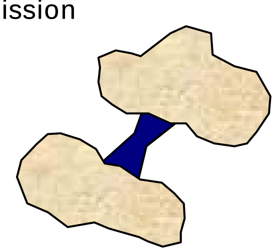
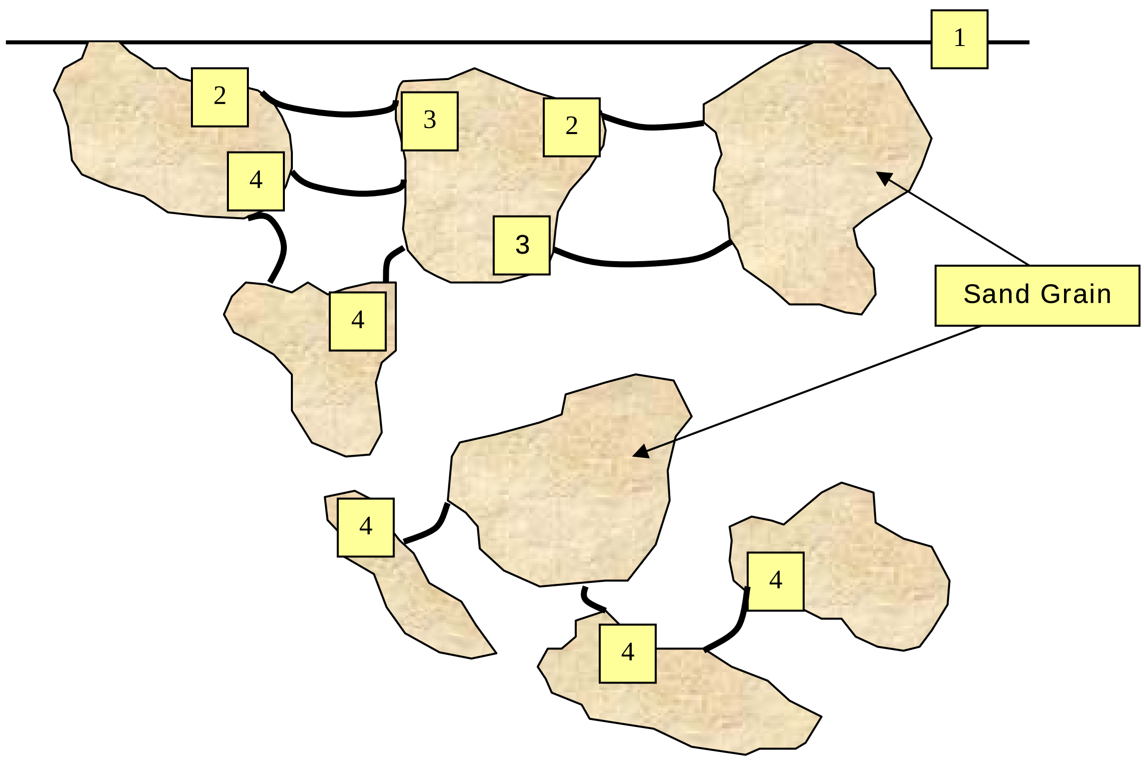
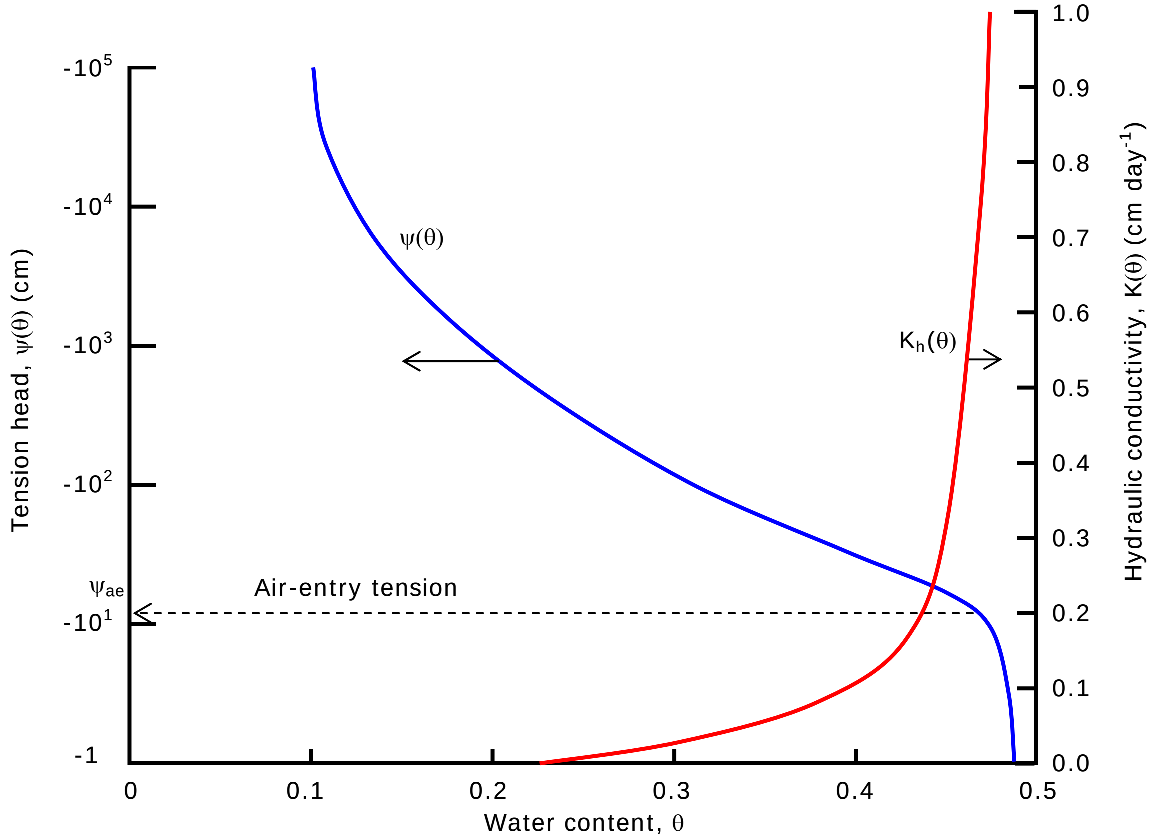
Lecture Packet #13: Stages of Desaturation

Stages of Desaturation

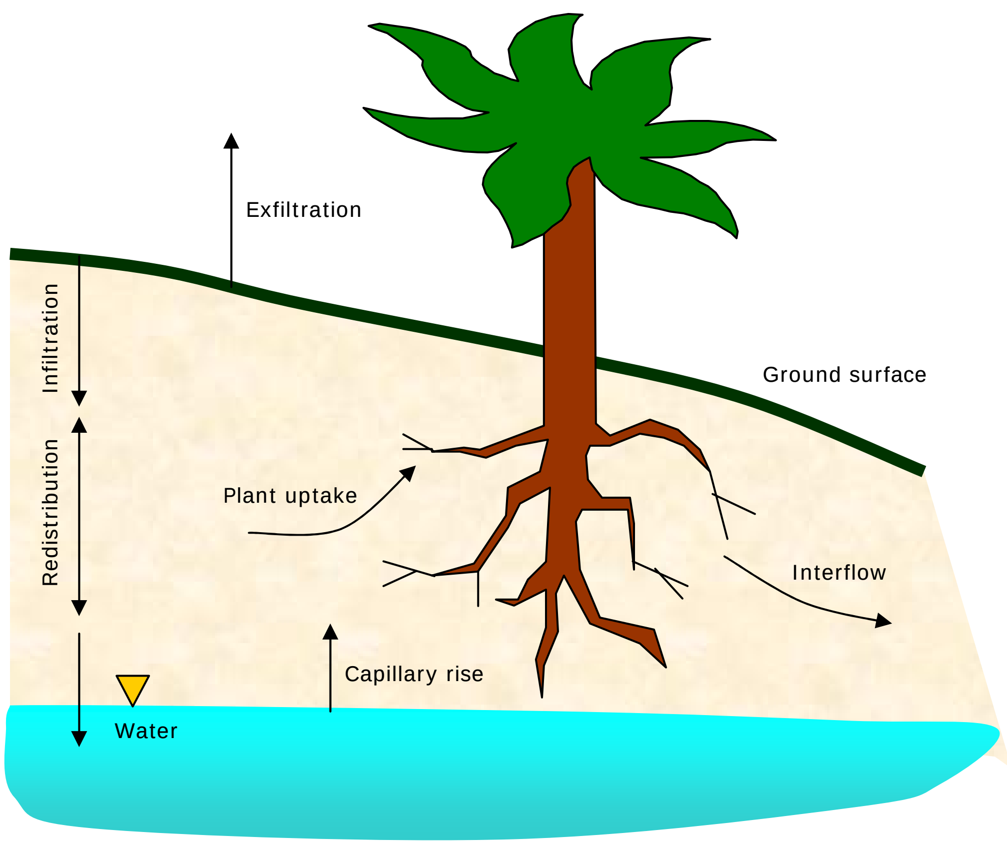
1. Complete saturation
2. Air entry
3. Funicular saturation
    a. Pores dewater from large to small
    b. Air and water phases are continuous
    c. Average suction (over REV) dominated by direct suction transmission through the continuous phase, although films of sorbed water exist at very large negative potentials.
4. Pendular saturation
    a. Water phase discontinuous – no direct pressure transmission
    b. Air phase is continuous.
5. Hydroscopic water
    a. Sorbed water
    b. Large suctions
    c. May or may not be continuous



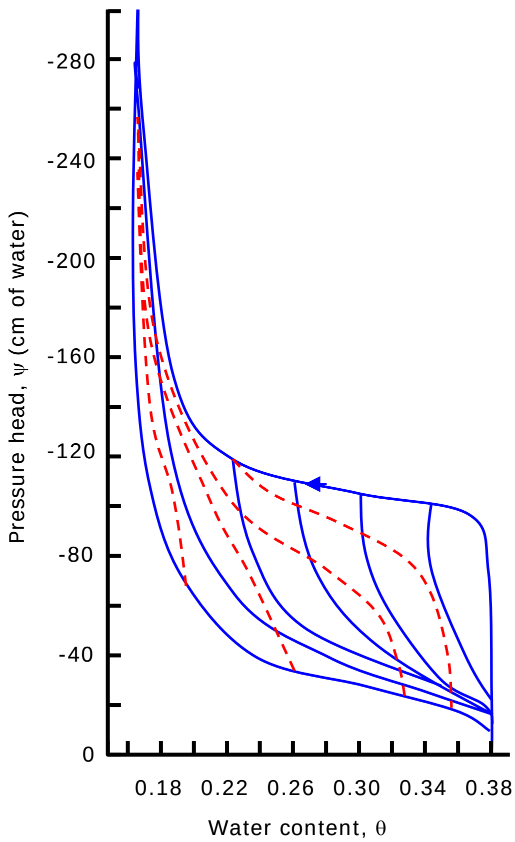


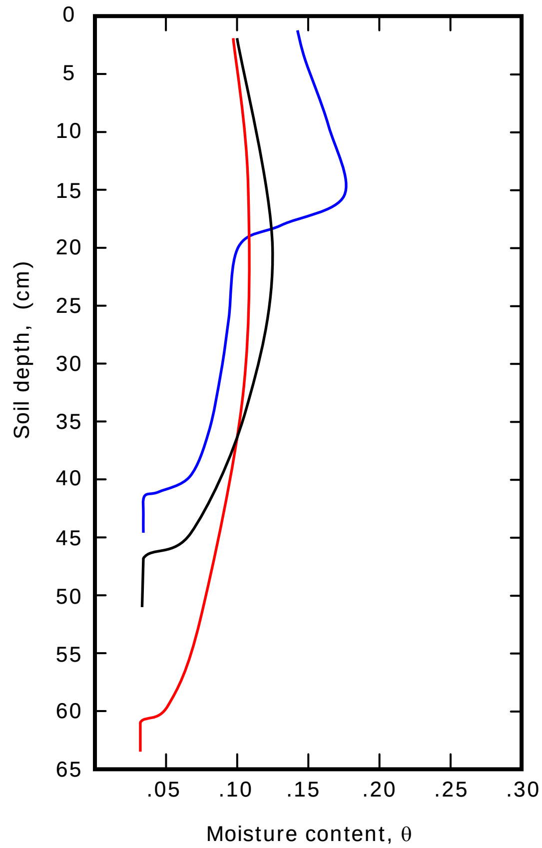


Tension head, ψ(θ) (cm)
-10^5
-10^4
-10^3
-10^2
ψae
-10^1
-1
ψ(θ)
Air-entry tension
K_h(θ)
Hydraulic conductivity, K(θ) (cm day^-1)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
0.1
0.2
0.3
0.4
0.5
Water content, θ



Exfiltration
Infiltration
Redistribution
Ground surface
Plant uptake
Interflow
Capillary rise
Water





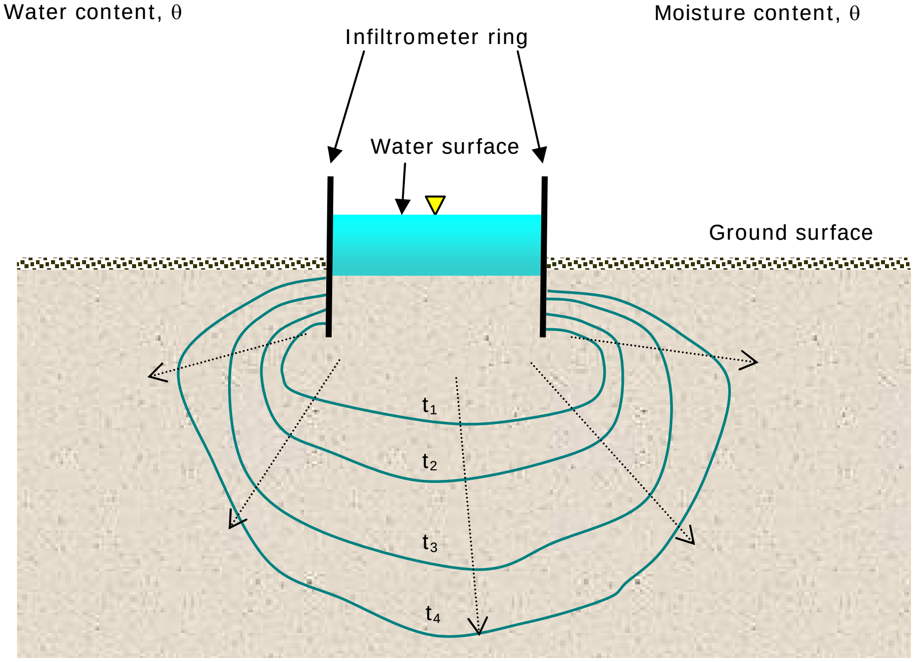


Figure: Infiltrometer diagram showing wetting-front movement from time t_1 to t_4.

Darcy's Law for vertical unsaturated flow

z is elevation (positive up)

$$q_z = -K(\theta)\frac{\partial[z - \psi(\theta)]}{\partial z}$$

$$= -K(\theta)\frac{\partial z}{\partial z} + K(\theta)\frac{\partial \psi(\theta)}{\partial z} \quad = -K(\theta) + K(\theta)\frac{\partial \psi(\theta)}{\partial z}$$

Mass balance $-\frac{\partial q_z}{\partial z} = \frac{\partial \theta}{\partial t}$

Richard's Equation (vertical unsaturated porous-media flow)

Differentiate Darcy's Law:

$$\frac{\partial q_z}{\partial z} = -\frac{\partial K(\theta)}{\partial z} + \frac{\partial}{\partial z}\left[K(\theta)\frac{\partial \psi(\theta)}{\partial z}\right]$$

Use Mass Balance equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial K(\theta)}{\partial z'} - \frac{\partial}{\partial z}\left[K(\theta)\frac{\partial \psi(\theta)}{\partial z}\right]$$

<u>ψ form:</u>

Noting that: $\frac{\partial \theta}{\partial t} = \frac{\partial \theta}{\partial \psi(\theta)}\frac{\partial \psi(\theta)}{\partial t} = C(\psi)\frac{\partial \psi(\theta)}{\partial t}$

Richard's Equation becomes:

$$C(\psi)\frac{\partial \psi}{\partial t} = \frac{\partial K(\psi)}{\partial z'} - \frac{\partial}{\partial z}\left[K(\psi)\frac{\partial \psi}{\partial z}\right]$$

<u>θ form:</u>

Noting that: $\frac{\partial \psi(\theta)}{\partial z} = \frac{\partial \psi(\theta)}{\partial \theta}\frac{\partial \theta}{\partial z} = \frac{1}{C(\psi)}\frac{\partial \theta}{\partial z}$

Richard's Equation becomes:

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

Where $D(\theta) = \frac{K(\theta)}{C(\theta)}$ ← Unsaturated Diffusivity

Advantages

1. D does not vary over as many orders of magnitude as K
2. D is not as hysteretic as K
3. If gravity can be neglected (horizontal flow) equation is nonlinear diffusion equation

Disadvantage

Does not work for $\psi < \psi_{ae}$ $\quad C(\theta) = \frac{\partial \theta}{\partial \psi(\theta)} = 0$

Infiltration ("percolation")

- The process by which water arriving at the soil surface enters the soil.

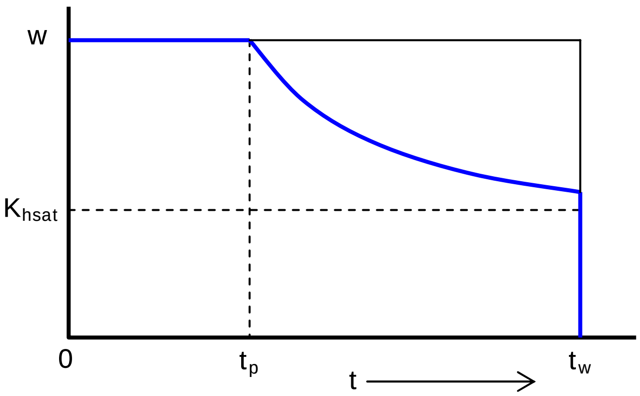
The rate of infiltration changes in a systematic way during rainfall, even though the rainfall rate may be constant.

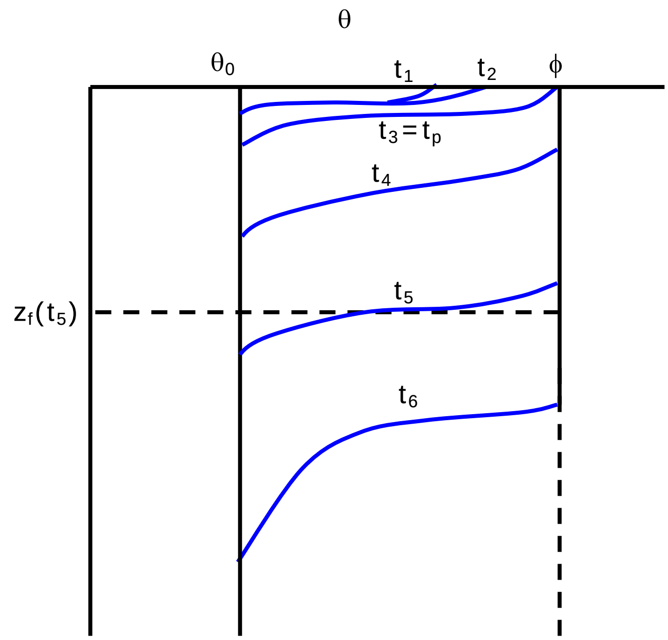
Consider three different conditions:

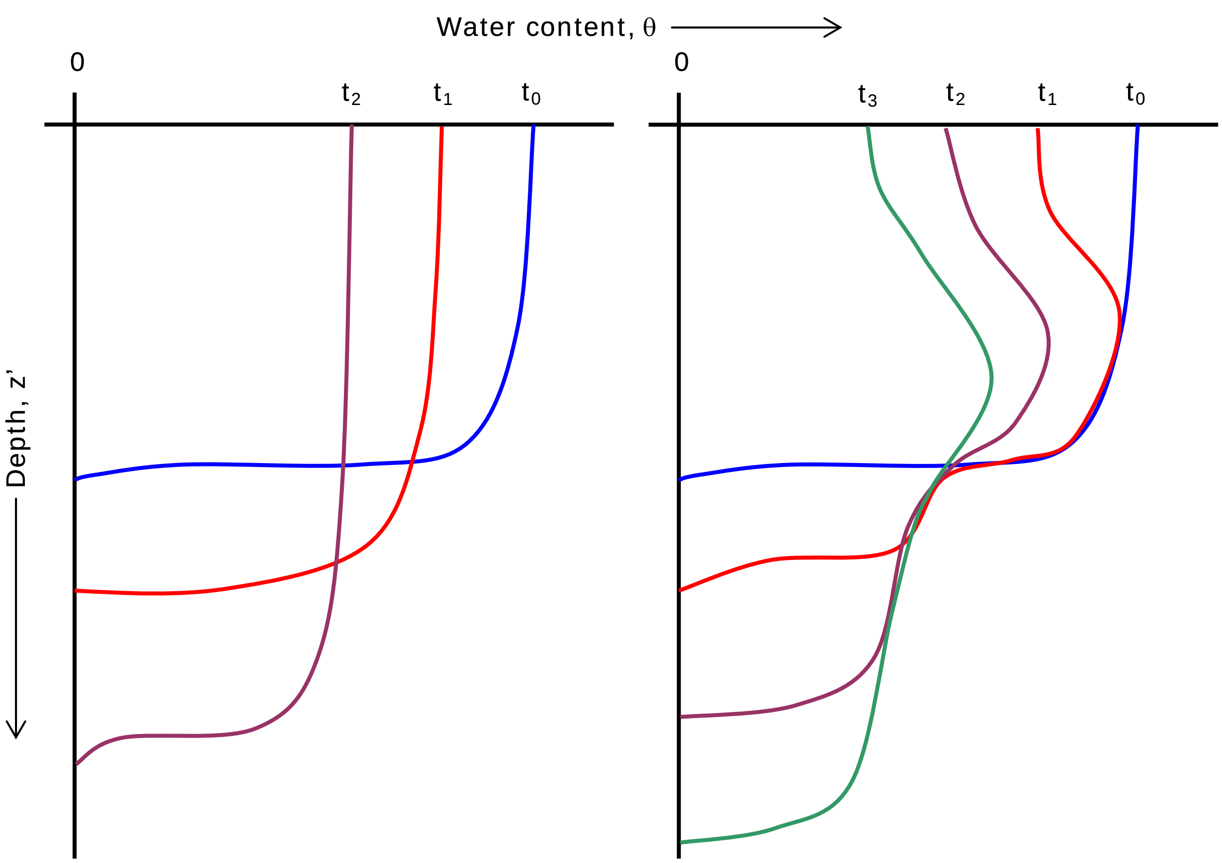
1. No ponding. Infiltration rate is less than or equal to the infiltration capacity, the maximum possible rate.
2. Saturation from above. Water input rate exceeds the infiltration rate, so ponding develops. The infiltration rate is equal to the infiltration capacity.
3. Saturation from below. The water table has risen to or above the surface so the soil is saturated. Ponding occurs and the infiltration rate may be zero.

Factors affecting infiltration rate:

1. Rate at which water arrives.
2. Conductivity at the surface
    a. Plants
        i. Large pores
        ii. Shingling (leaves spread on the ground)
    b. Frost
        i. "concrete" effect
        ii. Polygonal cracks
    c. Swelling-Drying
    d. Inwashing of fines
    e. Modification of soils
3. Water Content
    a. Saturation
    b. Antecedent water content (how wet is the soil before the rainfall?)
4. Surface slope and "roughness" controls ponding
5. Chemistry of soils



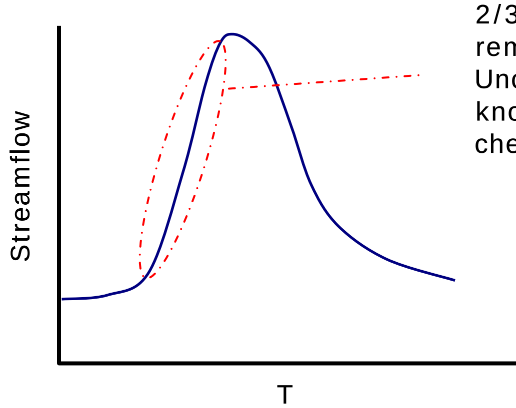




Profiles show a typical water distribution after deep soil infiltration in the absence of evaporation. t_0 is defined as the time when redistribution begins.

a) Redistribution with dominant capillary force over gravitational force
b) Redistribution when gravitational force dominates capillary force

Rainfall-Runoff Mechanisms



2/3-3/4 groundwater remainder is rainfall. Unclear why but we know this based on chemical studies

Surface Processes

Channel Interception

- Rainfall right into the channel
- Channels usually represent a small area of the watershed. But this mechanism has been found to represent up to 40% of the event response

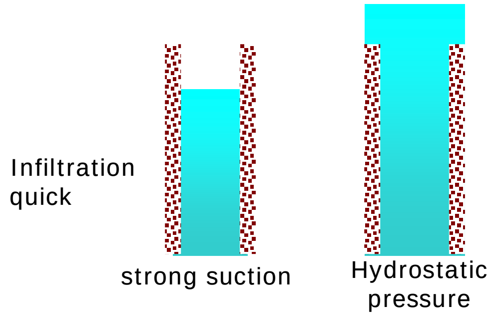
Hortonian Overland Flow

- Water input rate exceeds the saturation hydraulic conductivity, so the top becomes saturated and ponding and runoff occurs
- Widely accepted as the primary mechanism for event response from 1930's to 1960's
- Now we believe that it's rare – only very intense rains on very impermeable soils

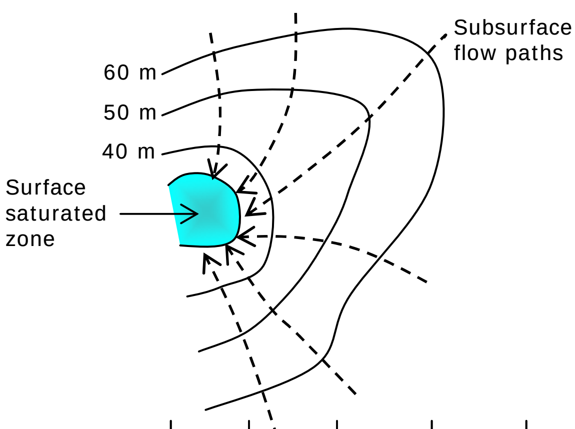
Saturation Overland Flow

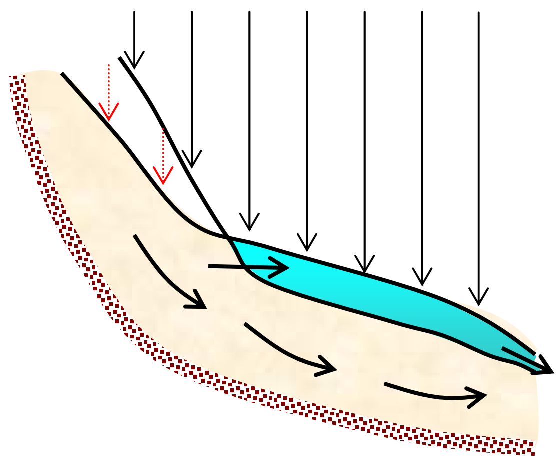
- Saturation from below. The water table rises to the surface.
- Occurs near streams because the depth to the water table is low and flow is toward streams. Flow on the surface dumps directly into the stream.
- Most of the flow is rainfall runoff, but if the storm continues groundwater discharge can become important.
- *Variable source area*. During a storm the saturated area may grow increasing the amount of runoff. This effect amplifies the event response.

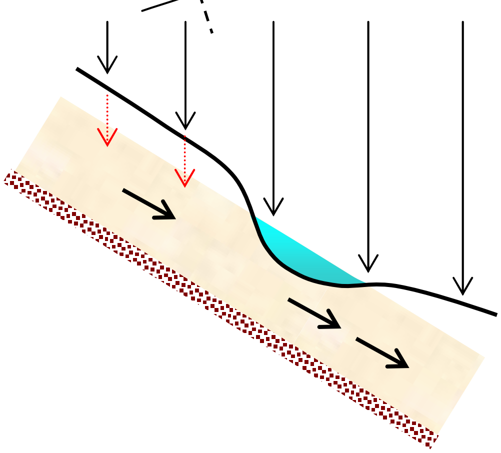
Subsurface Processes

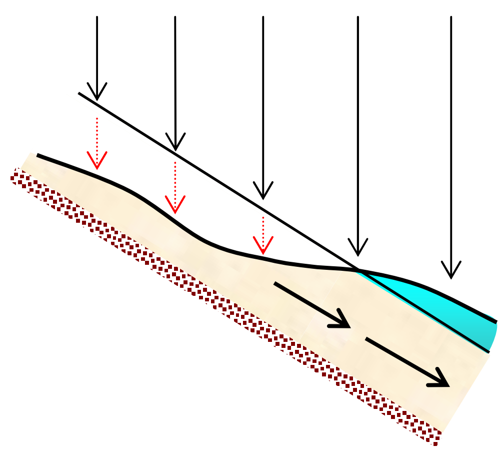


- Large scale groundwater flow
- Groundwater mounds near streams
- Pressurization of capillary fringe
- Perched water table
  - Common to have a less permeable layer below the surface
  - Saturation layer develops that is not connected to regional water table
  - “Sloping slab” flow down hill
  - Response time too slow to explain event response - days
- Flow in the unsaturated zone – interflow or throughflow
  - Moisture dependent anisotropy – water wants to flow laterally because of higher conductivities due to higher moisture content
  - Response might be quick because water does not have to penetrate very far downward.
- Saturation from below can also occur when:
  - Groundwater flowlines converge in surface concavities
  - Slope breaks
  - Thin spots in the most transmissive material
  - Decreasing conductivity









Chemical and Isotopic Indicators

Mass balance for dissolved constituents:

$$CQ = C_rQ_r + C_oQ_o + C_sQ_s + C_gQ_g$$

Stream water (CQ); Direct Rain (C_rQ_r); Overland flow (C_oQ_o); Subsurface stormflow (C_sQ_s); Groundwater (C_gQ_g)

Mass Balance for water:

$$Q = Q_r + Q_o + Q_s + Q_g$$

Approximate: $Q_r = 0$ $\qquad Q_d = Q_o + Q_s$ (Direct runoff)

$$CQ = C_dQ_d + C_gQ_g$$
$$Q = Q_d + Q_g$$

Solutes such as Na, Ca, Mg, Cl, etc.

$$Q_g = Q\left(\frac{C - C_d}{C_g - C_d}\right)$$

Isotopes such as $\delta^{18}O$ (Oxygen-18)

$$Q_g = Q\left(\frac{\delta^{18}O - \delta^{18}O_d}{\delta^{18}O_g - \delta^{18}O_d}\right)$$