8.0 INFILTRATION & SOIL MOISTURE

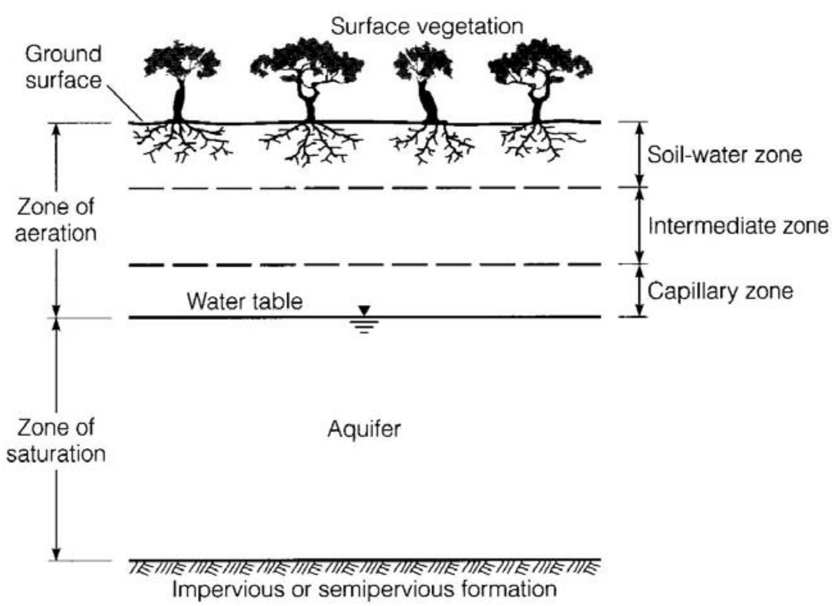
Readings: Ward & Robinson (2000): Ch. 6

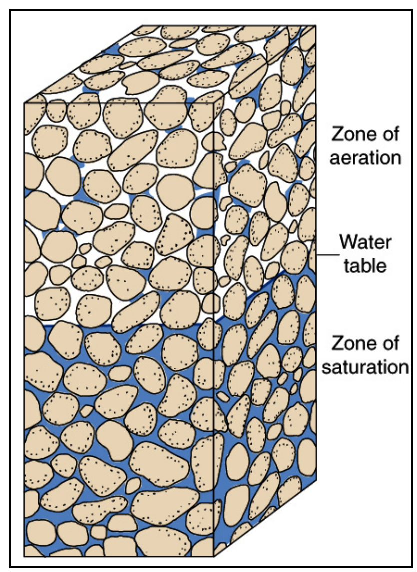
"The thirsty earth soaks up the rain,
And drinks, and gapes for drink again;
The plants suck in the earth, and are
With constant drinking fresh and fair."

- Abraham Cowley

8.1 Soil moisture

- soil water: H_2O contained in the soil &/or sediment 'matrix' - a mixture of soil & sediment solids & void spaces in between
- referred to as the aeration zone… unsaturated with aerated pore space… typically extends cms to 100s cm deep & exists above the saturated groundwater table
- moisture that infiltrates is redistributed by gravity drainage, lateral interflow, or vertical capillary action





8.1.1 *Why is soil moisture important?*

- soil moisture is only a small portion of the total global water balance (0.005% total or 0.174% fresh)… however,
- approx. 76% of all PPT that reaches the surface infiltrates (L'vovich 1974)
- soil water also has a relatively short residence time of 3 months to a year (due to ET losses, drainage, etc.)… thus cycled up to ≈4 times a year which quadruples it's annual contribution of 65 000 to 260 000 km^3
- this moisture is used by most natural & cultivated plants, recharges groundwater, & is key to soil development (e.g., illuviation & eluviation processes)

8.1.2 *Infiltration & soil moisture processes*

- once water reaches the earth's surface it either runs off, is evapotranspired or infiltrates the surface by permeating into cracks, grooves, root canals, animal/insect burrows or small pores in the soil matrix…
- once in the soil matrix, water is redistributed in all directions as it is acted upon by many forces… dominant forces control directions of movements and are defined by soil energy (pressure) potentials (Ψ)
- for instance, high ET at soil surface can cause water to move up from within soils to the surface via exfiltration as driven by heat gradients & vapour pressure gradients between the soil & atmosphere
- soil water can also move upward from the saturated zone to the unsaturated zone via capillary action which results from surface tension force of water molecules to the walls of thin pore channels (sediment surfaces)
- soil water can also percolate downward under it's own weight (if pores are large or moisture content is great) & drain to the water table, thereby contributing to groundwater recharge
- soil water may also flow laterally in the unsaturated zone downslope to re-emerge at the surface as return flow or as groundwater baseflow in river systems
- infiltration rates controlled by: soil texture, structure, porosity, specific surface area available for water adhesion & surface tension

8.1.3 ***Soil water types***

- each is distinguished by the amount of energy (pressure or tension) required to hold it in the soil/sediment matrix (see fig below)

1. hygroscopic water: a very thin (microscopic) layer of water held (adhered) tightly on the surfaces of mineral grains
   - stored at very high tension (-ve pressure) & is lost only as vapour… thus, essentially 'unavailable' for redistribution & for plant use… defines the permanent wilting point (θ_{pwp})
2. capillary water: water held by surface tension in smaller pore spaces… due to a fairly high tension, capillary water is resistant to gravitational drainage but can flow upward (and to some extent laterally) via capillary action
3. gravitational water: stored in largest pores & drains readily under it's own weight… defines the field capacity (θ_{fc})

- managing these 3 types of water has important implications for: runoff, groundwater recharge, nutrient &/or pollutant transport, crop irrigation & drainage management…

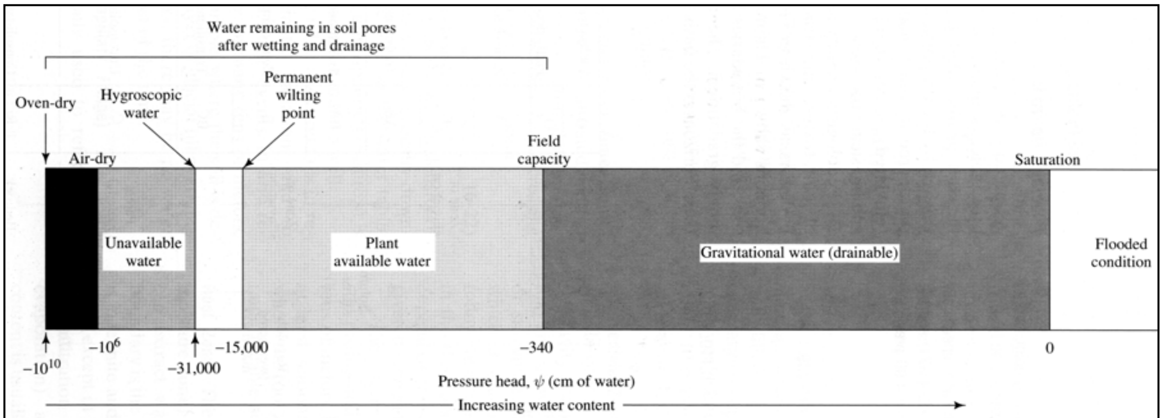
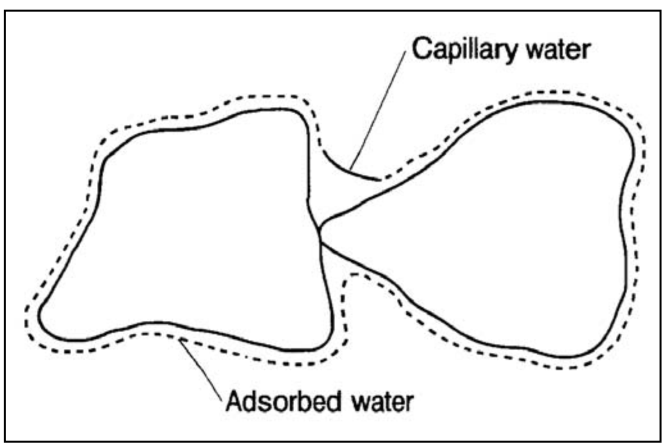


FIGURE 6-13
Soil-water status as a function of pressure (tension). Natural soils do not have tensions exceeding about −31,000 cm; in this range, water is absorbed from the air. After Donahue et al. (1983).



8.2 Soil moisture energy & potential

- Terzaghi (1942) first noted that if gravity were the only force acting on soil water, soils would drain completely after each PPT event… thus, soil water would only be found below the water table
  - under such conditions, plant growth would be limited to areas where rainfall occurred frequently or to areas with shallow groundwater tables… however, most soils (even in very dry climates) always contain some amount of moisture in their matrix that is held in place against gravity via additional forces
- essentially 4 main forces responsible for soil moisture retention & movement:

1. adsorption[8] force: generated by electrostatic charges between polar water molecules & charged surfaces of mineral grains (e.g., clays)… water molecules held (adhered) very tightly (i.e., held with high tension)
2. capillary force: upward force generated by surface tension between air & soil water such that in smaller pores water is able to rise further because cohesive force between molecules (i.e., surface tension) + adhesion to mineral surfaces > air pressure + gravity acting down on pore water (see fig. 6.2, p. 188)
   - upward (& to some extent lateral) movement against gravity & air pressure
   - height of capillary rise inversely proportional to pore radius & fluid density (viscosity)… doubles with ½ reduction in radius
   - rate controlled by porosity, pore orientation & shape, air pockets
   - finer soils (with smaller pores) have ↑ rise of water but at slower rates due to greater surface contact (friction)
3. gravitational force: downward force acting on water mass stored in largest pores in the soil matrix (i.e., only effective if moisture is not held via capillarity or adhesion)
4. osmotic force: force caused by concentration gradients in soil solution (e.g., salts)… often small except in arid environments

8.2.1 *Soil moisture potentials (Ψ, ϕ)*

- forces of attraction in soil matrix (i.e., adsorption, capillary surface tension, osmotic) serve to reduce the energy of water to flow 'freely' as it would above the soil surface (i.e., by gravity only)
- capillary & adhesion forces are said to exert tension or suction force (i.e., a negative pressure) on soil water compared to atmospheric pressure

[8] note adsorption ≠ absorption… absorption is the ability for moisture to enter a substance (similar to infiltration) whereas adsorption is ability to adhere to solid particle surfaces

- as such, under unsaturated conditions water will flow from H $\rightarrow$ L energy (or pressure) along this negative (favourable) pressure gradient…
  - e.g., from atmosphere into soil, or within soil matrix from wet $\rightarrow$ dry, large pores $\rightarrow$ small pores, etc.
- often referred to as soil moisture pressure potential, Ψ_p[9] (p. 194), measured as:
  - $F\ L^{-2}$ in Pa or $N\ m^{-2}$… or
  - bars (where 1 bar = 0.99 standard atmosphere at 101.3 kPa)… or
  - like surficial quantities (e.g., ppt, runoff) can also be expressed as a length term or pressure 'head'[10]… e.g., Ψ_p as 'h' in mm or cm H_2O
- thus, Ψ_p describes force with which water is attracted into (&held within the soil matrix)… this can facilitate infiltration and inhibit moisture loss via drainage or ET
- amount of absorptive (capillary) force available in soil matrix can be estimated using:

$$\Psi_m = 2\,s * \cos\alpha / g\,r$$

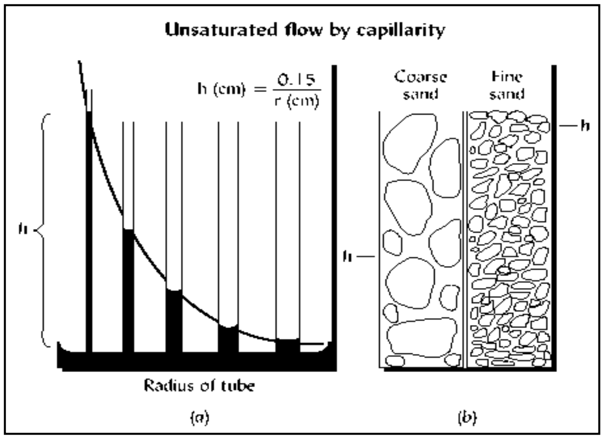
where Ψ_m = matric or capillary water pressure (suction head in mm)
s = surface tension of water (72.4 mN m^{-1} @ 10 °C)
α = contact angle between water & soil grain surface (measure of capillarity… usually 1 for water – sand contact)
g = specific weight of water (9.81 kN m^{-3})
r = pore radius (mm)

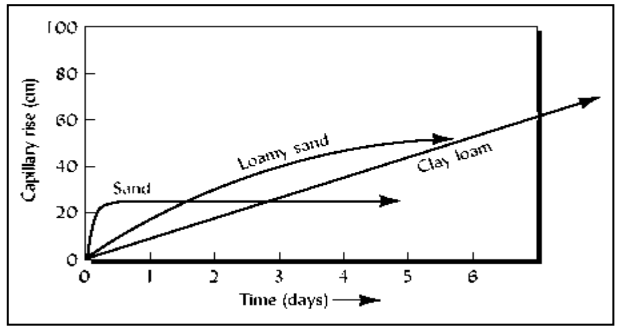
  - for average soil conditions, this simplifies to $\Psi_m = 14.76 / r$
  - thus, for a sandy soil with pore radius $\approx$ 0.01mm, Ψ_m = 1476 mm of potential suction head $\rightarrow$ a 'thirsty' soil indeed!
  - this relates to the specific surface available for capillary action (Table 6.1 below) & in general, increases with finer grain sizes

Table 6.1 Specific surface areas according to mineral type and particle size. (Based on a table in White 1987.)

Mineral or size class	*Specific surface sq m/g*
Coarse sand	0.01
Fine sand	0.1
Silt	1
Clay mineral groups	
Kaolinites	5–100
Ilites (hydrous micas)	100–200
Vermiculites	300–500
Montmorillonite	700–800

[9] or the term 'matric' potential (Ψ_m) is often interchanged with pressure potential, Ψ_p
[10] note: though Ψ values for soil moisture studies is often reported as 'positive', they actually refer to a negative suction pressure.. 'head' terms often assigned an 'h' symbol





- soil moisture retention (fig. 6.2 text) for different soil textures is determined largely by this specific surface available in a soil

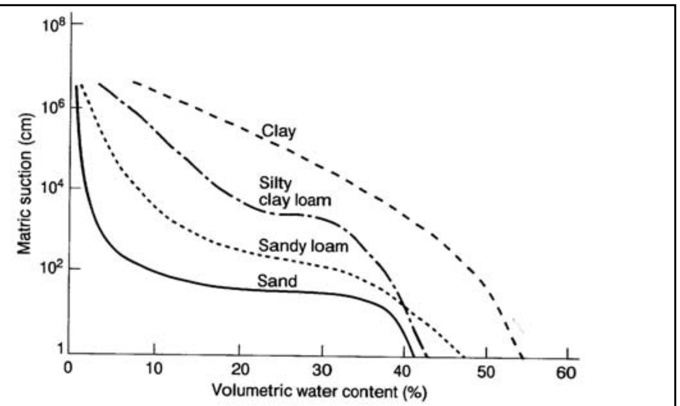


Figure 6.2 Soil moisture characteristics of different soil materials (redrawn from an original diagram by Bouma, 1977).

total soil moisture potential, ϕ[11]: a measure of total available energy for soil water movement relative to atmospheric pressure (p. 194)

$$\phi = \Psi_g + \Psi_p + \Psi_o \qquad \text{(in cm or mm } H_20)$$

- where Ψ_g = gravitational potential = g h $\rightarrow$ +ve (downward)(h = height above datum… usually sea-level)… Ψ_g drains water from upper horizons, recharges groundwater
- Ψ_p = pressure potential = -ve matric suction pressure potential[12]

[11] note: the symbol ϕ is also used by sedimentologists & soil scientists to denote porosity… ϕ often referred to as the total head or h as a length term (e.g., mm, cm total head)
[12] this value would be positive under saturated conditions due to outward hydrostatic pressure

- Ψ_o = osmotic potential = driven by solute concentration gradients (salts, organic compounds) in soil solution… generally negative as solutes move from [H] → [L] via dissolution… often assumed negligible
  - ↑ [solutes], ↓ Ψ_o as H_2O molecules are attracted to ions… ↓ flow rates
  - small effect on large scale soil water flow but very important for ET rates…
  - transpiration: ↑ solutes, ↓ root uptake through cell membranes via osmosis due to ↓ Ψ_o caused by –ve concentration gradient
  - evaporation: attraction of H_2O molecules to solutes ↓E & ↓ vapour exchange in salty soils

- under saturated conditions (e.g., groundwater), a positive (hydrostatic) pressure (also denoted with ψ) occurs that is greater than atmospheric pressure & produces an outward flowing force… why?

- the air-entry tension or pressure, ψ_{ae} is another pressure term that describes the ability of water to enter a soil… this is a measure of capillary absorption (or infiltration) into a soil (also measured as a 'head' in mm or cm)
  - at greater ψ_{ae}, soil pores are filled predominately with air that must be displaced by water entering the soil… this 'backpressure' may inhibit infiltration depending on water inputs (w(t)), pre-existing moisture content, porosity, etc.
  - high ψ_{ae} also indicates greater ability to store infiltrated moisture… though infiltration occurs slowly (due to typically high associated porosity)
  - ψ_{ae} values range from approximately 10mm for gravel (low tension due to large pore sizes and ready drainage) to 1500 mm for silts to several metres for clay

- Soils with high ψ_{ae} tension often pose a 'back pressure' or stagnation effect that can result causing ponding and runoff

8.2.2 ***Variations in total soil water energy (ϕ) with depth***

- total soil water energy, ϕ with depth = $f\,(\Psi_p + \Psi_g + \Psi_o)$
  - Ψ_g declines with depth… why?
  - Ψ_p increases with depth (i.e., becomes more positive)… why?

- at some depth, the gradient of ϕ becomes zero… known as the zero flux plane (ZFP) where there is no increasing or decreasing gradient in ϕ… thus no vertical soil water movement

- in fig 6.5 (below), above the ZFP there is a net upward movement of soil moisture, below ZFP a net downward movement…
    - what conditions would be required at the surface to maintain this condition?

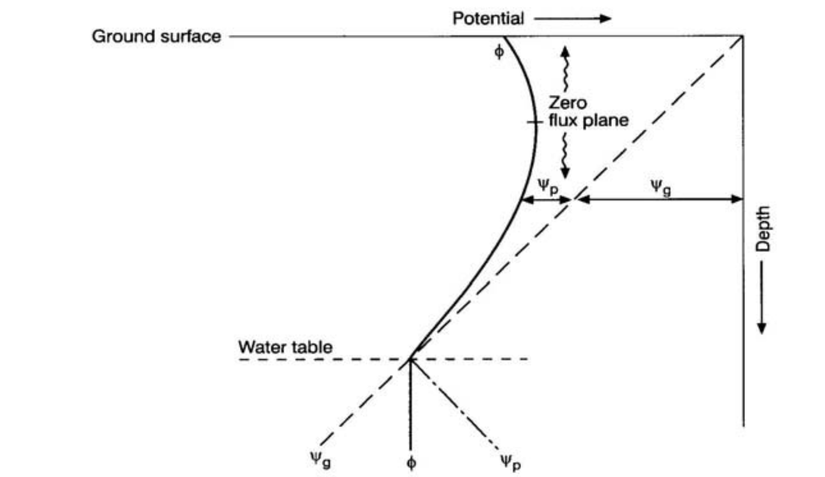
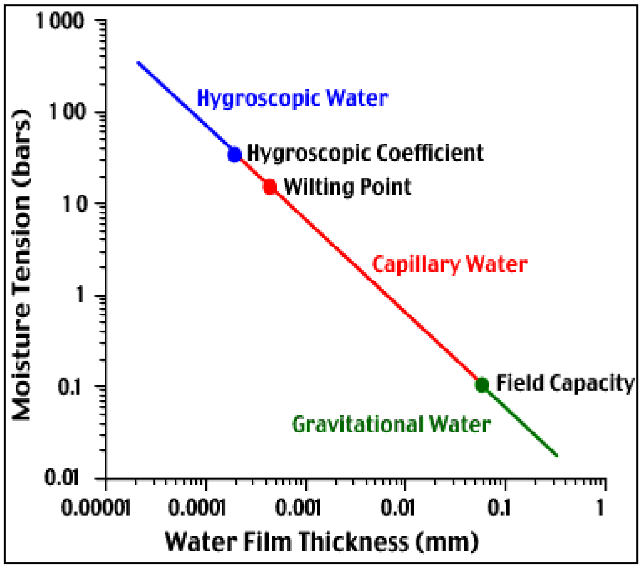


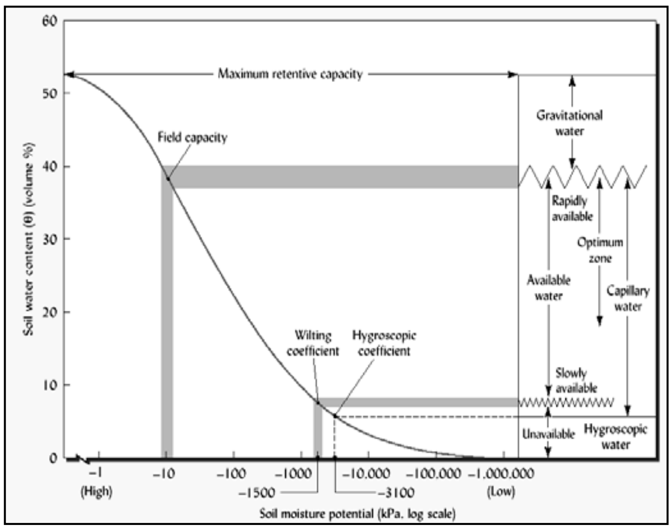
Figure 6.5 Total soil water energy profile (ϕ) below the ground surface, showing the gravitational (ψ_g) and pressure potential (ψ_p) components.

- seasonal variations in zfp (fig. 6.6)

8.3 Soil moisture availability

- defined by total energy (ϕ) as well as plant type, soil texture, moisture content, etc.
- field capacity: residual moisture in a drained soil (capillary + hygroscopic)… defines moisture that can be held *after…*** gravitational drainage* occurs
- wilting point: content where plants wilt (↓ turgidity) & are unable to attain water due to high negative Ψ_p in root zone
- moisture content between these 2 values defines the available moisture in a soil that can move readily under matric forces
- specific yield: volume of water that can freely drain from saturated zone under gravity… % of total volume of aquifer
- specific retention: volume of water that is retained by capillary force as % of total volume of aquifer





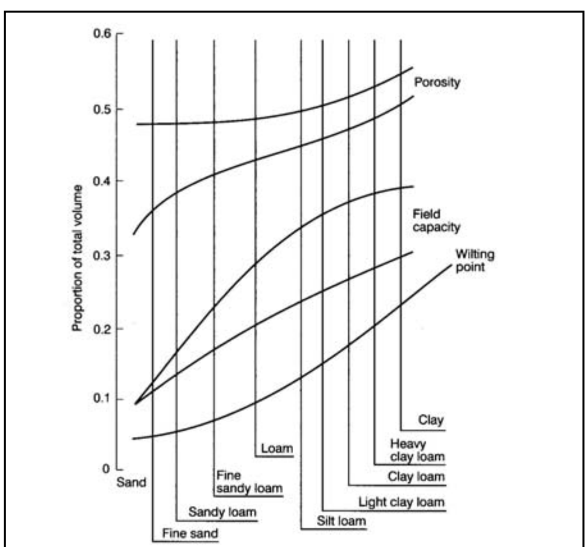
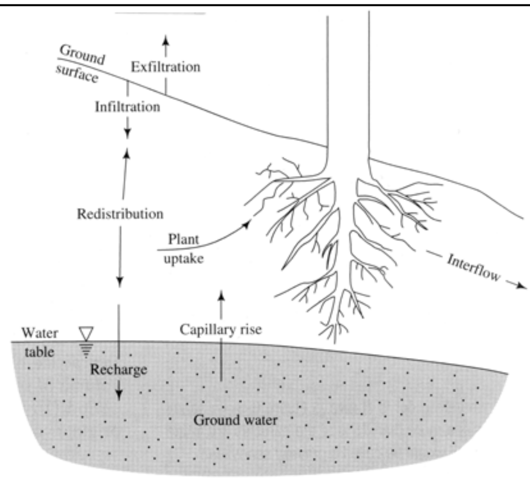


Figure 6.4 General relationship showing the total porosity, field capacity and wilting point of various soils. The volumes quoted are illustrative only, but demonstrate the increase in the available water capacity to plants (between field capacity and wilting point) from sand to clay soils. (From an original diagram in Dunne *et al.*, 1975.

FIGURE 6-1
Definitions of terms used to describe water movement in the unsaturated zone.



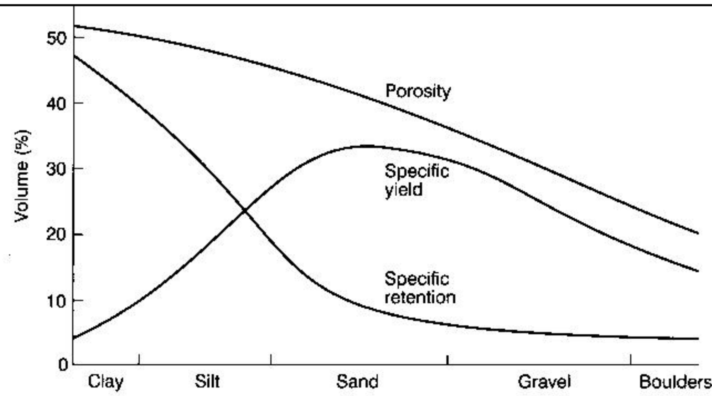


Figure 5.3 The relationship between porosity, specific retention and specific yield for different types of unconsolidated material, showing typical values which may differ significantly from values at a particular site. (From an original diagram by Eckis, 1934.)

8.4 Soil moisture measurement

- many ways to measure & characterize soil moisture content & potential (p. 198-201)
- volumetric moisture content (θ): ratio of water volume to soil volume… measured by:
    - gravimetric method (i.e., wet-dry weighing where weight loss on drying is proportional to θ)… labour intensive, precise, requires sample removal
    - electrical resistance blocks measure resistivity of a volume of porous material (e.g., gypsum block) as function of θ… relatively inexpensive, block degrades over time, not accurate in saline soils

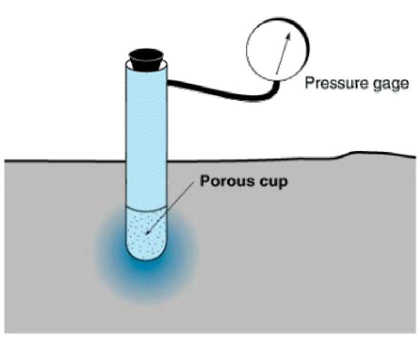
  - capacitance probes measure di-electric constant of soil which will change with θ… relatively inexpensive & precise point measurements
  - time-domain reflectrometry (TDR): measures decay in time return signal pulse as proportion of θ… measures di-electric constant of soil based on travel time of signal between probes… reliable & precise, easy to install, quick, but costly

  - neutron scattering: θ determined from radioactive source as high/fast radioactive neutrons are slowed/absorbed by moisture… very precise though controlled radioactive substances are hazardous, installation time of source & receptors into soil

  - satellite technologies: measure surface soil moisture using IR microwavelengths or synthetic aperture radar (SAR) which estimates di-electric constant… expensive infrastructure, remote sensing of large areas, penetrates clouds, only measures near surface moisture content

- moisture content tells how much H_2O present but pressure potential reveals the ability of that water to move

- soil water pressure potential (Ψ_p)
  - tensiometers: measure -ve suction pressure using porous cups installed at depth in soil or pressure membranes, thermocouple psychrometer (matric + osmotic)



suction lysimeters – used to sample the soilwater

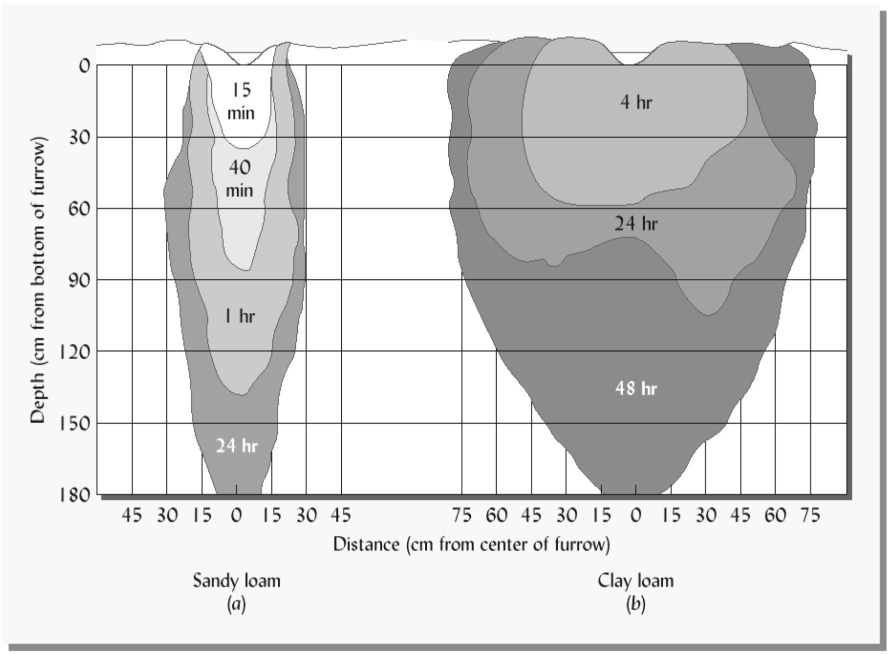
8.5 Soil moisture movement: infiltration & unsaturated flow

- in general, soil moisture moves via gradients in potential energies as discussed above via several processes:

  1. infiltration into soil matrix at surface
  2. unsaturated flow of water & air in pore matrix via capillarity, percolation drainage
  3. saturated flow of water when all pores filled with water via percolation… aka groundwater flow (next section)
  4. vapour movement due to vapour pressure differences with atmosphere (occurs mainly at surface) via evaporation & vapour flow

8.5.1 ***Infiltration***

- movement of water into soil through small pores or larger macropore structures (e.g., dessication cracks, root channels, burrows)
- Infiltration rate f(t): volume of water flow into soil per unit area soil… controlled by rate of supply of water (e.g., intensity, amount) & soil properties… like PPT, has units of $L\ T^{-1}$ in cm or mm/hr over some unit area
- infiltration rate initially high due to high soil pressure potential (ψ_p)… would the total potential (ϕ) gradient at this stage be -ve or +ve?



- infiltration rate controlled by <u>soil texture</u> (fig. above from Cooney & Peterson (1955) as in Brady & Weil 1999)… why & how?
- infiltration progresses over time along a <u>wetting front</u> or boundary between drier underlying soil & wetted soil

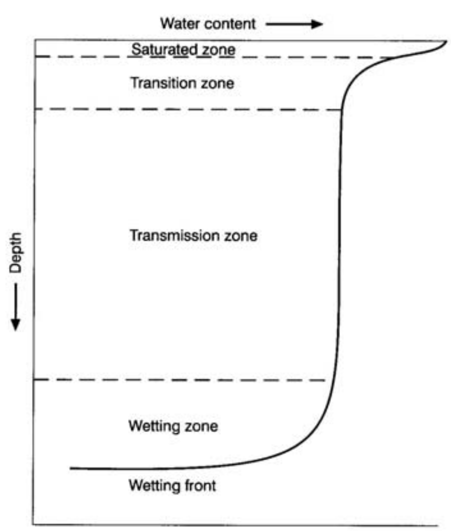
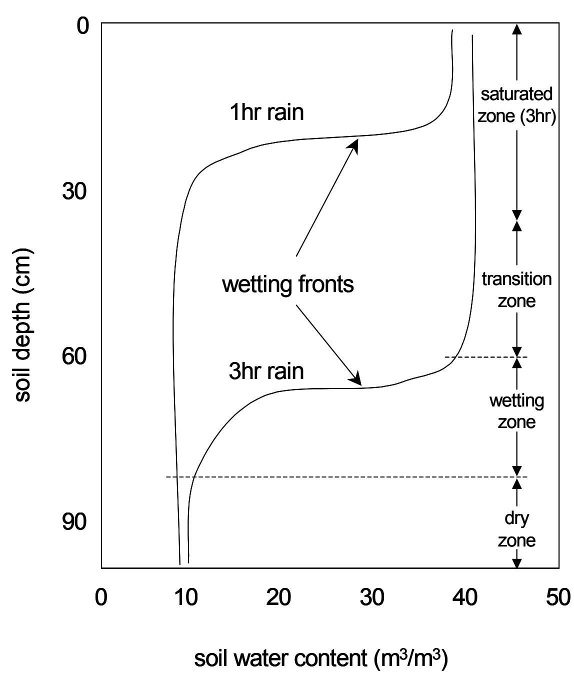


Figure 6.11 Moisture zones during ponded water infiltration (from an original diagram by G.B. Bodman and E.A. Colman, *Proceedings of Soil Science Society of America*, **8**, pp. 116–22, 1943, and adapted by permission of the publisher).



- during inputs (rainfall or irrigation), rate declines & becomes steady → controlled by some <u>infiltration capacity</u>
- <u>Infiltration capacity</u>: maximum rate (cm/hr) at which water can enter soil… defined by properties (e.g., texture, porosity) that limit ability of the soil to absorb water

- recall that pore size governs the contribution of gravitational potential (Ψ_g) vs. pressure potential (Ψ_p)… however, for most finer soils & sediments (i.e., not gravels) the main force responsible for infiltration is capillary force via surface tension

8.5.2 ***Unsaturated flow***

- recall that soil water will move from high energy to low energy… (p.201)
- because its movement is slow (i.e., low kinetic energy) the total potenial energy (ϕ) is used to describe unsaturated flow and is often expressed as: $\phi = \Psi_p + z$…
    - where z is the gravitational potential expressed here not using Ψ_g, rather z as elevation above some datum (e.g., sea level)… again, ϕ often referred to as the total 'head' or h
- hydraulic conductivity (K_h): rate at which water flows through soil in response to a moisture potential gradient…
- Darcy's Law for unsaturated flow (p. 203):

$$v = -K_h(\theta)\,[dh / dL]$$

- where: v = unsaturated flow speed ($\propto$ pore radius)[13]
- K_h = hydraulic conductivity at a given moisture content, θ… increases to max. at saturation K^*_h, lowest when dry… why?
- varies with soil texture (courser soils have higher K)
- dh/dL = hydraulic gradient, change in head with distance in direction of flow[14]

- for purely downward flow (L = z) under potential pressure gradient ($d\psi_p / dz$):

$$v = - K_h(\theta)\,[d\psi_p / dz - 1)]$$

- or if moisture content gradient ($d\theta/dz$) is available:

$$v = - K_h(\theta)\,[d(z + \psi(\theta)) / dz] = - K_h(\theta)\,[1 + (d\psi(\theta)/dz)]$$

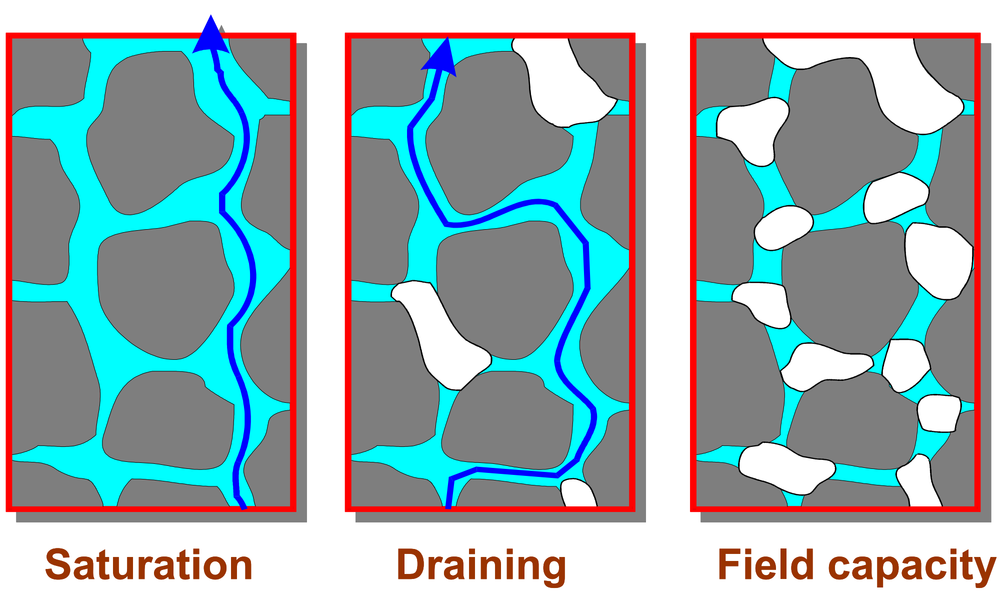
- structural porosity (e.g., macropores, animal burrows, cracks, root pathways, etc.) promotes more rapid flow… not accommodated in Darcy eqn. unless incorporated into K_h values… usually K_h expresses only textural (grainsize) porosity

[13] v is volumetric flow rate (often denoted q_z) through a unit of cross-sectional area of soil surface [L T^{-1}]
[14] note: soil water can flow horizontally or vertically depending on direction of the dominant gradient

- flow can also be impeded significantly by changes in pore size & texture… large pores drain via gravity, small pores conduct moisture via capillarity… rapid change in energy components (i.e., Ψ_p vs. z)

Hydraulic Conductivity

- Refers to the characteristics of porous media and the fluid - - coefficient of permeability
- Saturated
  - soil depends mainly upon geometry and distribution of the pore spaces. More or less constant for a given material
  - includes textural voids and macropores (e.g. root channels)
    - macropores may increase saturated conductivity by several orders of magnitude
- Unsaturated
  - varies with soil moisture content
  - greatest at/or near saturation and decrease rapidly with reducing water content
    - can only take place through existing films of water on and between soil grains
    - air-filled pores act as non-conducting part of system



8.6 Factors controlling soil moisture movement

- mainly soil texture & porosity… how?

- porosity (ϕ or P): ratio of volume of void space to total volume of soil

  $$P = [1 - (\rho_{bulk} / \rho_{particles})]$$

  e.g., medium textured soil: $\rho_{bulk} = 1.3$ g cm^{-3}, $\rho_{particle} = 2.65$ g cm^{-3} P = 0.51 or 51%

- ranges 25% in compacted soil to ≈ 60% in well-aggregated surface soils with ↑organic matter

- porosity controls total amount of water a soil can store & transmit… depends on soil depth and 'effective' porosity

- effective porosity P_e: pore space that permits active water flow compared to total volume of soil

  e.g., coarse, sandy soils have effective porosity of ≈ 20-35%, clays <5%…

  often P_e<< actual P of 40 – 70 % for most soils… most pore space is occupied by hygroscopic (unavailable) water

- pore connectivity (see lab)

- soil texture: grain size & sorting control available surface for adhesion, porosity & flow pathways

- moisture content (θ): affects pressure potential… as approach saturation, ↓Ψ_p due increasing +ve (outward) hydrostatic pressure… levels out infiltration rate to K^*_h

- rainfall intensity

- land use… how?

- slope via promoting runoff OR contributes ↑ Ψ_g (gravity head)

8.7 Self-summary

- *Use this space to summarize the main points & concepts of this section. Also include any questions you may have on this content.*