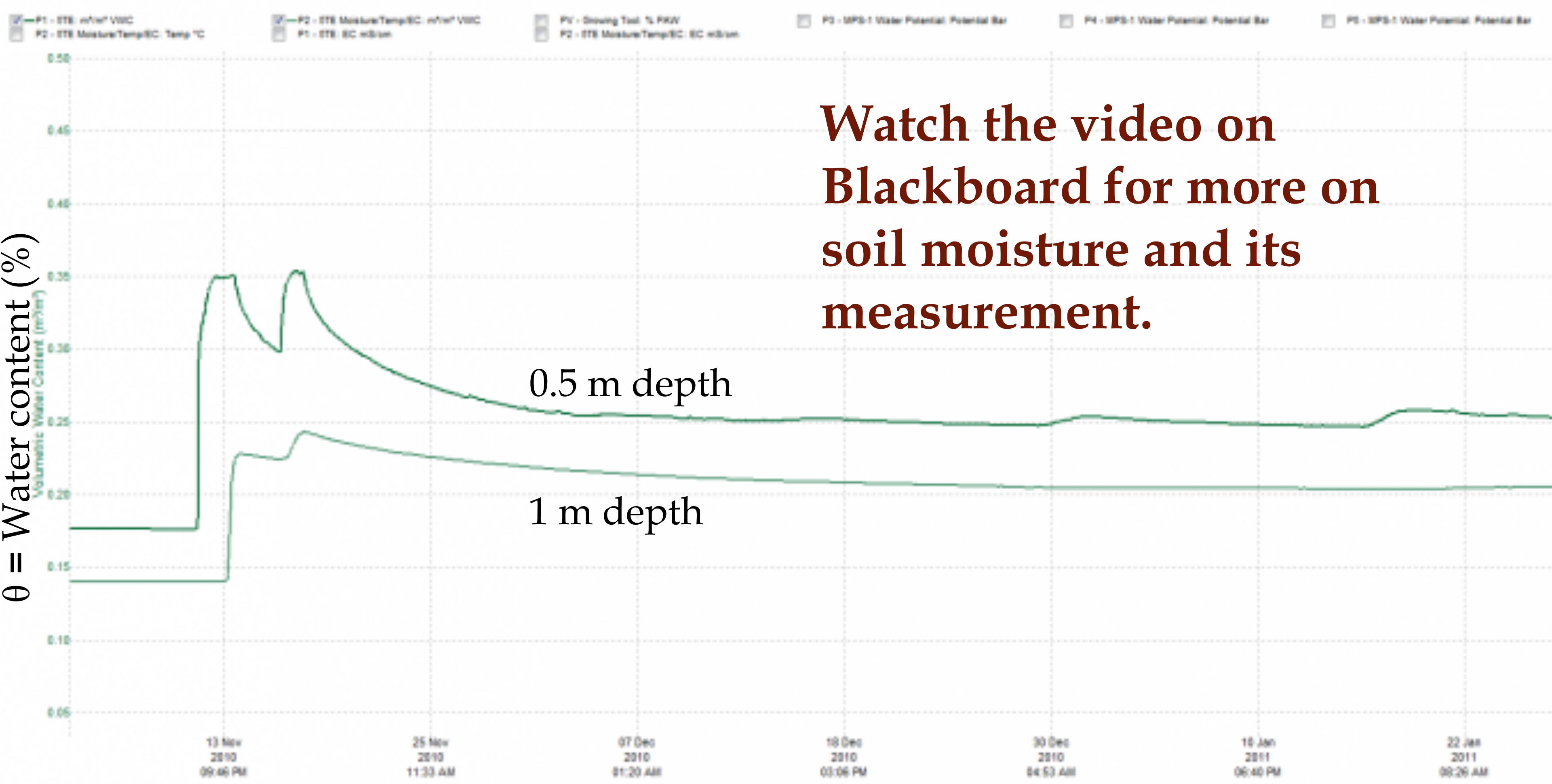
Water flow in soil



What does field capacity look like?

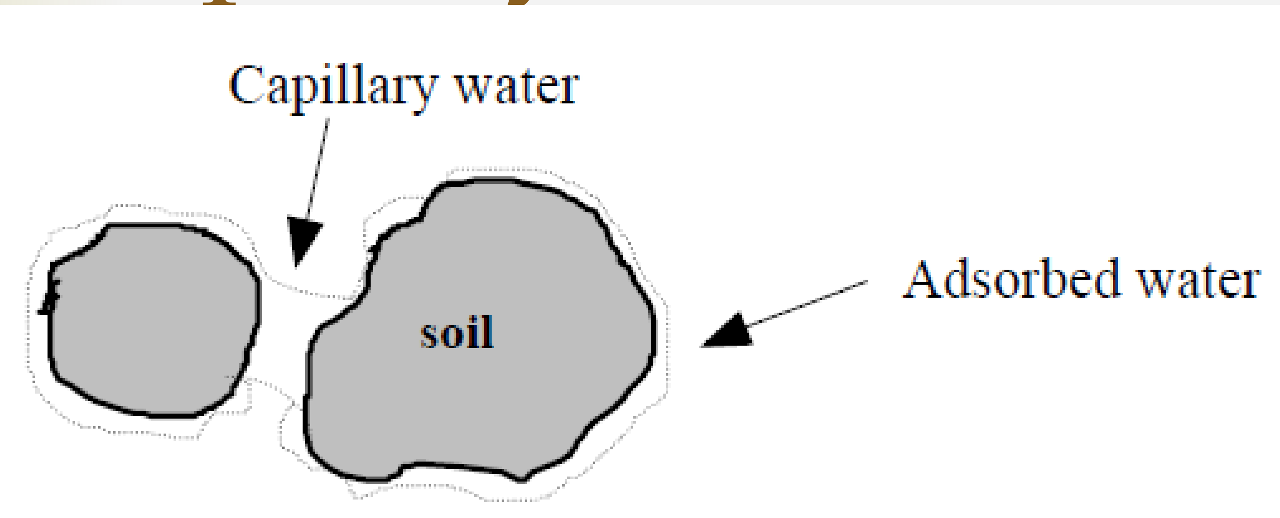


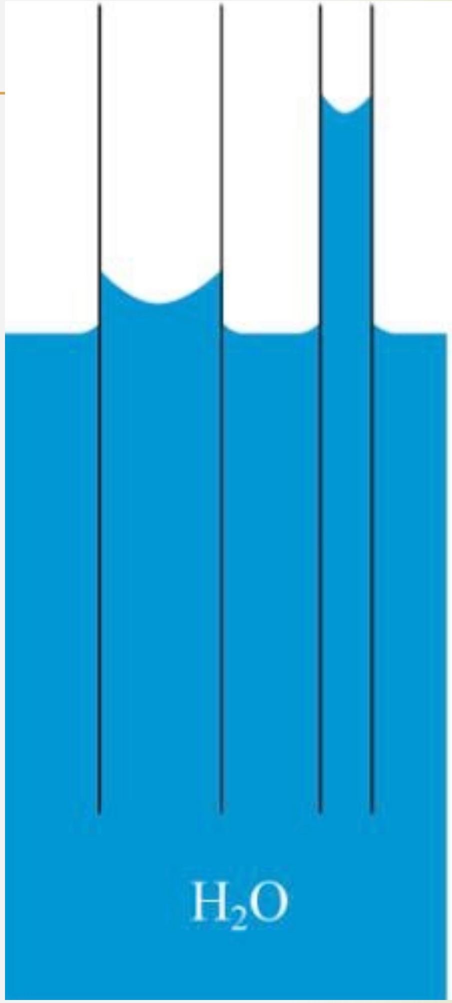
Watch the video on Blackboard for more on soil moisture and its measurement.

These data were collected in cool weather, not during the growing season. What would they look like if plants were growing?

http://www.decagon.com/support/datatrac-3-online-help-files/how-do-i-graph-plant-available-water/plant-available-water-how-do-i-determine-field-capacity-and-permanent-wilting-point/

Capillary and Adsorbed Water





- Adsorbed water is attracted to the soil surface by hydrogen bonds. It's tight and generally unavailable to plants.
- Capillary water is held in place by a balance between upper surface tension force and the downward force of the weight of the water. Smaller pores allow greater capillary rise.

Soil water potential
(potential is free energy and can be converted to do work)

- Potential = Force x Distance
  $= m*g*l = \rho_w*V*g*l$ (N*m)

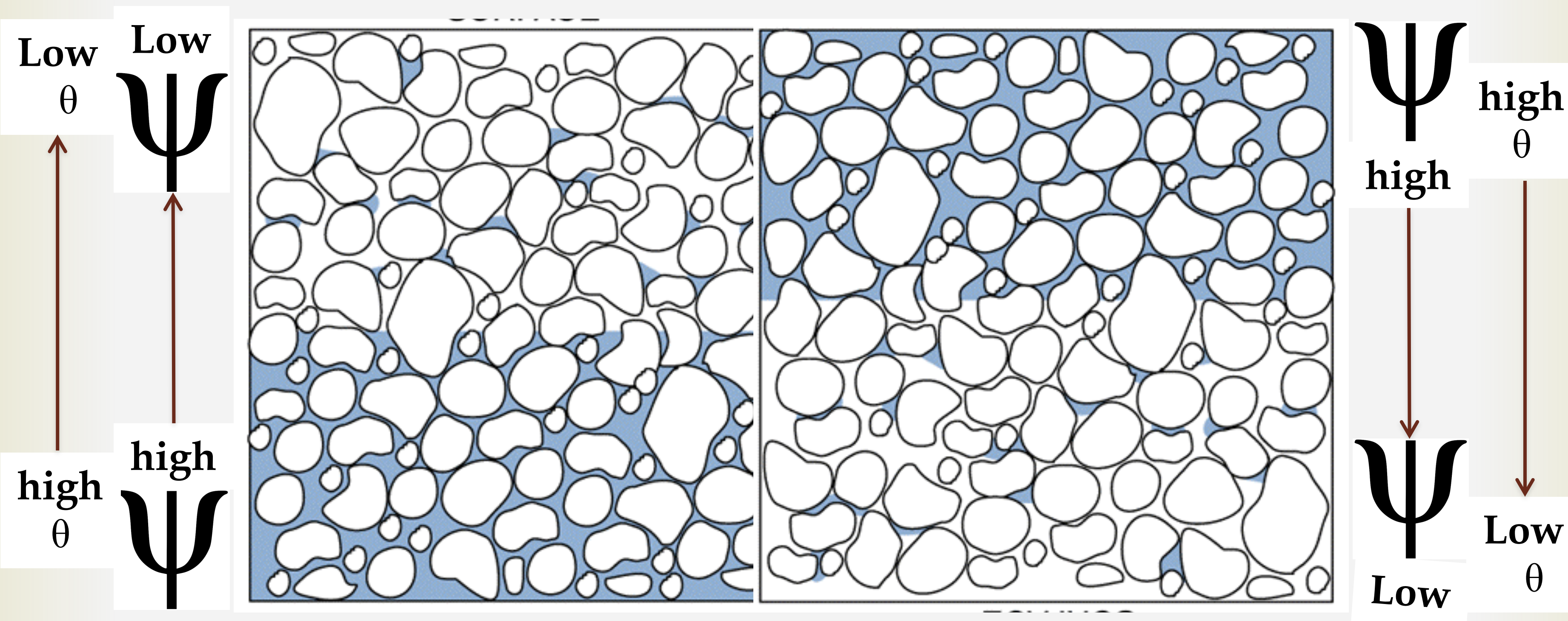
Usually expressed as:

- Potential per unit weight (h) = $m*g*l / m*g = l$ (m, head units, equivalent height of water)
- Potential per unit volume (ψ)= ρ_w*g*l (N/m^2, pressure units)
  - -33 kPa = field capacity, -1500 kPa = wilting point

Soil water potential:

$$\psi_s = \psi_m + \psi_g + \psi_p + \psi_o + \psi_t$$

- Water flows to lower potential (wetter to drier)

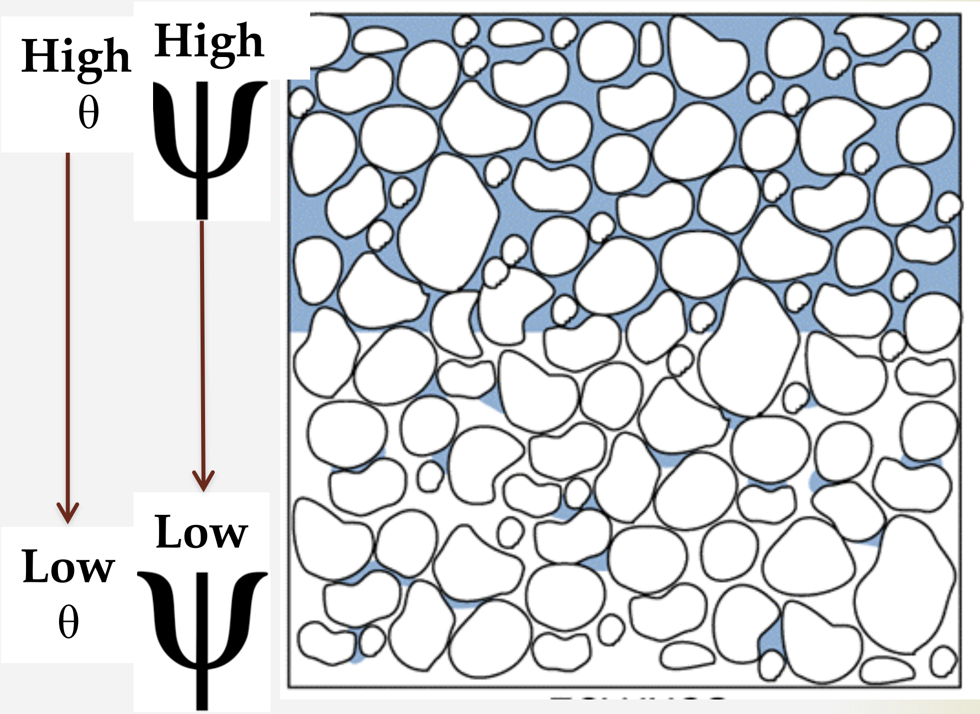


Evaporation Infiltration

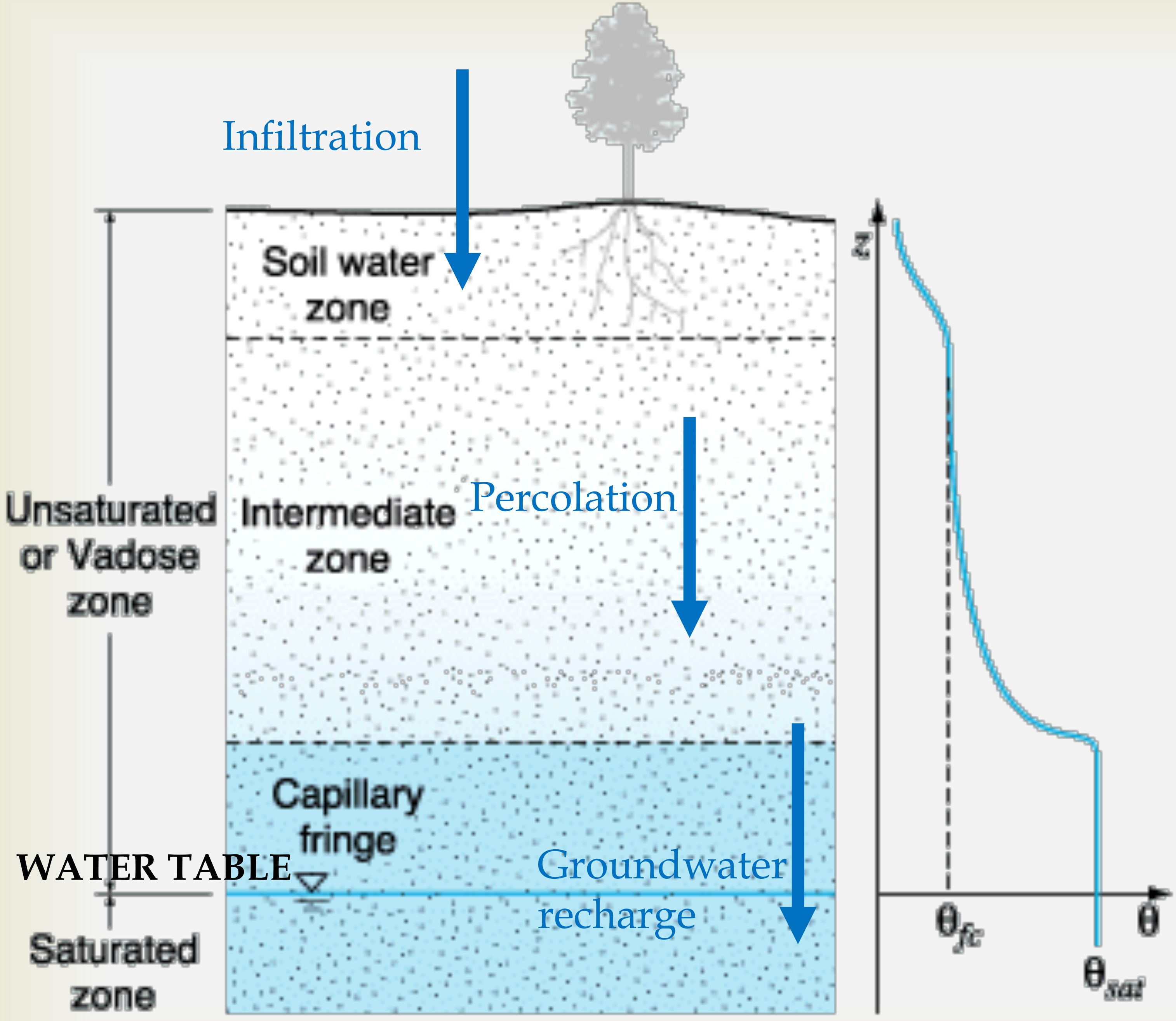
Soil water potential

$$\psi_s = \psi_m + \psi_g + \psi_p + \psi_o + \psi_t$$

- During and following rainfall, high potential exists above low potential → water infiltrates



Watch the video on Blackboard for more on water potential.



P < 0 in capillary fringe

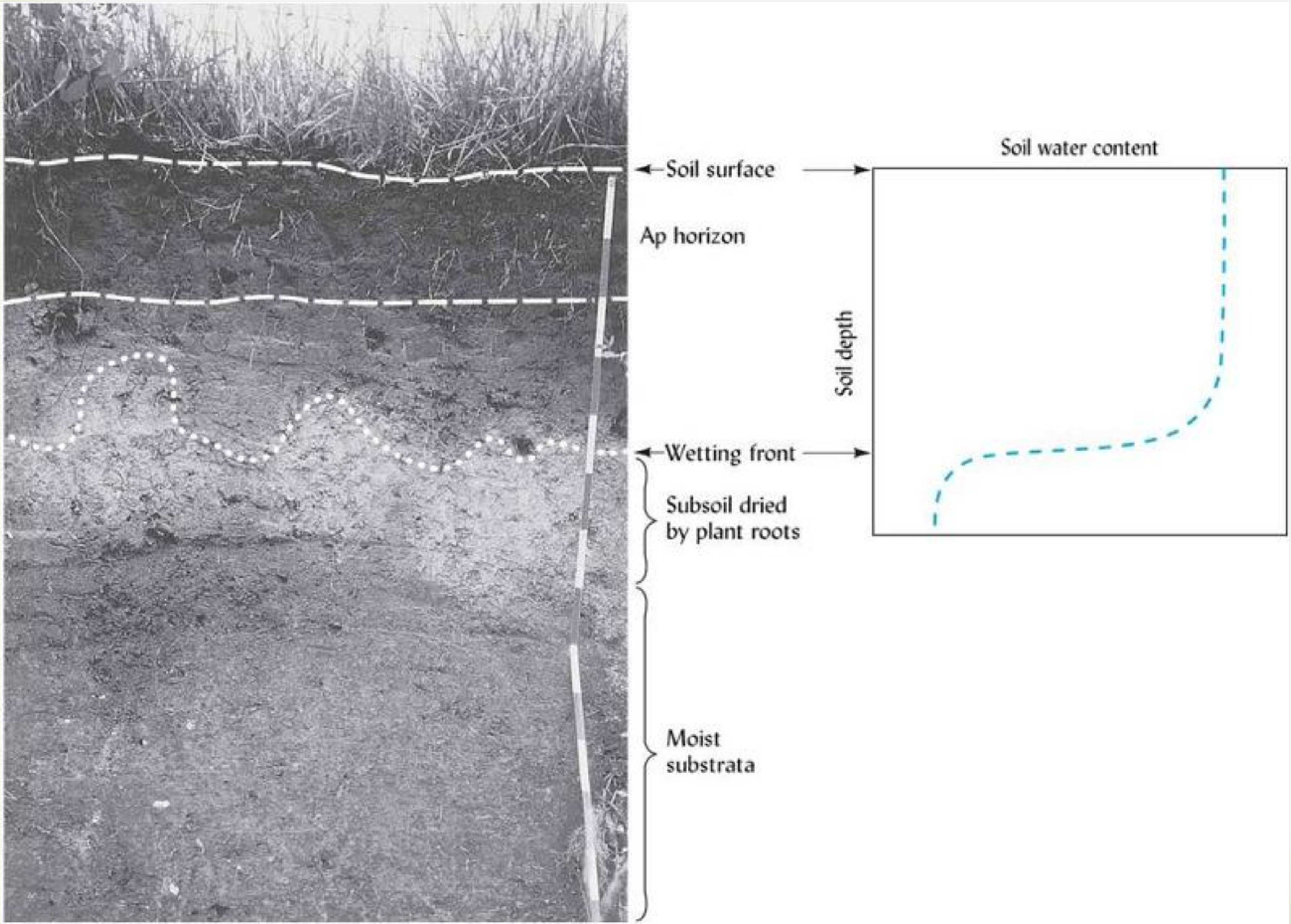
P > 0 below water table

https://www.ldeo.columbia.edu/~martins/hydro/eph/EPH/CHAP8A.HTM

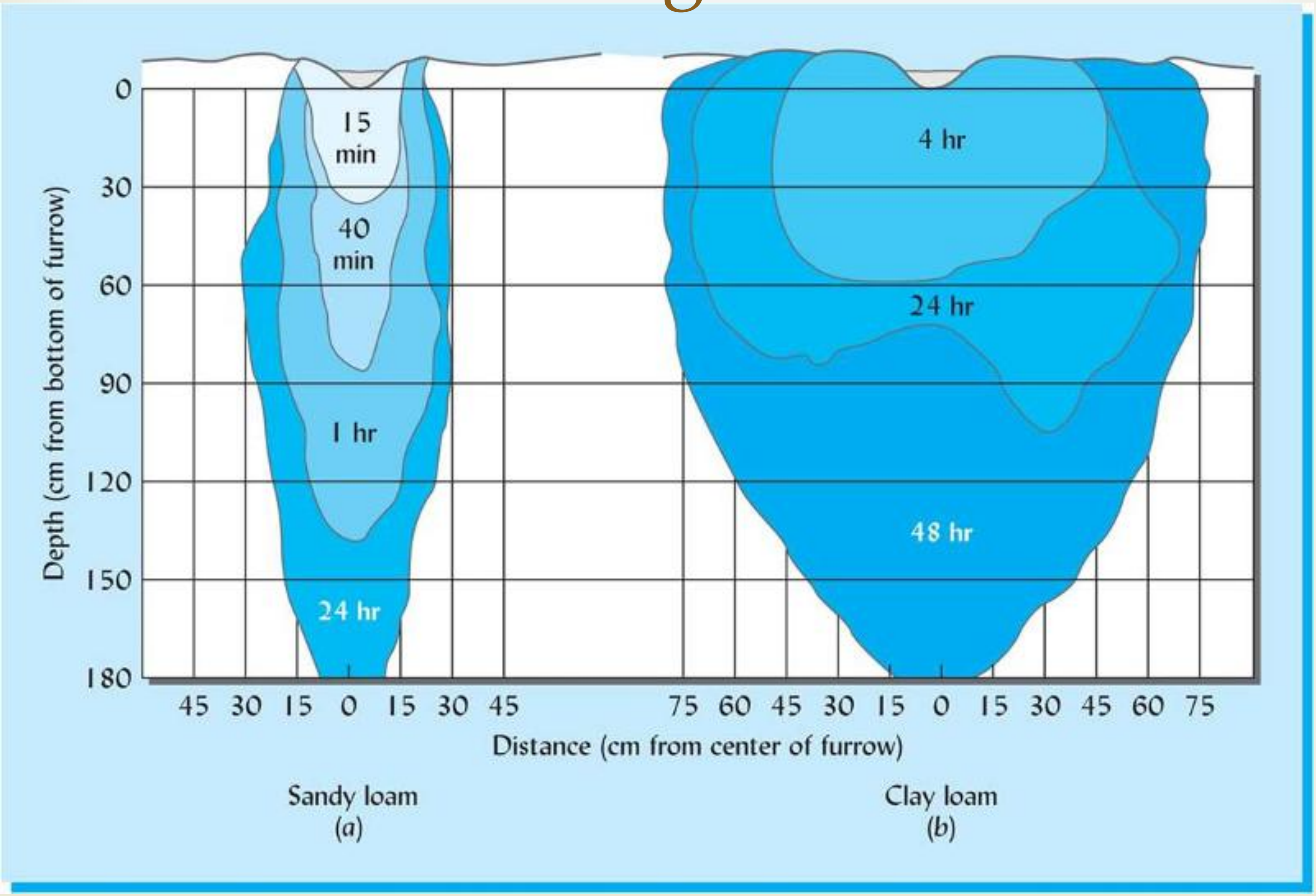
Infiltration: Water enters soil, from gravitational and capillary forces, through pores

What does infiltration look like?

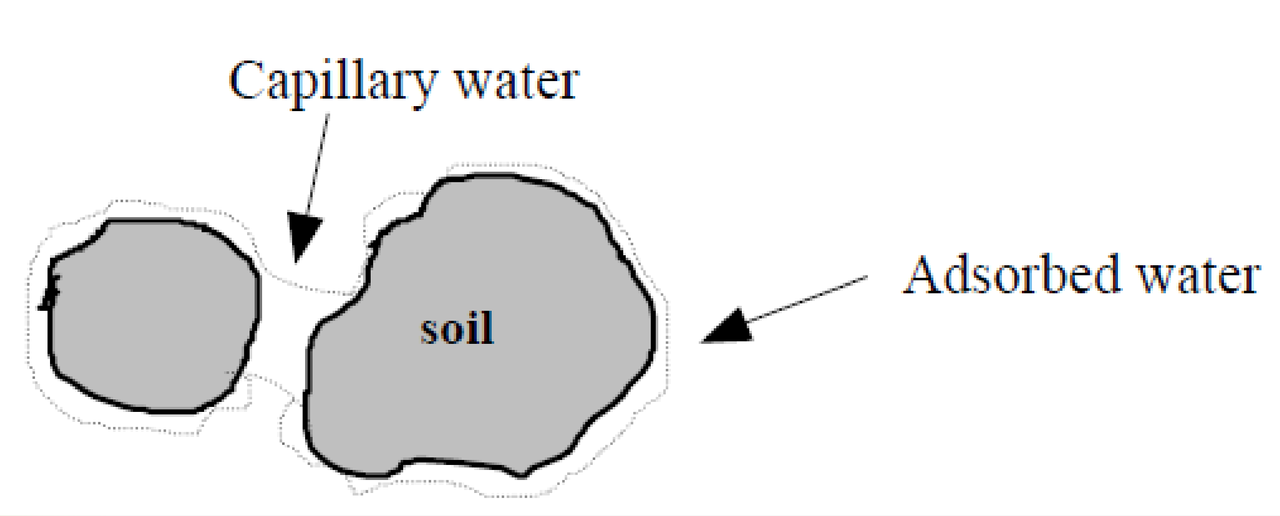
Wetting Front

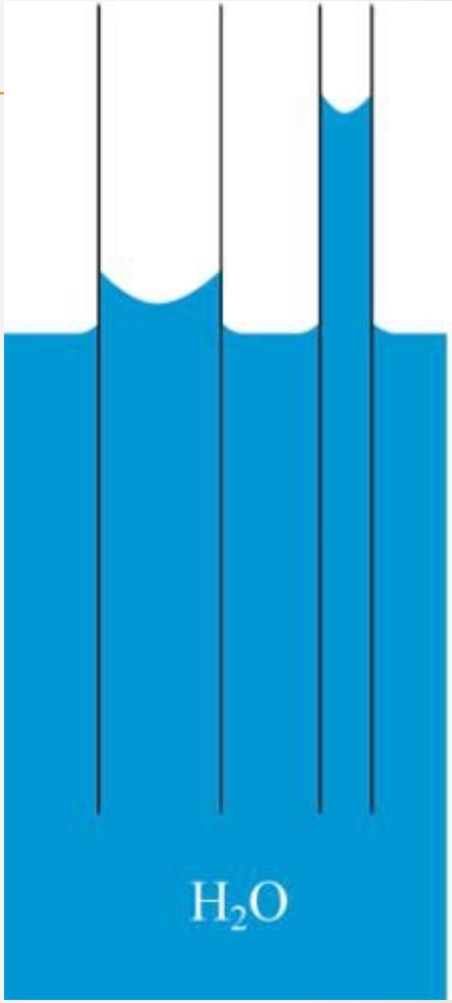


Soil texture affects rate and shape of wetting front.



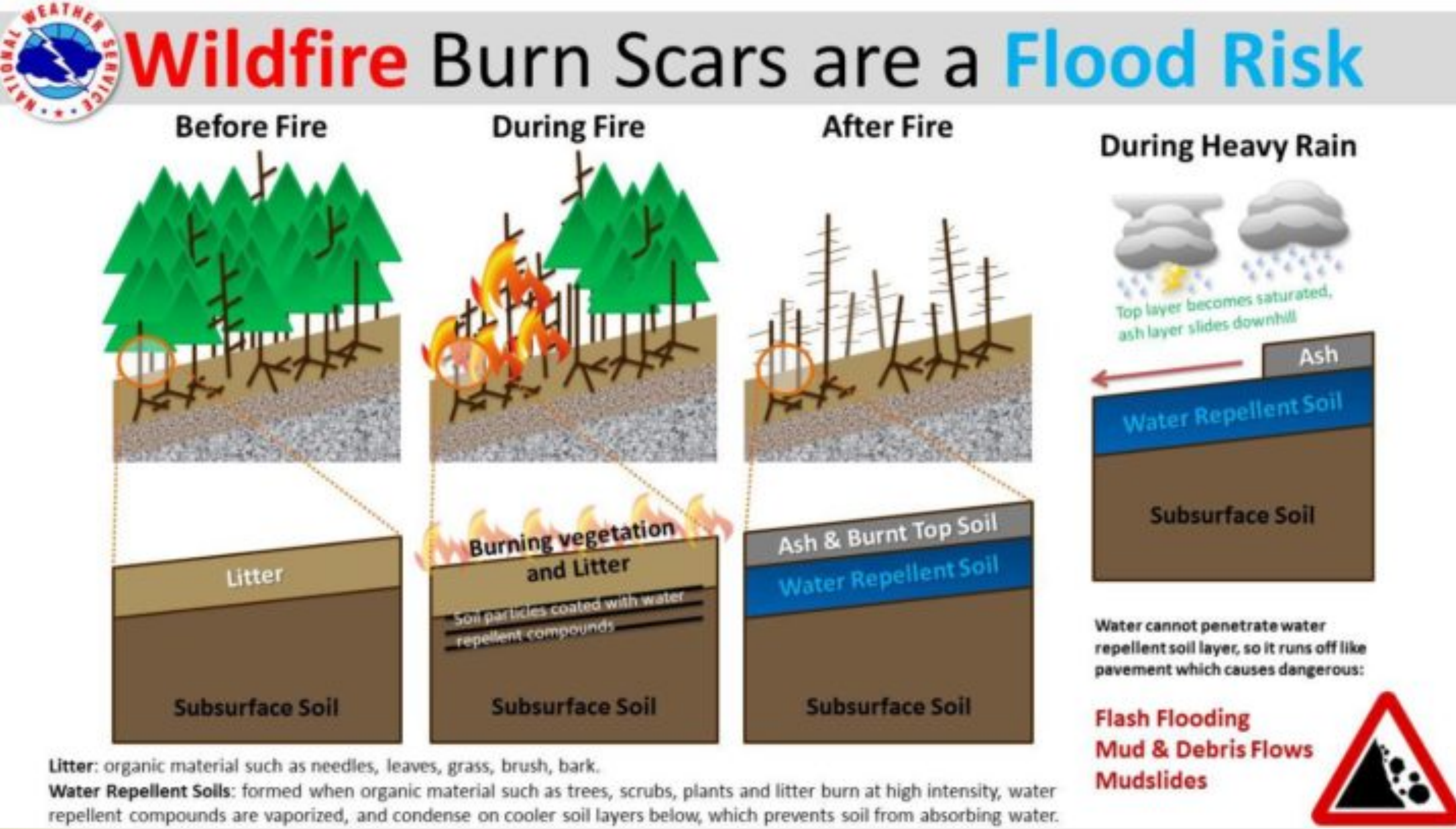
Capillary and Adsorbed Water



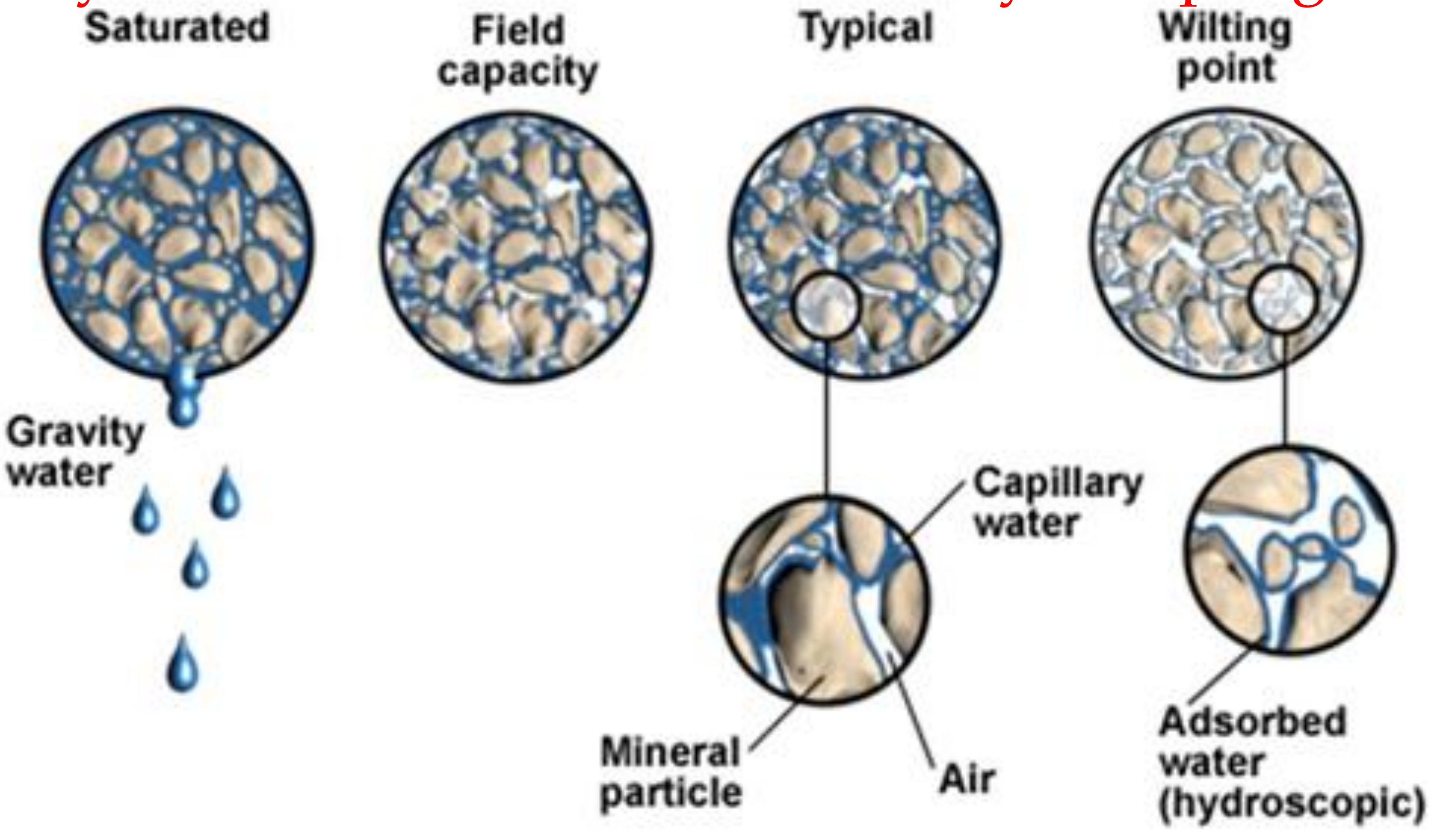


- Adsorbed water is attracted to the soil surface by hydrogen bonds. It's tight and generally unavailable to plants.
- Capillary water is held in place by a balance between upper surface tension force and the downward force of the weight of the water. Smaller pores allow greater capillary rise.

Hydrophobic soils repel water

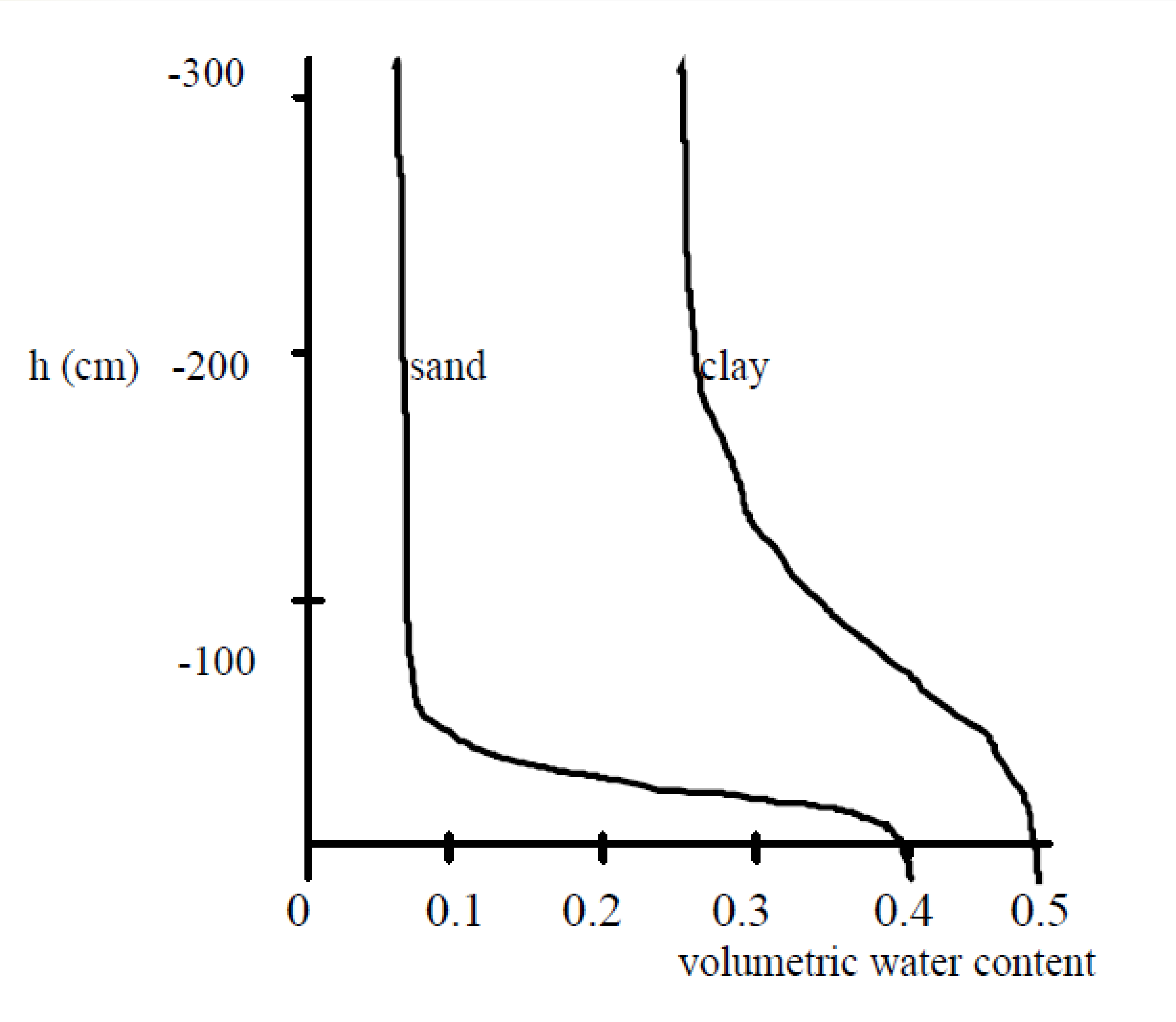

Wildfire Burn Scars are a Flood Risk
Before Fire
During Fire
After Fire
During Heavy Rain
Top layer becomes saturated, ash layer slides downhill
Ash
Water Repellent Soil
Subsurface Soil
Litter
Subsurface Soil
Burning vegetation and Litter
Soil particles coated with water repellent compounds
Subsurface Soil
Ash & Burnt Top Soil
Water Repellent Soil
Subsurface Soil
Water cannot penetrate water repellent soil layer, so it runs off like pavement which causes dangerous:
Flash Flooding
Mud & Debris Flows
Mudslides
Litter: organic material such as needles, leaves, grass, brush, bark.
Water Repellent Soils: formed when organic material such as trees, scrubs, plants and litter burn at high intensity, water repellent compounds are vaporized, and condense on cooler soil layers below, which prevents soil from absorbing water.

Can you simulate each of these with your sponges?



1. Let sponge drain to field capacity held horizontally.
2. Rotate it to short vertical axis.
3. Rotate it to long vertical axis.

Soil water characteristic curve



- Describes relationship between soil water potential (h) and volumetric water content (θ)
- Function of the pore size distribution

http://lawr.ucdavis.edu/classes/ssc107/SSC107Syllabus/chapter2-00.pdf

From sponges to cities to "sponge cities"

https://cities-today.com/sponge-cities-can-chinas-model-go-global/

Infiltration: Water enters soil, from gravitational and capillary forces, through pores

- Infiltration rate = how fast water is entering a soil
- Infiltration capacity = maximum rate at which water can enter a soil, under the given conditions.
- Hydraulic conductivity = ease with which a fluid moves through a porous medium
  - Saturated hydraulic conductivity ~ Equilibrium infiltration capacity
  - Saturated hydraulic conductivity is > unsaturated hydraulic conductivity.

Infiltration capacity is a function of:

- Soil texture and structure → **hydraulic conductivity**
- Soil colloids and organic content → adsorb water
- Surface conditions
- Depth to impermeable layer
- Macropores

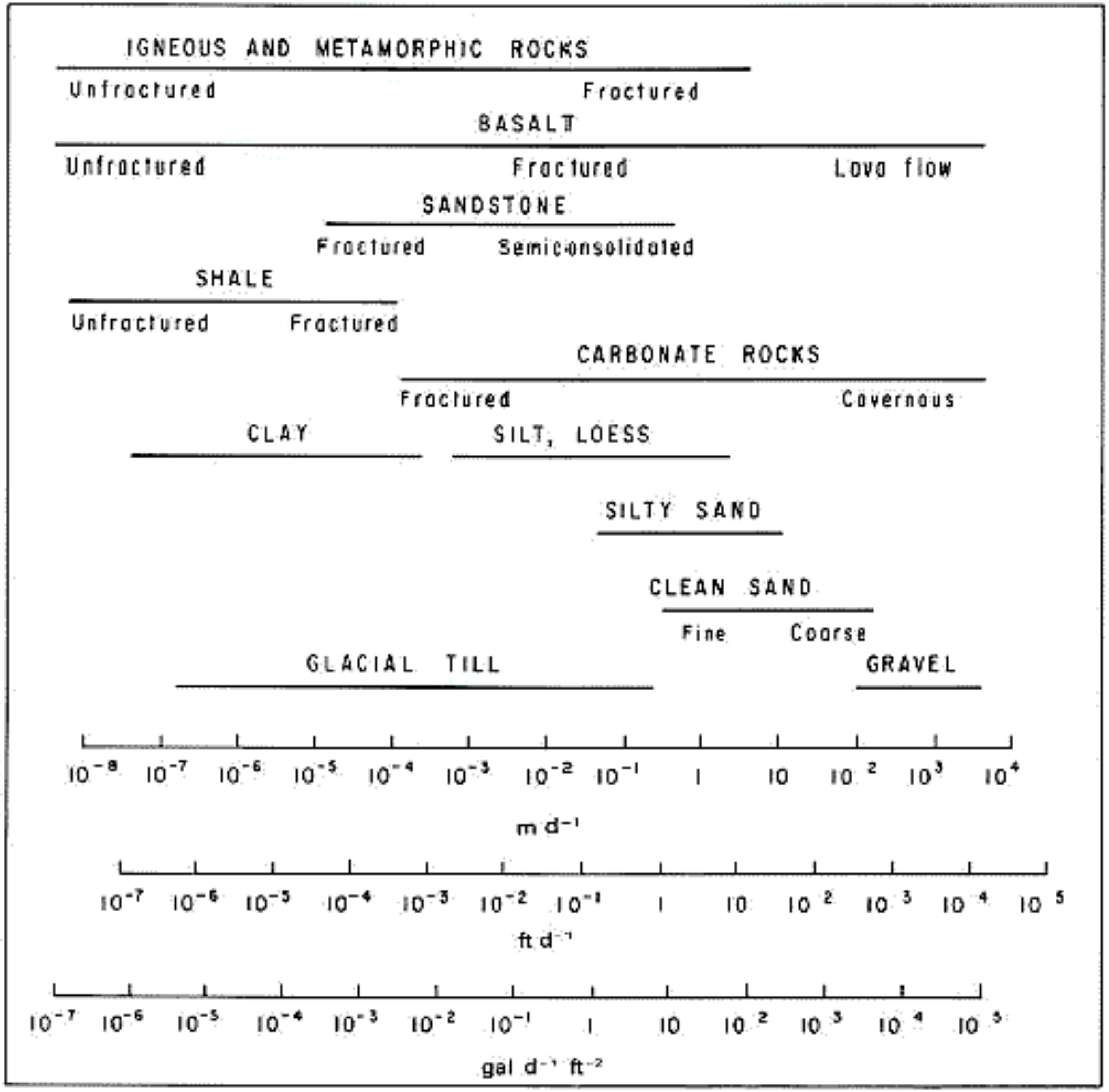
Hydraulic conductivity and Darcy's Law

- Describes flow under saturated conditions
- q = water flow rate [L/T]
- K = hydraulic conductivity = ease of water movement through soil/rock [L/T]
- h = hydraulic head = way of representing potential in terms of [L]
- dh/dx = hydraulic gradient [-]

$$q = -K\frac{dh}{dx}$$

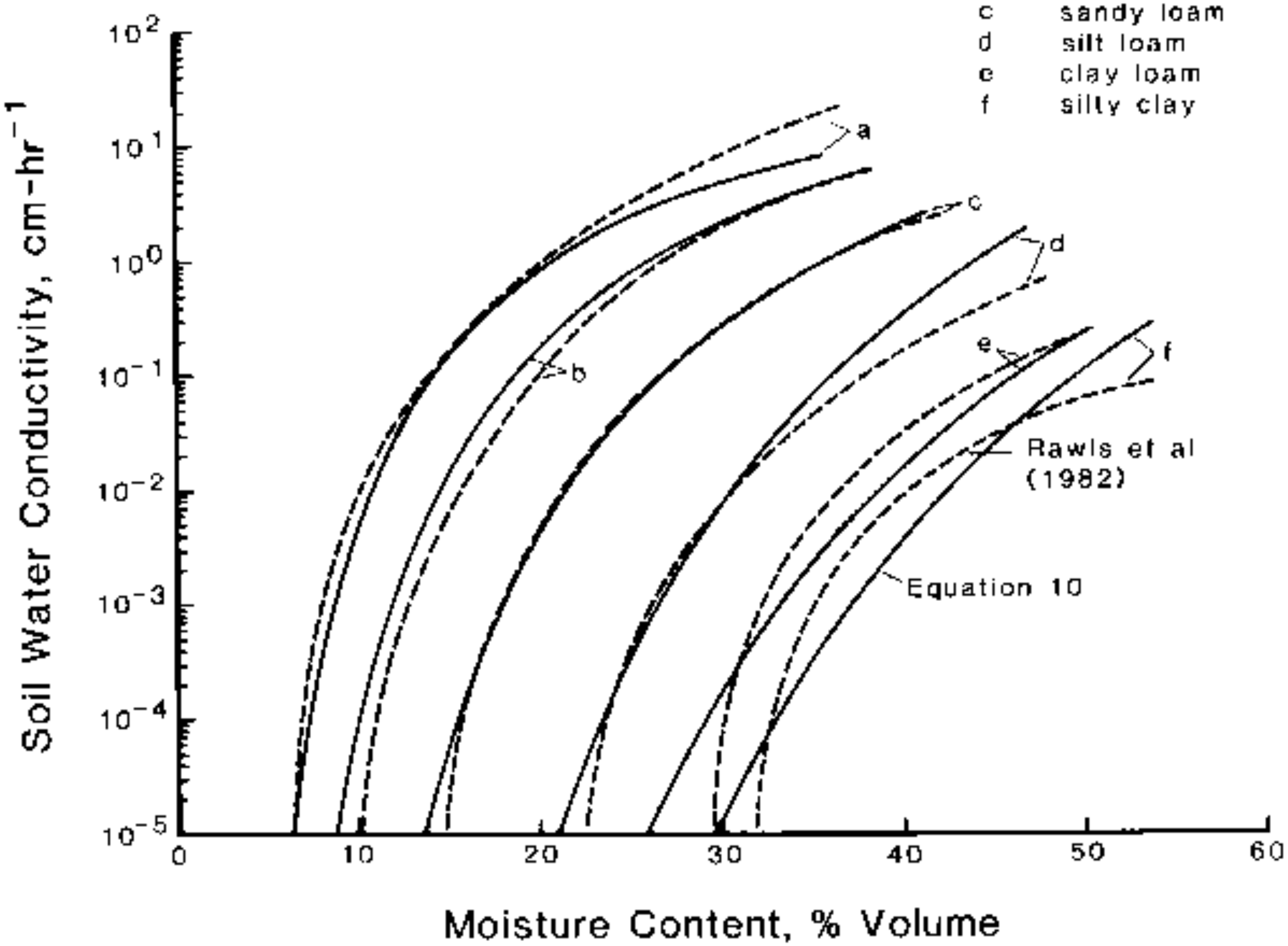
K = is f() of porosity, pore size, and connectedness + water density, viscosity

Hydraulic Conductivity



http://www.aqtesolv.com/aquifer-tests/aquifer_properties.htm

When unsaturated, hydraulic conductivity is a function of pores and water content.

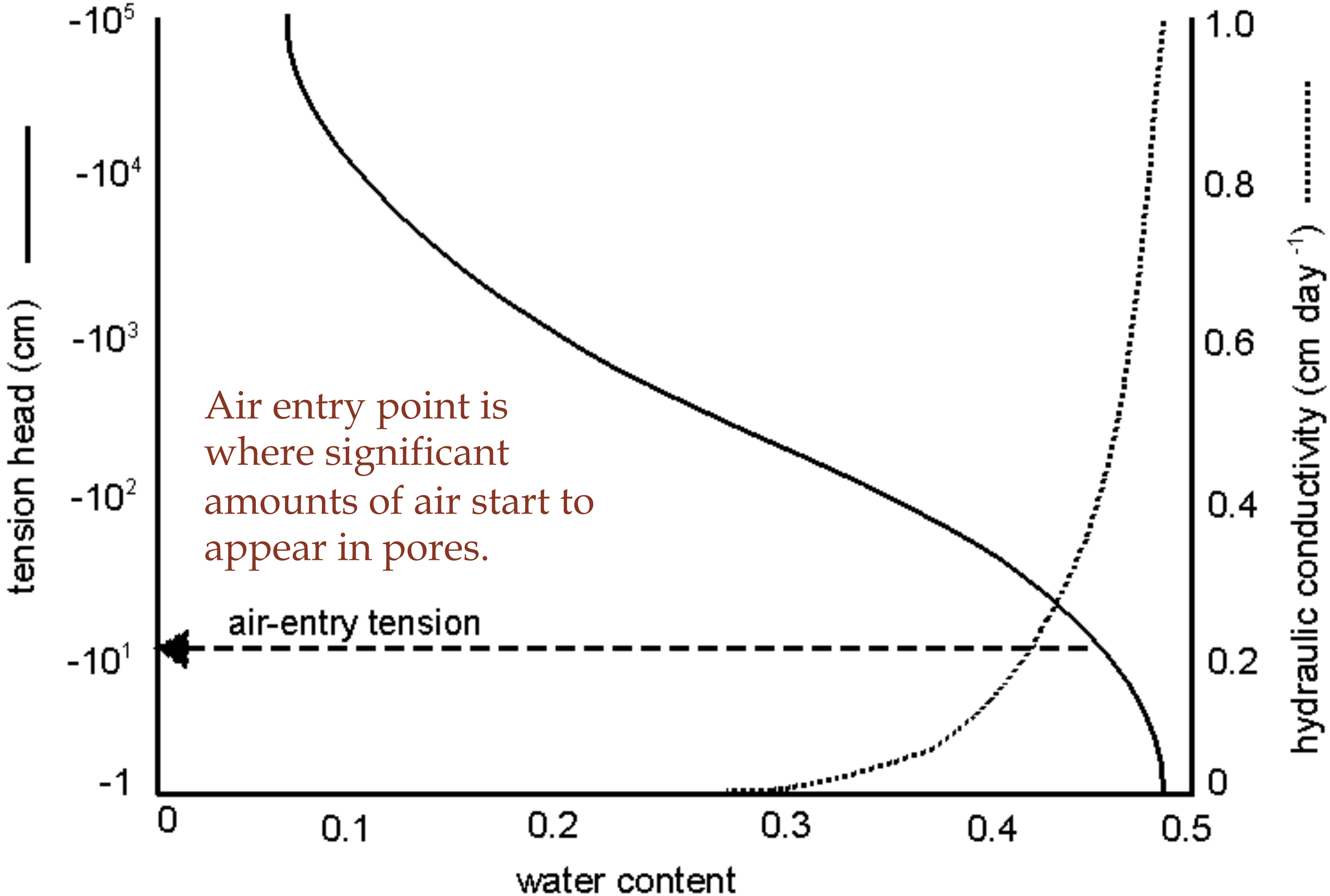


Curve	Texture	% Sand	% Clay
a	sand	92	5
b	loamy sand	82	6
c	sandy loam	65	10
d	silt loam	20	15
e	clay loam	35	35
f	silty clay	8	45

Saxton et al., 1986, Esimating generalized soil-water characteristics from texture. SSSAJ

Water content, tension, and hydraulic conductivity

Tension head is another way of talking about **matric potential.**



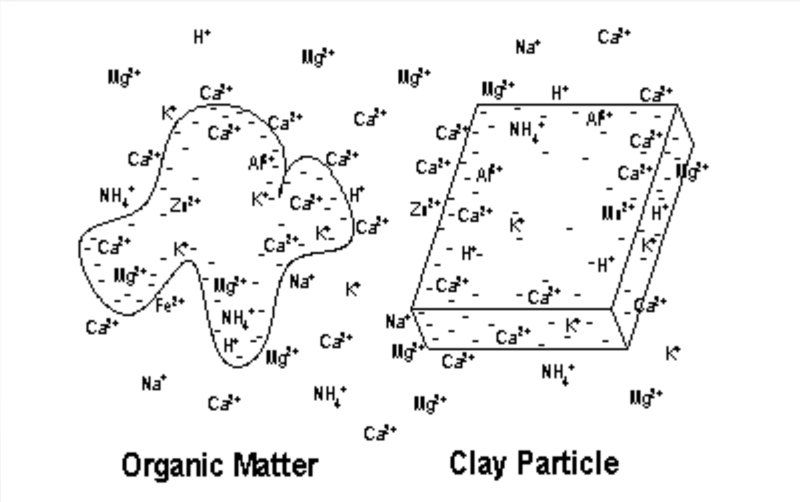
Air entry point is where significant amounts of air start to appear in pores.

Infiltration capacity is a function of:

- Soil texture and structure → hydraulic conductivity
- **Soil colloids and organic content → adsorb water**
- Surface conditions
- Depth to impermeable layer
- Macropores

Soil colloids determine physical and chemical properties of soil.

- <0.001 mm in size
- *Inorganic colloids* include some clay minerals, hydrous oxides
- *Organic colloids* include humus (highly decomposed organic matter), very chemically reactive
- Colloids adsorb, hold and release ions → cation exchange capacity.

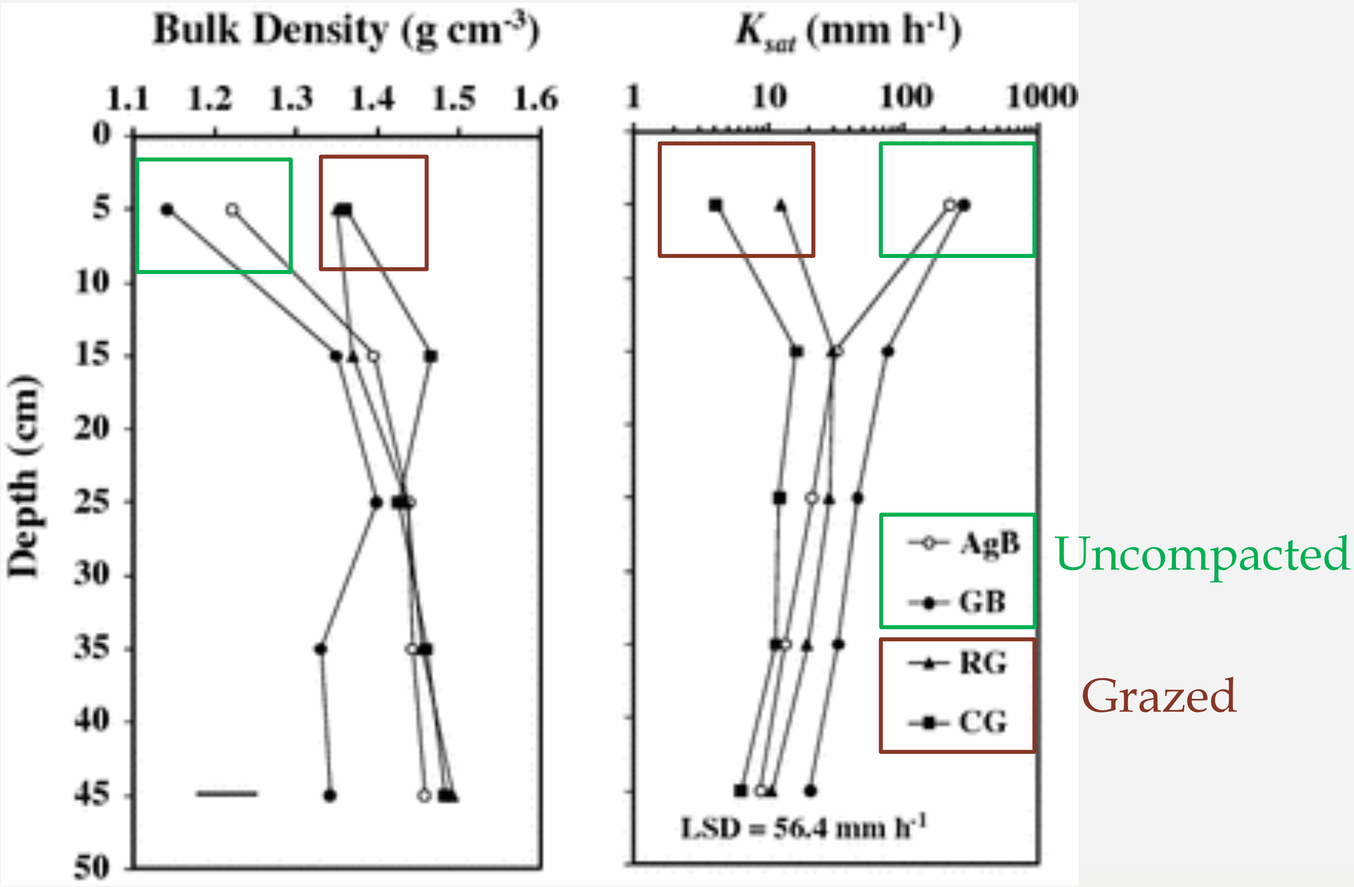


Colloids have negative surface charge.
→ Attract swarms of cations.
→ Water hydrates the cations and is adsorbed.

Infiltration capacity is a function of:

- Soil texture and structure → hydraulic conductivity
- Soil colloids and organic content → adsorb water
- **Surface conditions**
- **Depth to impermeable layer**
- **Macropores**

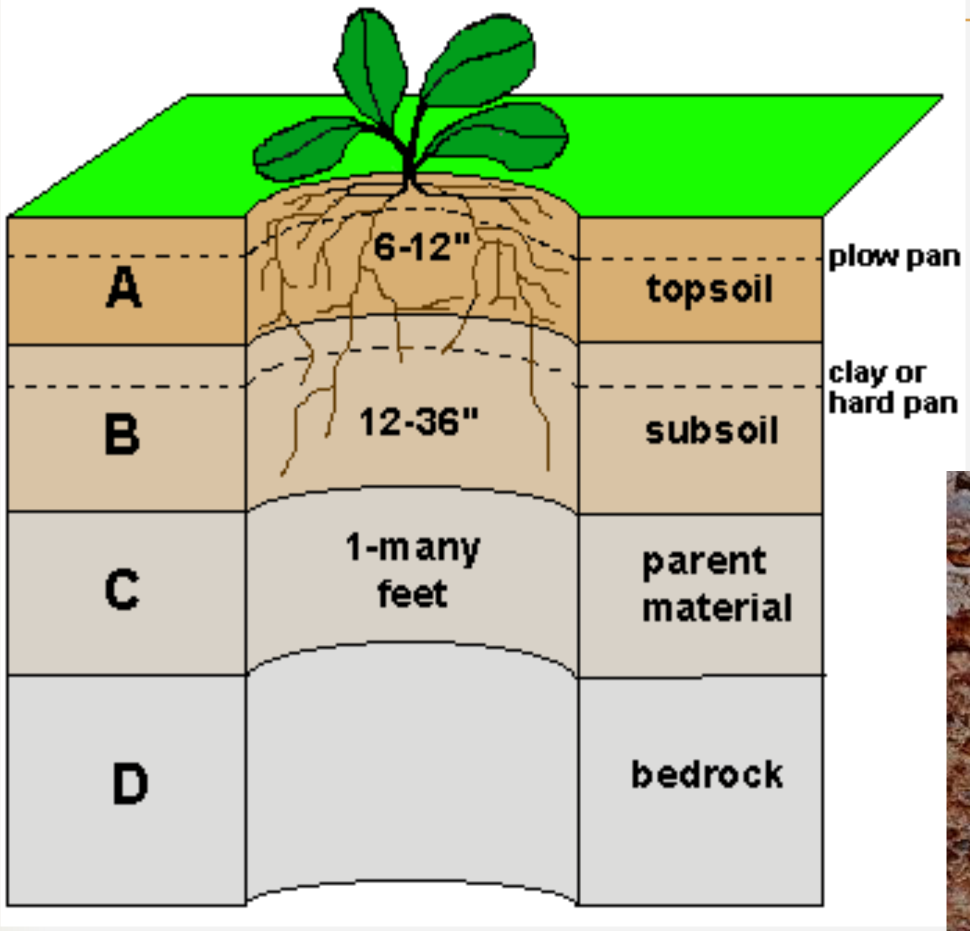
Soil bulk density increases and hydraulic conductivity decreases with depth



Kumar, S., Anderson, S. H., Udawatta, R. P., & Gantzer, C. J. (2010). CT-measured macropores as affected by agroforestry and grass buffers for grazed pasture systems. Agroforestry systems, 79(1), 59-65.

Depth to impermeable layer

- Bedrock
- Caliche
- Hard pan
- Clay



Macropores

Photo by Jud Harvey (USGS)

http://www.ars.usda.gov/Main/docs.htm?docid=19100

Video: https://youtu.be/PYbr3UgE410

Wetting fronts with macropores

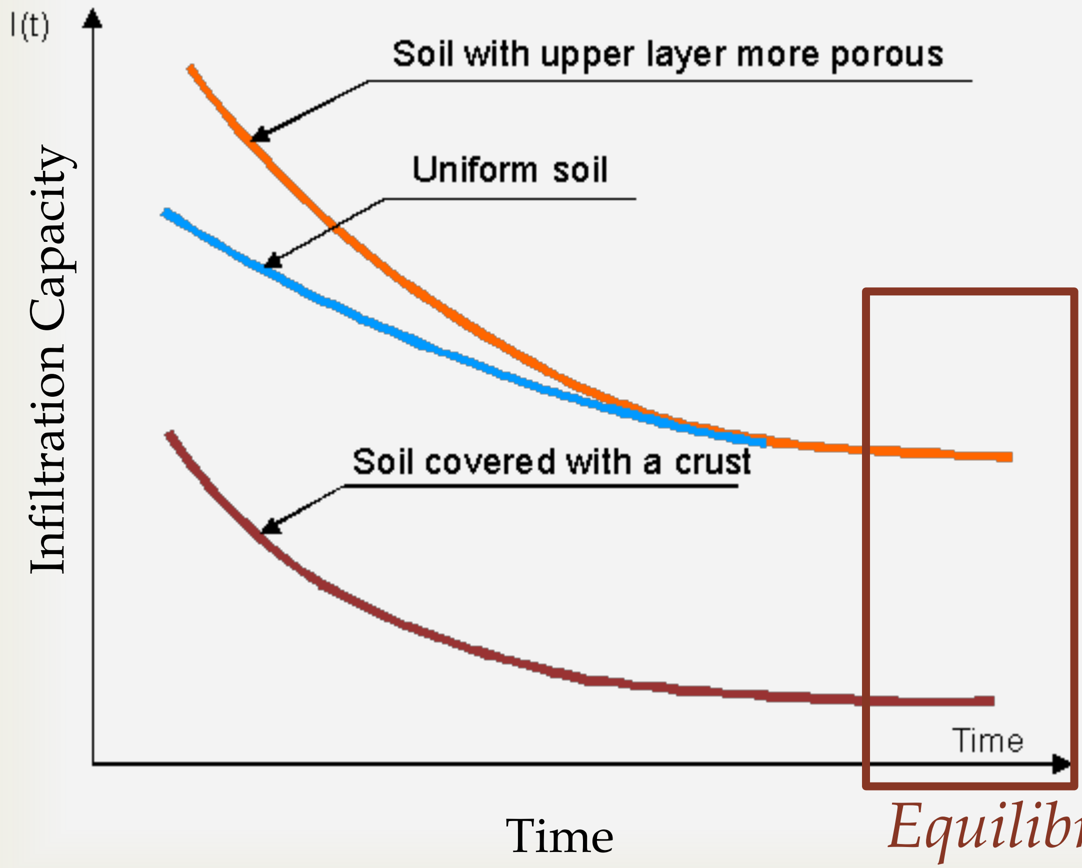
http://soilandwater.bee.cornell.edu/Research/pfweb/educators/intro/macroflow.htm

Infiltration capacity is a function of:

- Soil texture and structure → hydraulic conductivity
- Soil colloids and organic content → adsorb water
- Surface conditions
- Depth to impermeable layer
- Macropores

Infiltration capacity = maximum rate at which water can enter a soil, **under the given conditions.**

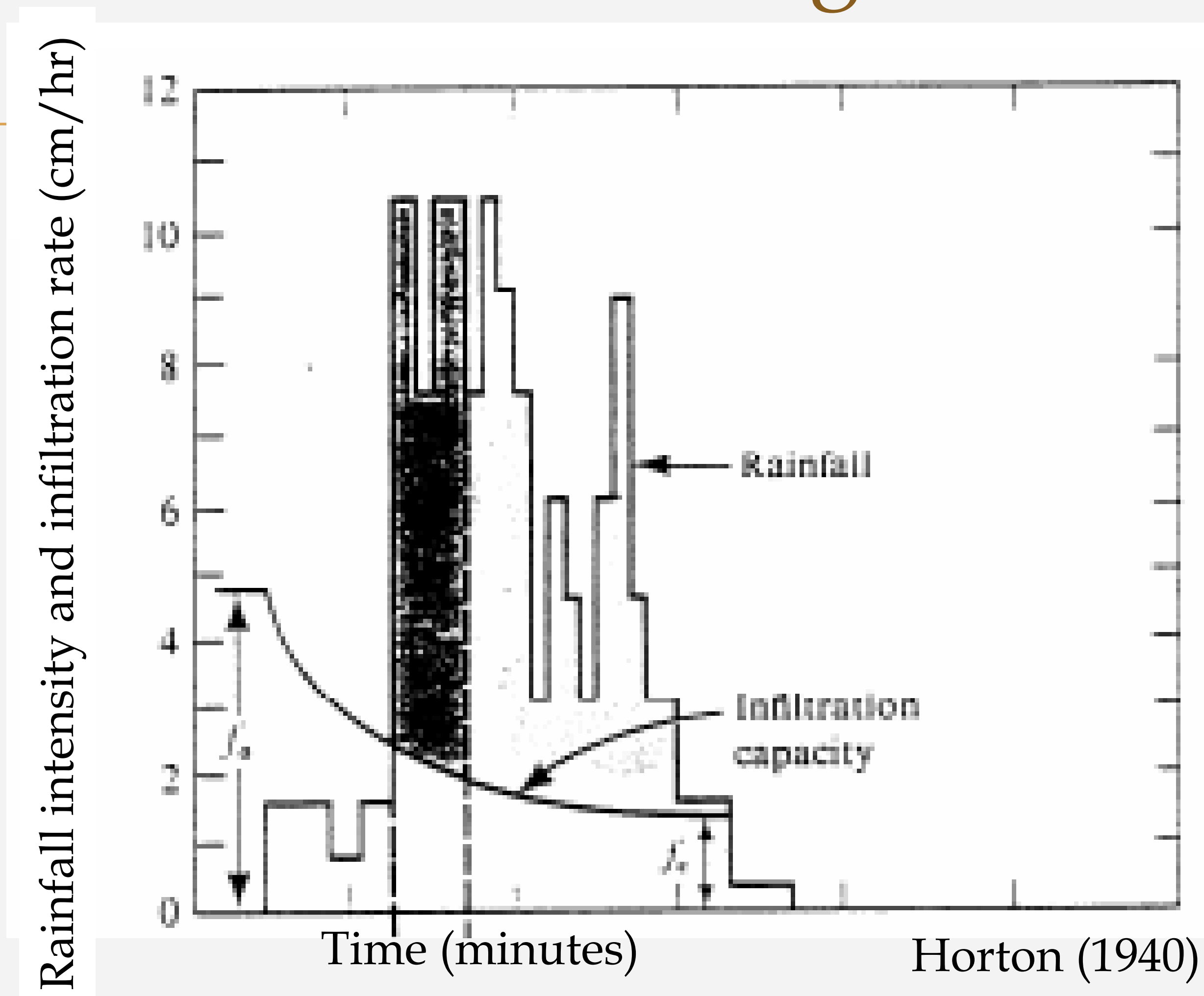
Infiltration capacity decreases over time



- At surface, soil colloids swell, rain splash seals surface, air gets entrapped.
- Soil pores fill with water, reducing matric potential
- Hydraulic gradient decreases
  - This will lead us to Green-Ampt Eqn.

Equilibrium infiltration capacity = rate at steady state

Infiltration capacity can determine whether overland flow* is generated.

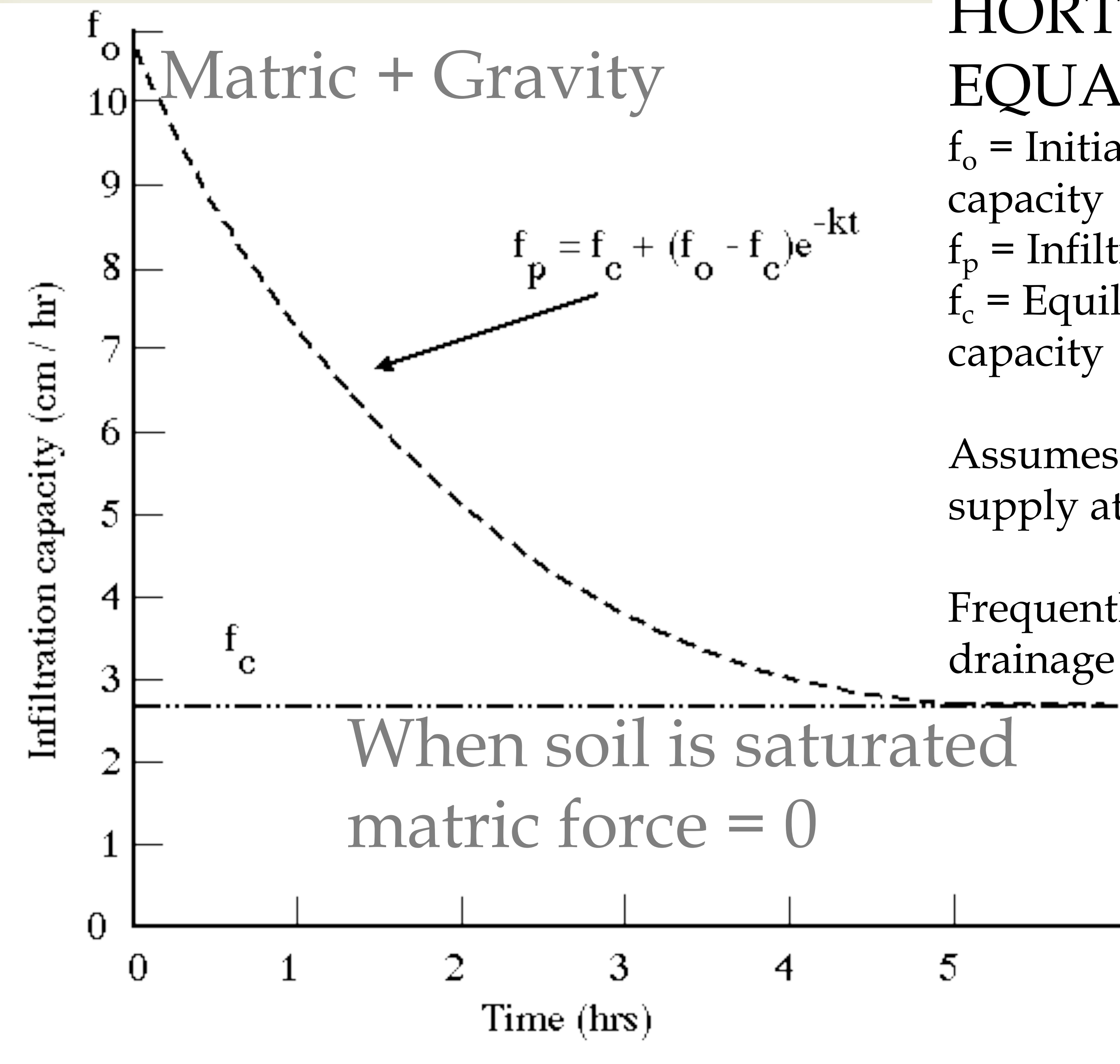


Horton (1940)

*We call this Horton or infiltration-excess overland flow

Equations for Infiltration

- Horton Equation – infiltration capacity decreases over time (negative exponential)
  - Easy to calculate, but over-simplified, not physically based
- Green-Ampt – assumes sharp wetting front
  - Requires K, porosity, wetting front matric potential
  - Somewhat simplified, but physically based, and can be solved
- Richard's equation – derived from Darcy's law and conservation of mass,
  - physically based, not always solvable analytically (partial differential equation)



HORTON EQUATION:

f_o = Initial infiltration capacity
f_p = Infiltration capacity
f_c = Equilibrium infiltration capacity

Assumes an infinite water supply at surface

Frequently used in urban drainage models

Richard's Equation

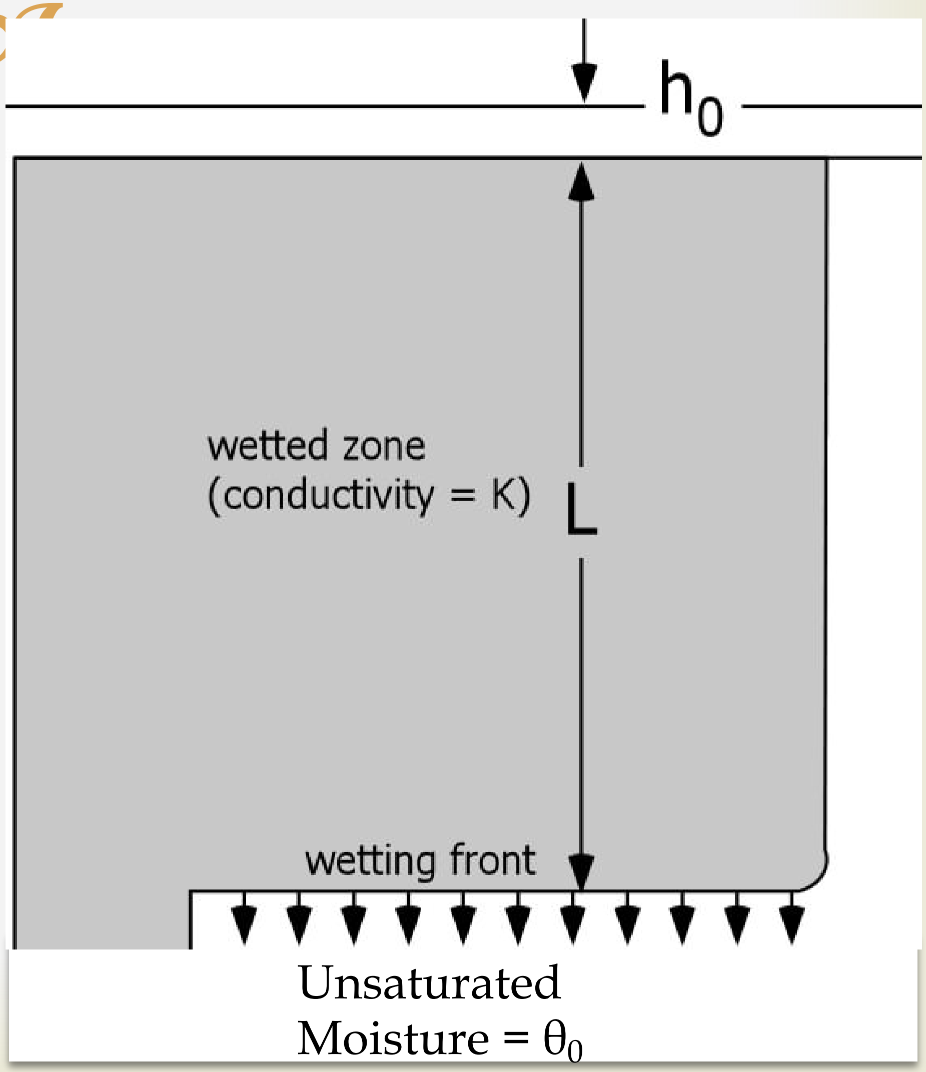
$$\frac{\partial \theta}{\partial t} = -\frac{\partial}{\partial x}\left[K(\theta)\frac{\partial \psi}{\partial x}\right]$$

$$\frac{\partial \theta}{\partial t} = -\frac{\partial}{\partial x}\left[K_x(\theta)\frac{\partial \psi}{\partial x}\right] - \frac{\partial}{\partial y}\left[K_y(\theta)\frac{\partial \psi}{\partial y}\right] - \frac{\partial}{\partial z}\left[K_z(\theta)\frac{\partial \psi}{\partial z}\right]$$

- This can only be solved analytically for special cases, otherwise needs to be solved iteratively.
- One tricky part is relating K and θ to ψ for a soil (characteristic curve).
- Green-Ampt simplifies by assuming a sharp wetting front, so only need 1 value of K, θ, and ψ.

If K increases as you move from unsaturated to saturated, why does infiltration capacity decrease over time?

- At top of soil column, everything is pretty much saturated very quickly. (thanks wetting front!)
- But the wetting front keeps moving deeper so the potential gradient keeps getting smaller.



Green-Ampt Part 1

$$q = -K \frac{dh}{dx}$$

- Remember Darcy's Law?
- Now Let's make q into f for infiltration rate and get rid of the derivatives

$$f = K \frac{h_1 - h_2}{z_1 - z_2} = K \frac{h_1 - h_2}{0 - -L} = K \frac{h_1 - h_2}{L}$$

- Where the subscript "1" means at the surface, and "2" means just on the dry side of the wetted front.
- At the surface, $z1=0$, and at the wetted front, $z2=-L$

Green-Ampt – Part 2

- h_1: At surface, head is only affected by pressure of ponded water. We call this h_0.
- h_2: At wetting front, head is from pressure of overlying water (-L) and capillary suction (-ψ).

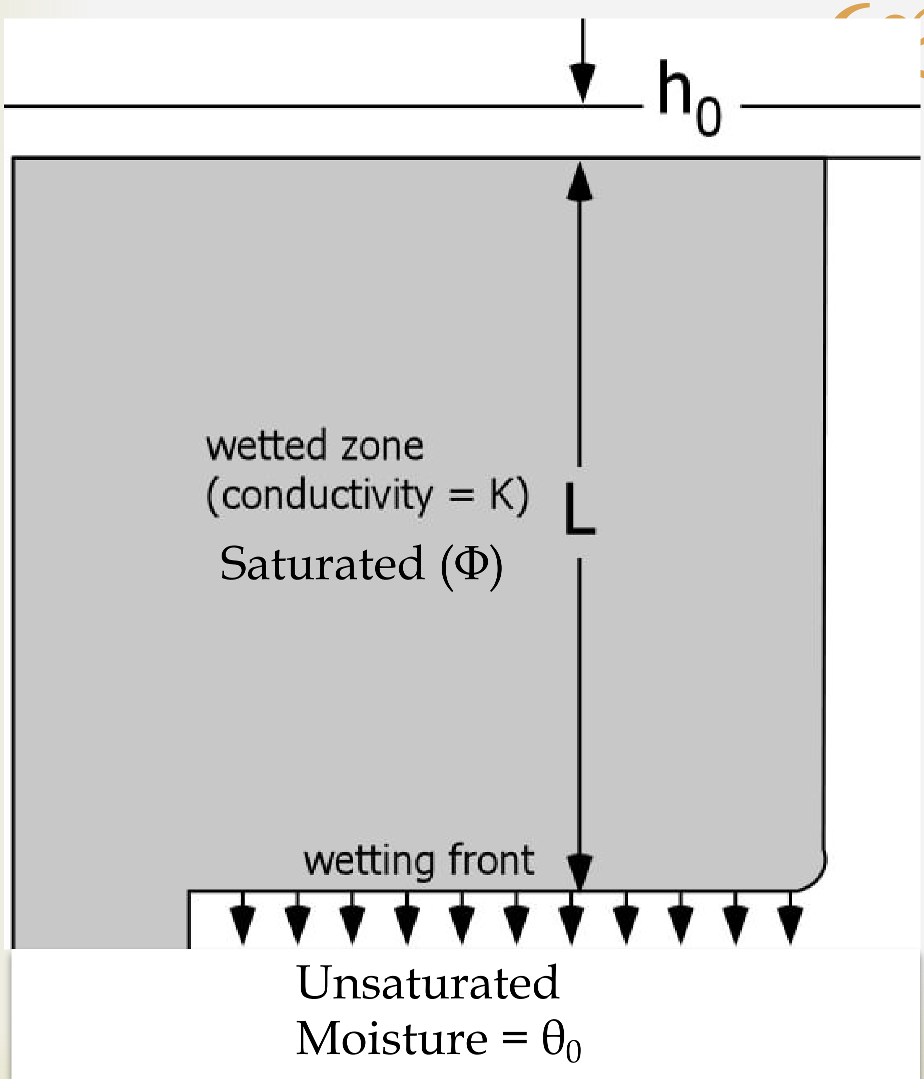
$$f = K\frac{h_1 - h_2}{L} = K\frac{h_0 - (-L - \psi)}{L} = K\frac{h_0 + L + \psi}{L}$$

Green-Ampt Infiltration Equation
(for conditions with ponding)

$$I_t = \frac{K_v\left(H_0 + S_w + L\right)}{L}$$

- I_t = infiltration rate [L/T]
- K_v = vertical saturated hydraulic conductivity [L/T]
- H_o = initial ponding depth at surface [L]
- S_w = Suction at wetting front (expressed as [L/T])
- L = distance from surface to wetting front [L]

More Green-Ampt – Part 3



- Cumulative Amount of Infiltration:

$$F(t) = L\,(\Phi - \theta_0)$$

Where L = depth of wetting front, Φ is saturated water content (= porosity), and θ_0 is initial water content.

More Green-Ampt

Combines $F(t) = L\,(\Phi - \theta_0)$ *(from part 3)*

with $f = K \dfrac{h_0 + L + \psi}{L}$ *(from part 2)*

by putting in $\dfrac{F(t)}{(\Phi - \theta_0)}$ wherever there's an L and noting

that f = dF/dt. And then integrating a couple of times to get:

$$F(t) - \psi \Delta\theta \ln\left(1 + \frac{F(t)}{\psi \Delta\theta}\right) = Kt$$

Where $\Delta\theta = \Phi - \theta_0$.

But note that you can't get F(t) on one side by itself.

Green-Ampt Infiltration Equation
(for conditions with ponding)

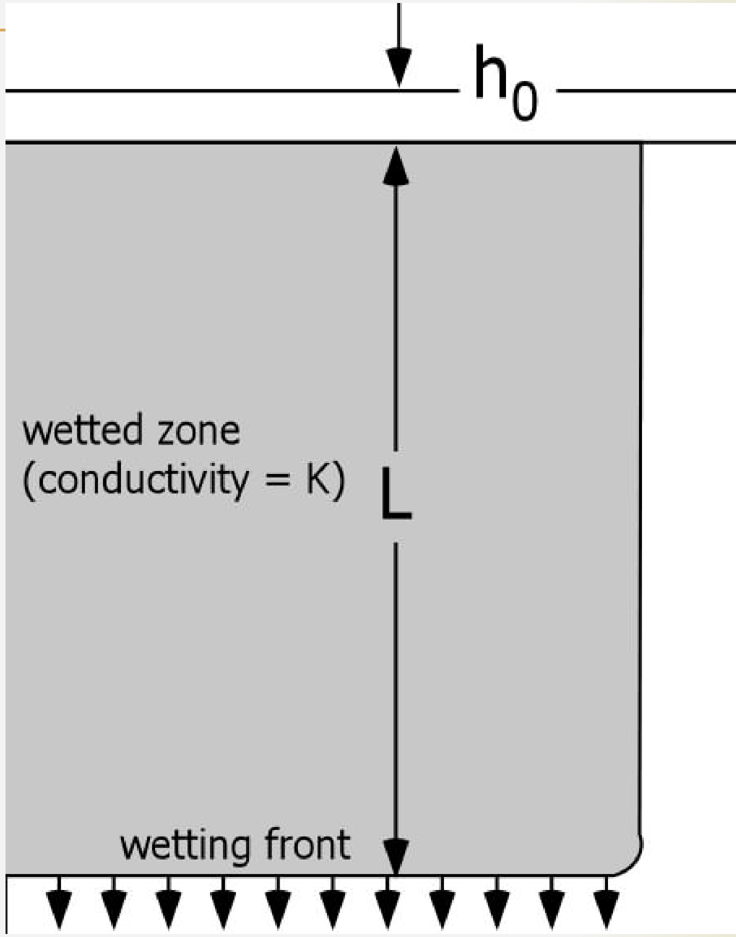
$$I_t = \frac{K_v(H_0 + S_w + L)}{L}$$

- I_t = infiltration rate [L/T]
- K_v = vertical saturated hydraulic conductivity [L/T]
- H_o = initial ponding depth at surface [L]
- S_w = Suction at wetting front (expressed as [L/T])
- L = distance from surface to wetting front [L]

What can we see in the equation that makes it work realistically?

Green-Ampt Assumptions

1. Wetting front is abrupt & "piston-like" (works better for sands than for clays)
2. Assumes homogeneous initial water content
3. Assumes homogeneous K
4. Complete infiltration until ponding



Unsaturated
Moisture = θ_0

Features of Green-Ampt

1. Parameters are measurable, physical properties
2. Gets quasi-exponential decline of infiltration rate
3. Decay in infiltration rate after ponding is due to steadily decreasing capillary gradient (Sw/L). This decay is asymptotic to saturated K.

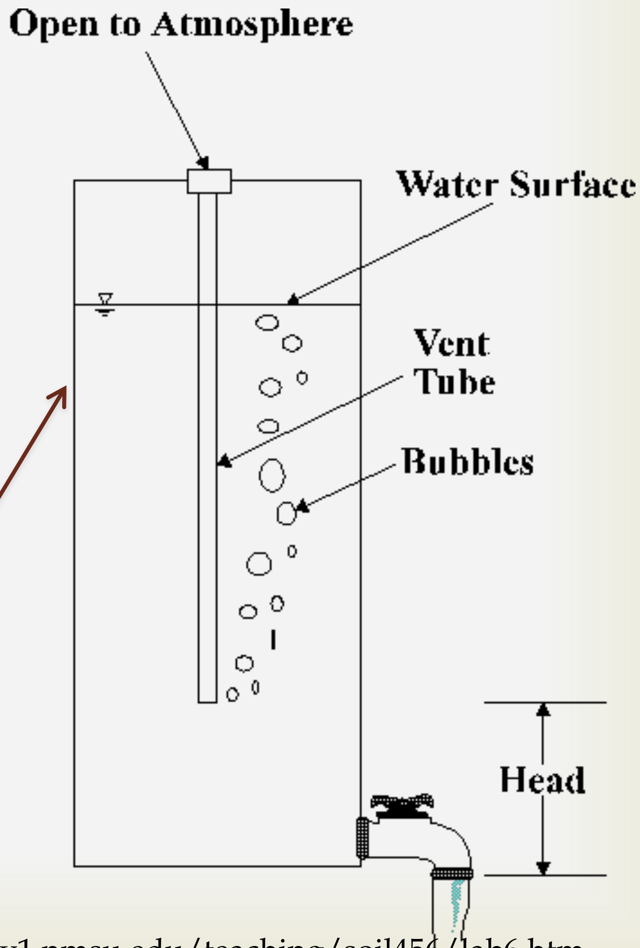
4. Can make it more complicated: shallow soils, depth-varying water content
5. Not as complicated as Richard's Eqn.

Measuring infiltration: Double ring infiltrometer

Measure until ~constant infiltration rate → equilibrium infiltration capacity ~ saturated hydraulic conductivity.

Double Ring Infiltrometers

- Inner ring ~30 cm in diameter
- Outer ring ~45-60 cm in diameter, keep water levels in the two the same.
  - Outer ring used to reduce boundary effects.
- Mariotte tubes can be used to keep constant head.



http://www.humboldtmfg.com/manuals/HM-4502_MAN_0813.pdf

http://hydrology1.nmsu.edu/teaching/soil456/lab6.htm

Measuring Infiltration: Guelph Permeameter

- Constant head permeameter.
- Measure until constant rate → equilibrium infiltration capacity.
- Similar to Double ring infiltrometer, but uses less water and can auger a deeper hole and measure infiltration rate for a soil profile.
- Is Canadian, eh?

Infiltromers in action

- Falling head infiltrometer: https://youtu.be/c-K-KuZi6cI (goes fast, but their procedure is a bit sloppy)
- Double ring infiltrometer (constant head) USDA instructional video: https://youtu.be/YawF0W8PBA0
- Guelph permeameter: https://youtu.be/ugfUg4TeagU
- Installing a double ring infiltrometer: https://youtu.be/PYvfTxQhbOQ