

Chapter 5 - Field Soil Water Regime

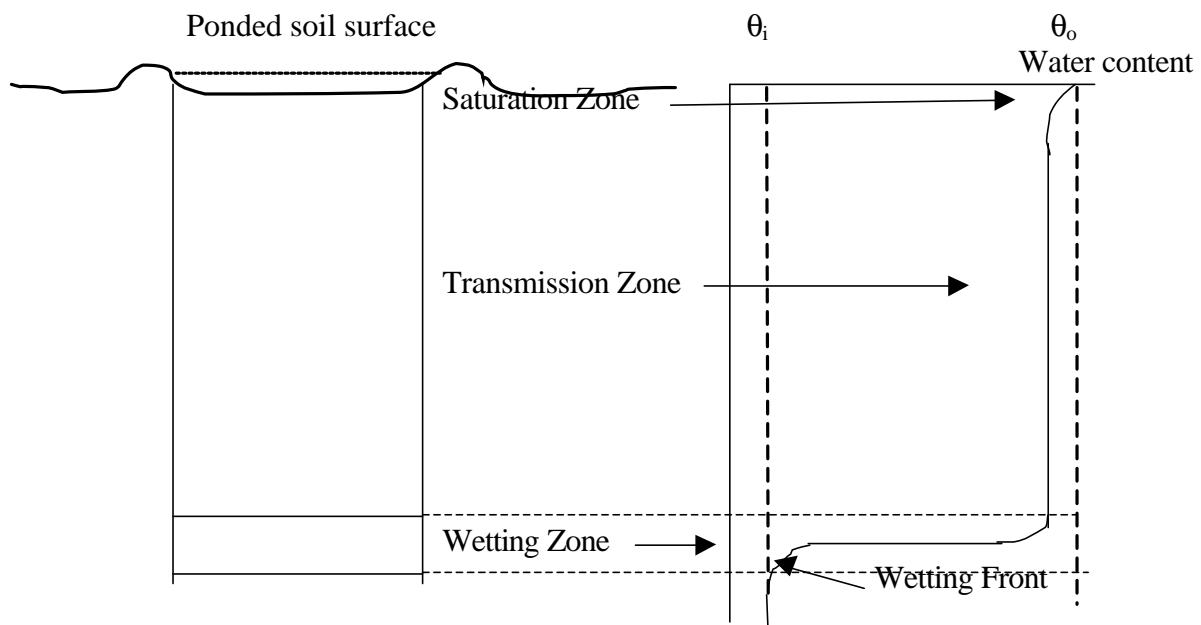
- Infiltration
- Redistribution and drainage
- Evaporation

Infiltration

Definition: Entry of water into soil through the soil surface.

Also, infiltration is typically not steady state, but infiltration rate, water content or h will all change with time.

In practice: Fraction of water that is applied to the soil surface (rainfall, irrigation), that is not directly intercepted by plant cover or is redirected across the soil surface by runoff.



As water infiltrates into the soil, the length of the transmission zone increases, and the infiltrating water wets the soil's wetting zone, which subsequently moves down in the soil profile.

Notation:

θ_i Initial volumetric water content (before wetting)

θ_o Volumetric water content at wetting (at or close to saturation)

Transmission zone - close to being saturated

- $K = K_o$ (conductivity of wetted soil)

- It is relatively large:
$$J_w = -K_o \frac{\Delta H}{\Delta X}$$

where $H = h + z$

- θ and h are constant with X and time

$$\frac{\Delta H}{\Delta X} = \frac{\Delta h}{\Delta X}^0 + \frac{\Delta z}{\Delta X}^1$$

or
$$\frac{\Delta H}{\Delta X} \approx I$$

Hence, the infiltration rate, denote by the flux of water moving through the transmission zone is about equal to hydraulic conductivity at the water content of the transmission zone.

Wetting zone - unsaturated

- K is relatively small
- Its position changes with time, i.e., the wetting front moves down as water infiltration into the soil.

$\frac{\Delta H}{\Delta X}$ is large because of large change in soil water potential (between transmission zone and wetting front) over a relatively small distance (wetting zone).

NOW CONSIDER THE SOIL PROFILE OR COLUMN IN VERTICAL ORIENTATION

At small times after infiltration begins

$$\frac{\Delta h}{\Delta X} \ggg \frac{\Delta z}{\Delta X} \quad \left\{ \frac{\Delta H}{\Delta X} \approx \frac{\Delta h}{\Delta X} \right\}$$

- Acts like horizontal infiltration
- Infiltration is controlled by soil-water potential gradient

Large times

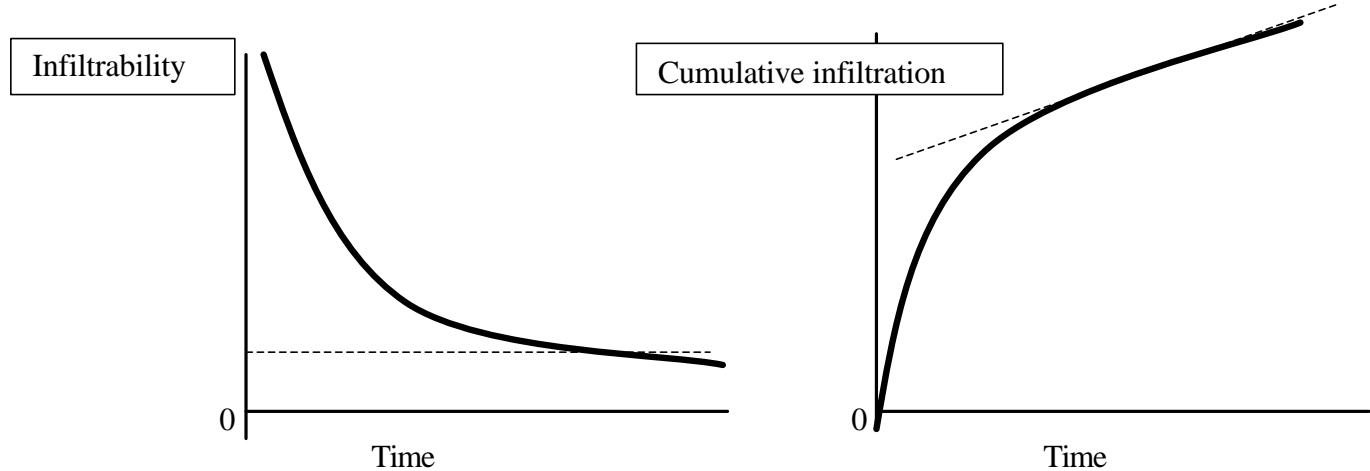
$$\frac{\Delta z}{\Delta X} > \frac{\Delta h}{\Delta X} \quad \frac{\Delta H}{\Delta X} \approx I$$

Infiltration is controlled by gravity.

(Hydraulic conductivity, K_o , in transmission zone determines the infiltration rate)

Infiltration vs. Time (vertical infiltration)

: Infiltration rate, when soil surface is ponded.



★ What are the units of Infiltrability (i) and Cumulative infiltration (I) ?

$$I = \int i dt \quad \text{and} \quad i = \frac{dI}{dt}$$

Infiltration rate curves show :

- Rapid initial decrease of infiltration rate;
- Infiltration rate decreases, as the total head gradient decreases
- Approximate steady state infiltration is approached at large times, at which the infiltration rate is about equal to the hydraulic conductivity of the transmission zone (K_o).

Equations for Cumulative Infiltration - Approximate solutions

Horizontal Infiltration (gravity gradients not present)

$$I = \frac{V}{A} = S t^{1/2} \quad \text{and} \quad i = dI/dt \quad \text{Also:} \quad L = N t^{3/2}$$

where I is cumulative infiltration (cm)
 i is infiltration rate (cm per unit time)
 V is volume of water (cm³)
 A is cross-sectional area of soil (cm²)
 S is sorptivity (cm time^{-0.5})
 t is time
 L is distance to wetting front (cm)

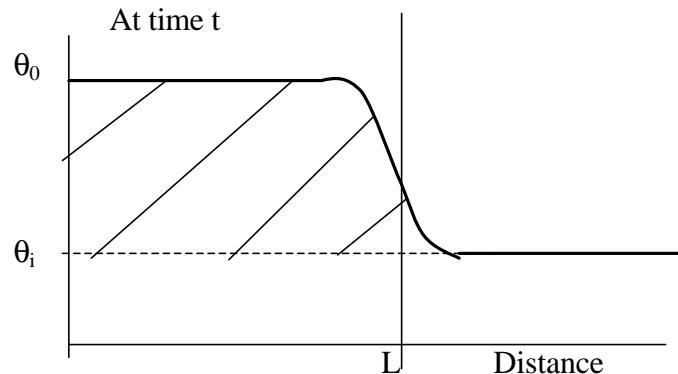
★ Explain the difference between cumulative infiltration (I) and L ?

$$I = \text{Cumulative infiltration} = \text{Volume of water added (cm}^3\text{) / Area (cm}^2\text{)}$$

Or: $I = (\text{Vol of water in column at time } t \text{ minus vol of water in column at initial time } t_i)/(\text{area of column})$

$$I = \frac{V_t - V_i}{A} \cdot \frac{L}{L} = [(\text{Vol of water at } t - \text{Vol of water at } t_i)L]/(\text{wetted bulk volume})$$

or: $I = (q_o - q_i)L$



Approximate solution for horizontal infiltration (Green and Ampt model)

Infiltration boundary
condition

$$\theta = q_o$$

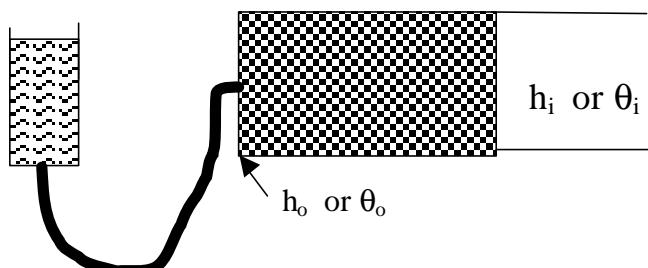
Initial condition

$$q = q_i$$

$$h = h_o$$

$$h = h_i$$

$$(h_o > h_i)$$



$$I = \frac{V}{A} \quad \text{and} \quad i = \frac{1}{A} \frac{dV}{dt}$$

$$V = A I = A (q_o - q_i)L$$

$$\frac{dV}{dt} = A (q_o - q_i) \frac{dL}{dt}$$

$$\mathbf{i} = \mathbf{J}_w = \frac{\mathbf{1} d\mathbf{V}}{A dt} = (q_o - q_i) \frac{dL}{dt}$$

Also:

$$\mathbf{i} = \frac{d\mathbf{V}}{Adt} = -K_o \frac{dH}{dX} = -K_o \frac{dh}{dX} = -K_o \frac{h_i - h_o}{L}$$

$$\text{Combine: } (q_o - q_i) \frac{dL}{dt} = -K_o \frac{(h_i - h_o)}{L}$$

$$\int_0^L L dL = - K_o \left(\frac{h_i - h_o}{q_o - q_i} \right) \int_0^t dt$$

$$\frac{L^2}{2} \Big|_0^L = - K_o \left(\frac{h_i - h_o}{q_o - q_i} \right) t \Big|_0^t$$

$$L = \sqrt{\frac{-2 K_o (h_i - h_o)}{q_o - q_i}} t^{0.5} \quad , \text{ or} \quad L = N t^{1/2} \quad , \text{ where}$$

$$N = \sqrt{\frac{-2 K_o (h_i - h_o)}{q_o - q_i}}$$

and

both $N = f(K_o, h_i, h_o, q_o, q_i)$

★ Using the above, derive the functional expression for S

$$I = \Delta\theta L = \Delta\theta N t^{0.5} = St^{0.5} \quad \{ \Delta\theta = q_o - q_i \}$$

Hence, $S = N \Delta\theta = \dots$

So, also $S = f(K_o, h_i, h_o, q_o, q_i)$

Vertical Infiltration (must add more terms to account for gravity)

A rigorous solution was presented by Philip, which is a series solution:

$$I = St^{1/2} + A_1 t + A_2 t^{3/2} + \dots$$

This series equation is generally approximated by dropping all but the first two terms to give the so-called Philip infiltration equation:

$$I = S t^{1/2} + A t$$

where A is a constant (not area) and S is defined as the sorptivity

Then infiltration rate can be calculated from its derivative with time:

$$i = dI/dt = 0.5St^{-1/2} + A$$

Also an expression for distance to the wetting front (L) can be computed from:

$$L = N t^{1/2} + N' t$$

where N' is an additional constant

The second term of these equations accounts for gravity

★ Give expressions for both N and N'

$$L = I/\Delta\theta = (S t^{1/2} + A t)/\Delta\theta = N t^{1/2} + N' t$$

$$\text{Hence, } N = S/\Delta\theta \text{ and } N' = A/\Delta\theta$$

Equations for Infiltration Rates at a Specific Time

Horizontal Infiltration Rate

$$i = \frac{d(I)}{dt} = \frac{1}{2} St^{-0.5}$$

where i is the infiltration rate

As t approaches ∞ , i goes to 0

Vertical Infiltration Rate

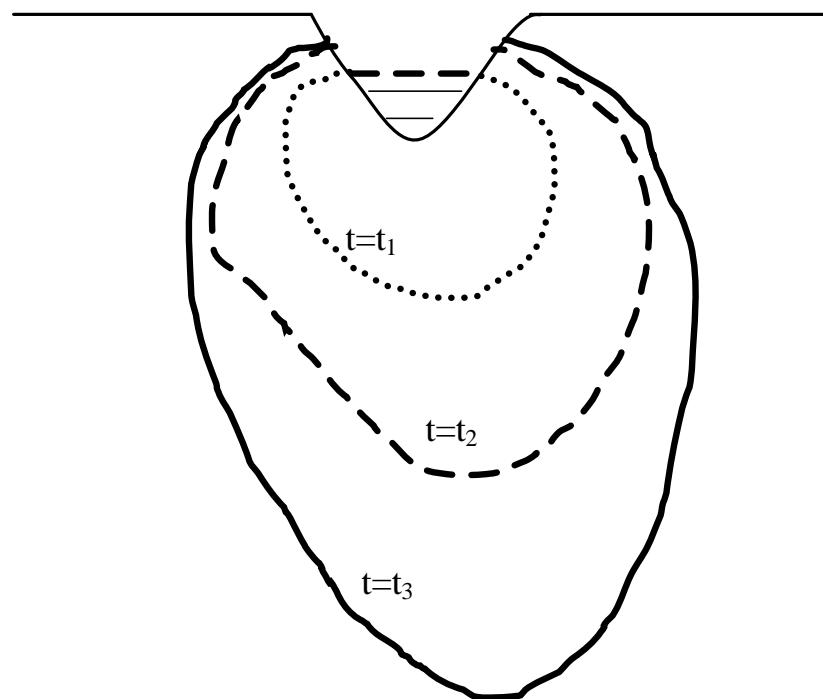
$$i = \frac{d(I)}{dt} = \frac{1}{2} St^{-1/2} + A$$

as t approaches ∞ , i becomes equal to A (a constant)

For small times, vertical infiltration behaves as if horizontal infiltration because soil water pressure potential gradients dominate over the gravitational gradient.

Example: Infiltration from an irrigation furrow into an initially dry soil.

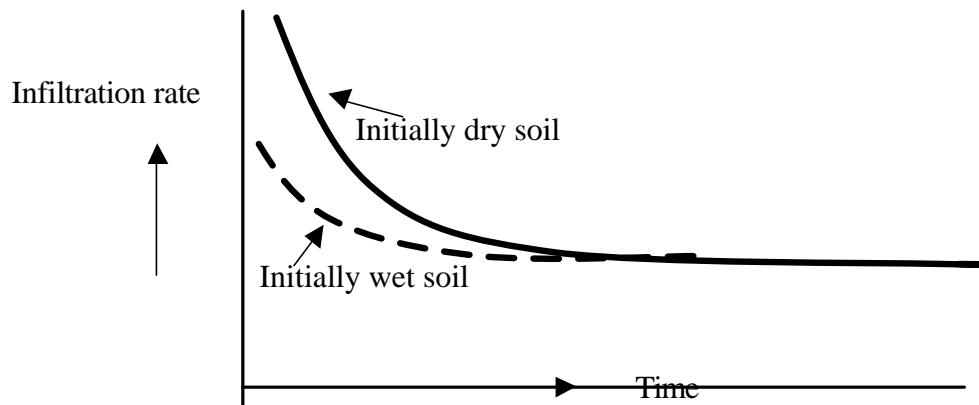
$$t_1 < t_2 < t_3$$



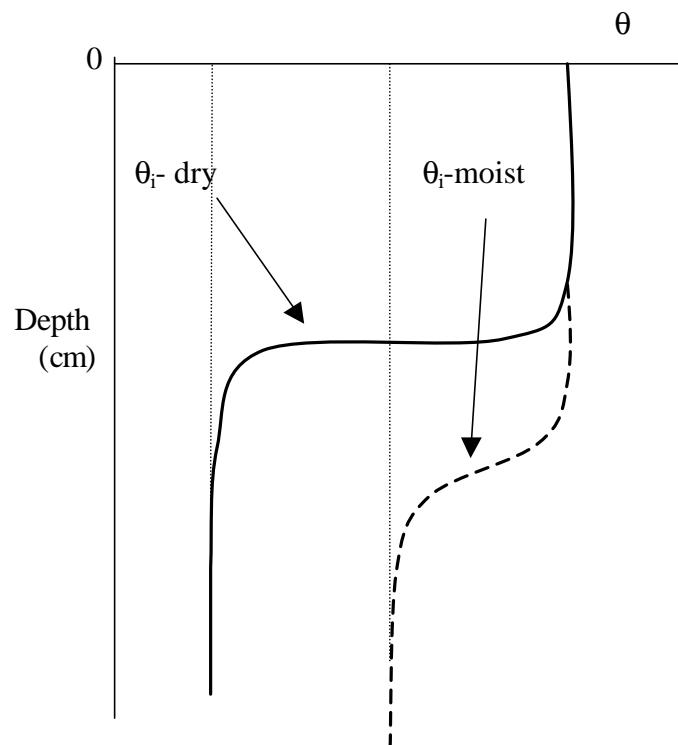
Effect of Soil Properties on Infiltration

- Effects of soil moisture, texture and layering:

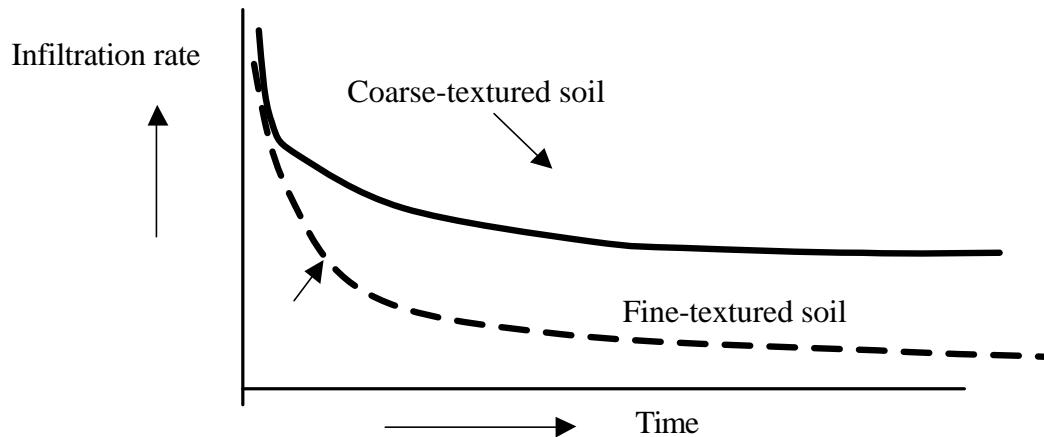
Soil moisture:



At equal infiltration time (t):

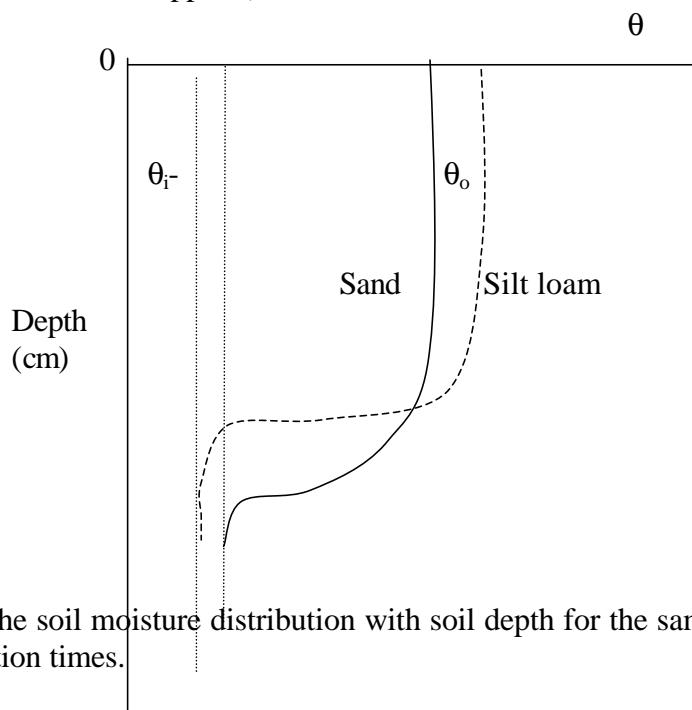


For both soils: $I = \Delta\theta L_{\text{wetting front}}$

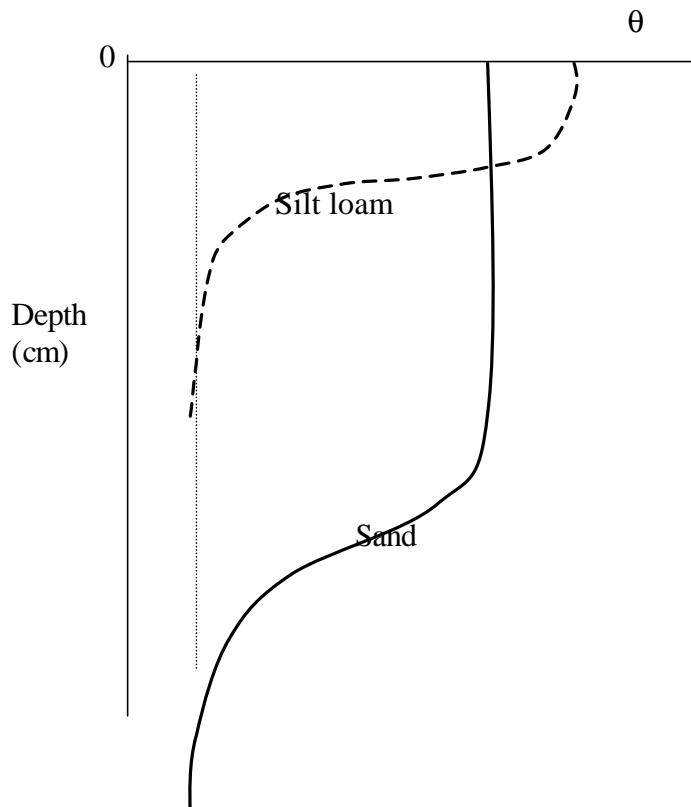
Soil texture:

Soil Type	Final infiltration rate (mm/hr)
Sands	> 20
Sandy/Silty soils	10-20
Loams	5-10
Clayey soils	1-5
Sodic clayey soils	< 1

Same I (same amount of water applied)



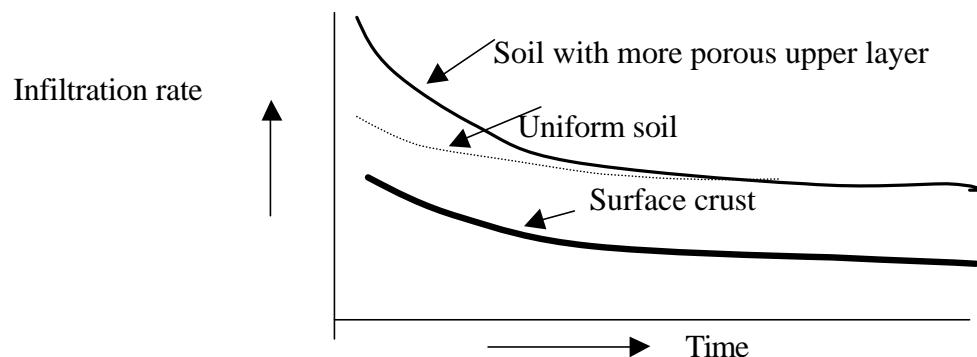
- ★ Show the soil moisture distribution with soil depth for the same two soils, but at equal infiltration times.



Surface crusts:

Can develop by:

- Soil surface compaction
- Slaking of soil aggregates at soil surface by rainfall/irrigation



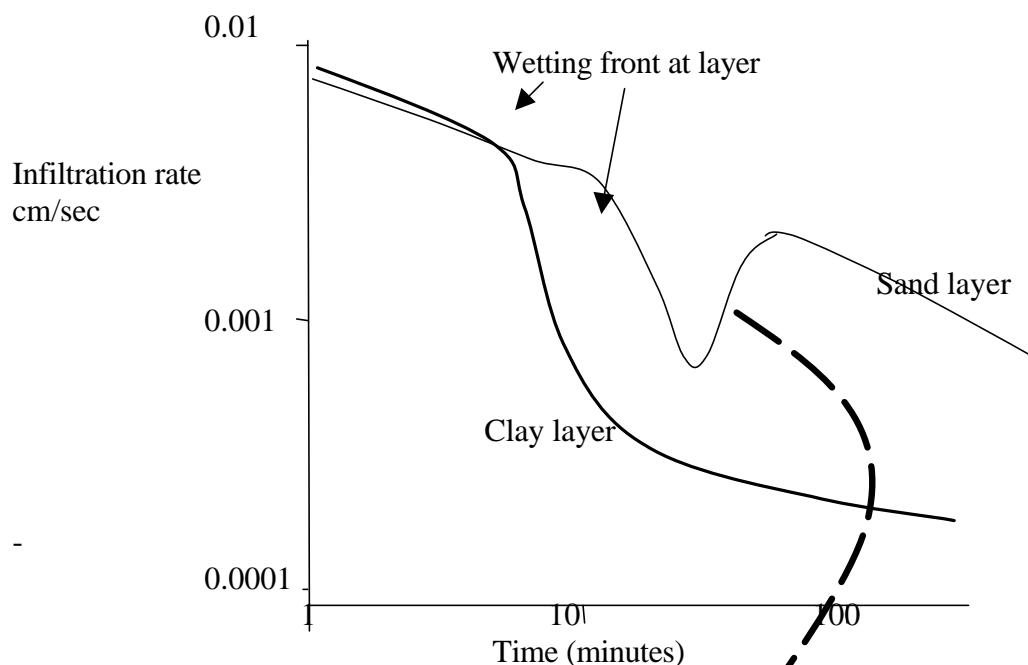
Soil layering:

- Effect of soil layering depends on soil texture variations between layers

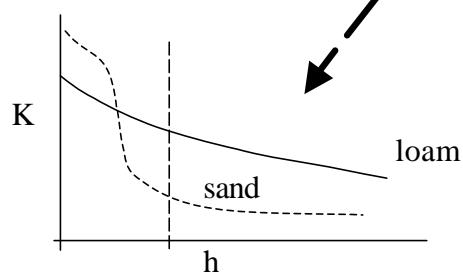
- Generally, any soil layers that are present will decrease water infiltration

If clay layer: Clay impedes infiltration because of lower saturated hydraulic conductivity

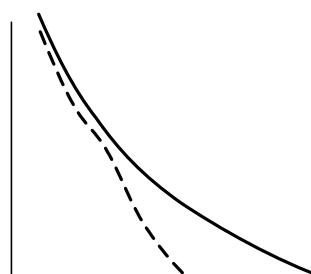
If sand layer: Sandy layer will reduce infiltration rate temporarily and retards moving of the wetting front due to its lower unsaturated hydraulic conductivity

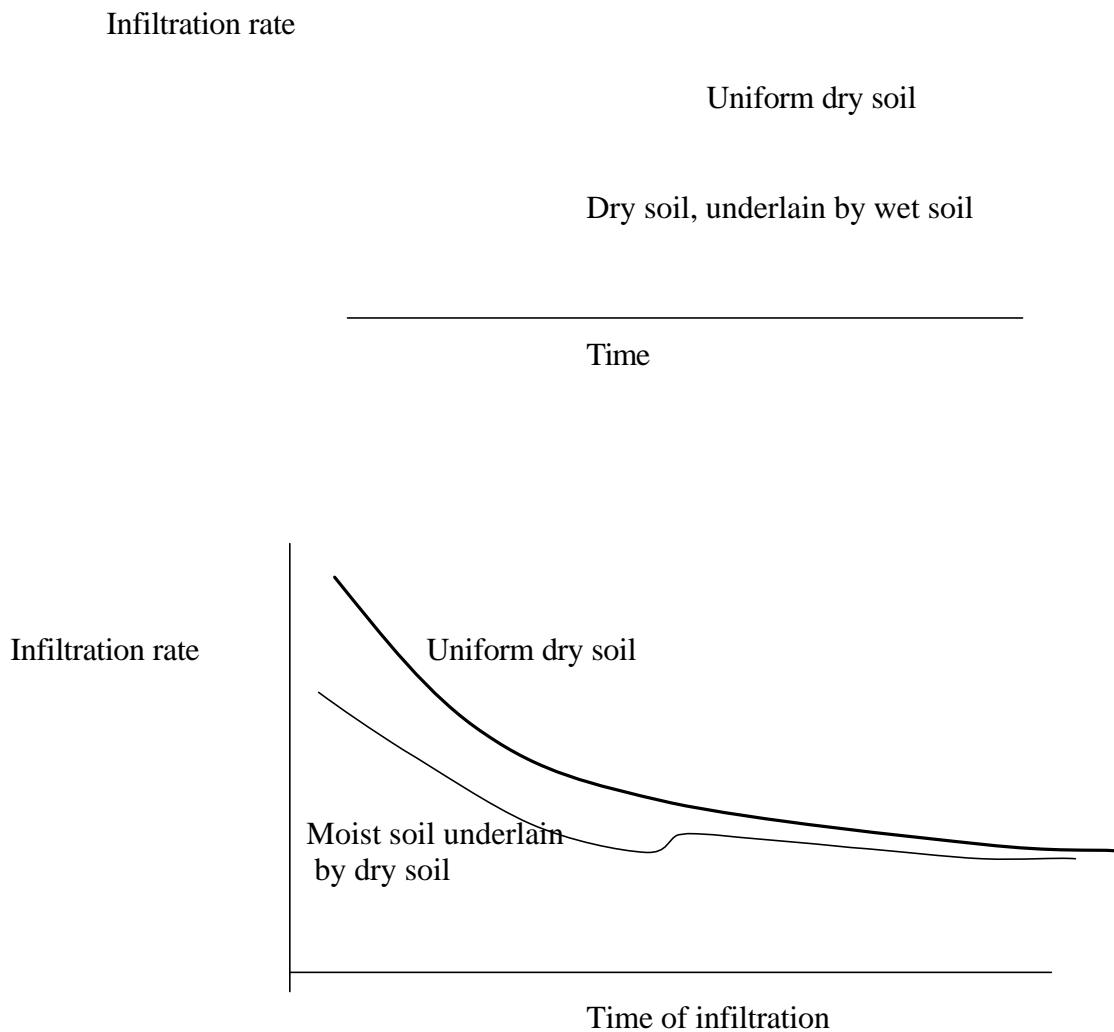


Infiltration rate into a horizontal, air-dry column of silt loam as a function of time as influenced by a clay and by a sand layer.

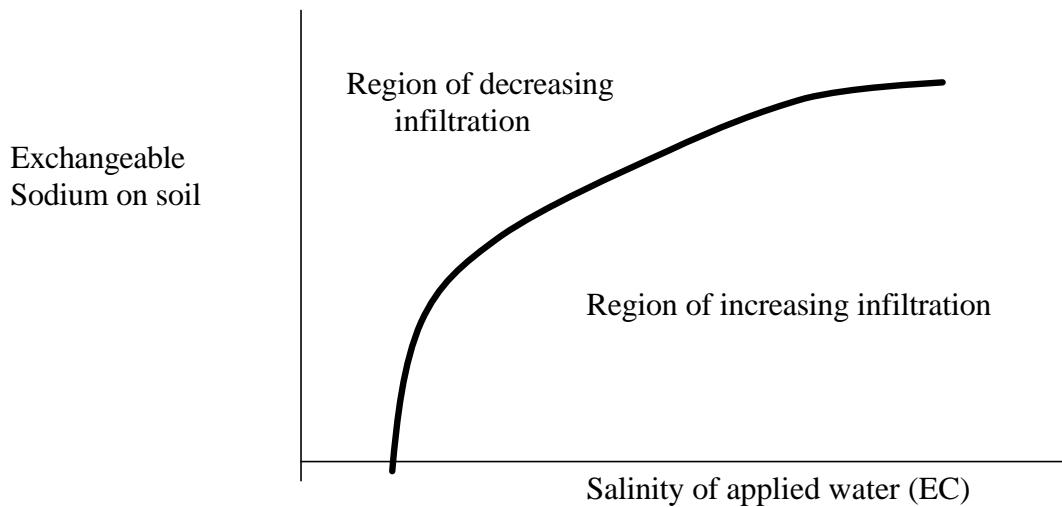


Other examples:

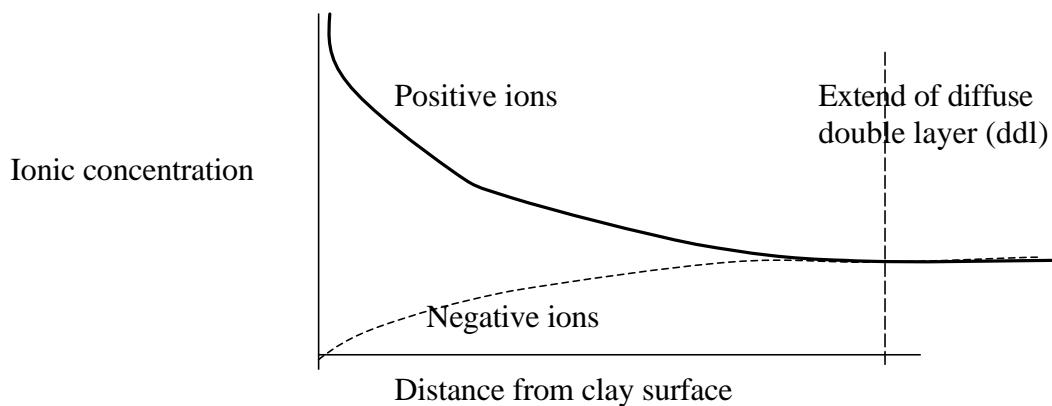




Effect of Irrigation Water Quality on Infiltration



This phenomena of the effect of irrigation water quality on infiltration is a complex process associated with the electrical double layer of clay particles and with swelling and dispersion. This process can be explained by differences in osmotic potential between the bulk soil solution and the water and cations between clay plates.

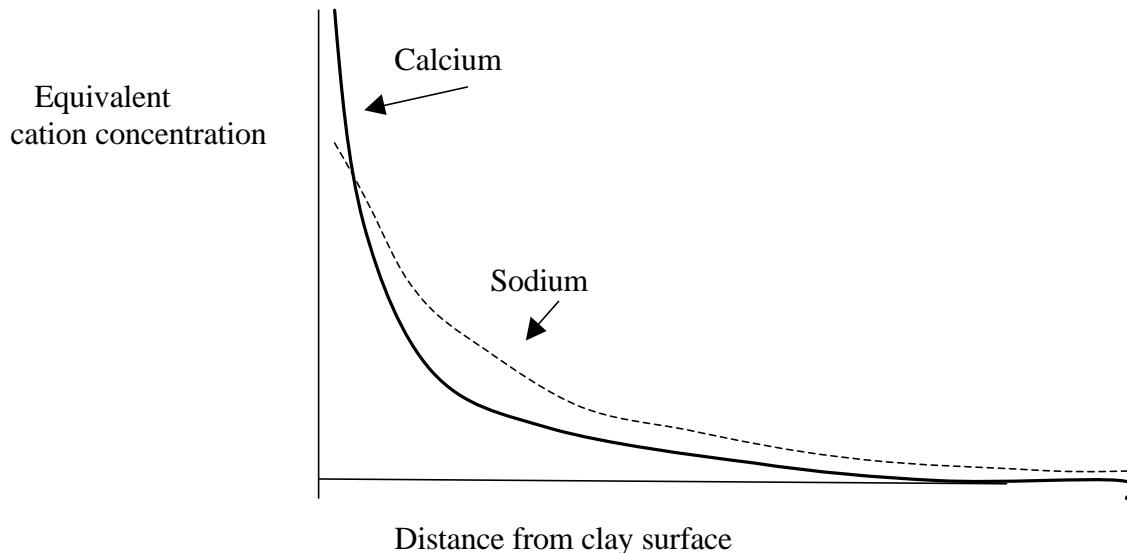


The concentration of cations between parallel clay plates is large due to the necessity to offset the negative charge of the clay. At a high electrolyte concentration of the bulk solution, the system can be considered to be somewhat at equilibrium with the osmotic potential being about the same in

the solution between the clay plates and the bulk solution. When the bulk solution electrolyte concentration is dropped drastically by adding pure water, an osmotic potential gradient is set up between the bulk solution and that between the clay plates. Thus, water moves from the bulk solution to the area between the clay plates causing the plates to be pushed apart or the soil to swell. This swelling decreases the volume of pores through which infiltration occurs and thus decreases infiltration rate. If a large amount of water is imbibed between clay particles, some of the particles may break away and move with the infiltrating water until a constriction is reached causing plugging of the pores.

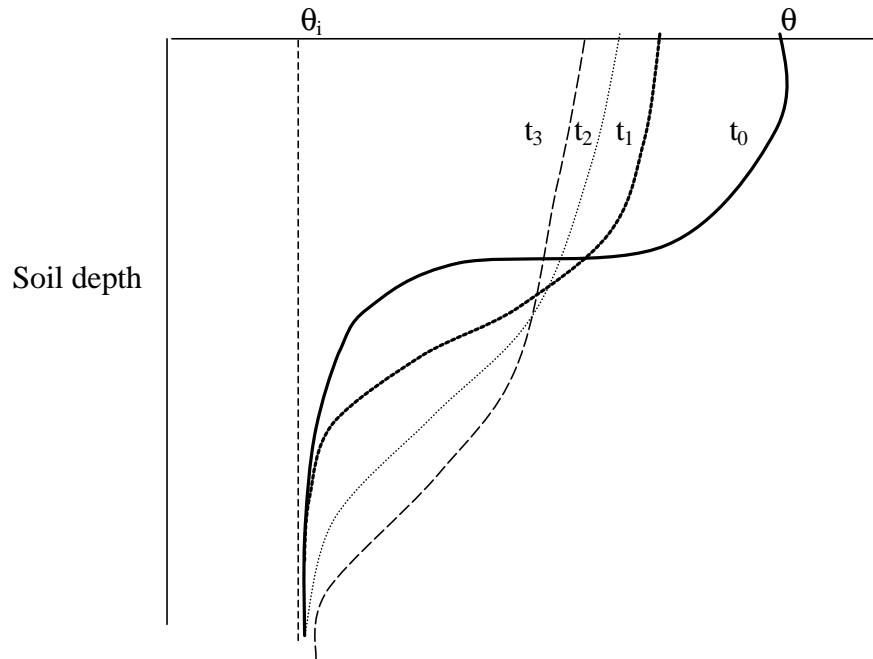
How does the amount of exchangeable sodium compared to divalent cations such as calcium and magnesium affect this process? Since sodium is monovalent, twice as many sodium ions would be required between the clay plates to balance the negative charge than if the cations were divalent (calcium). This means that sodium on the exchange sites of the clay would create a larger osmotic potential gradient than would calcium. Sodium also has a much larger hydration shell than calcium, which also causes more swelling and dispersion (if thickness of ddl becomes large).

Influence of cation valence of thickness of diffuse double layer (ddl):



Larger thickness of ddl for sodium soils is caused by the smaller electrostatic forces of attraction between cations and negatively-charged clay surface, than if cations are divalent.

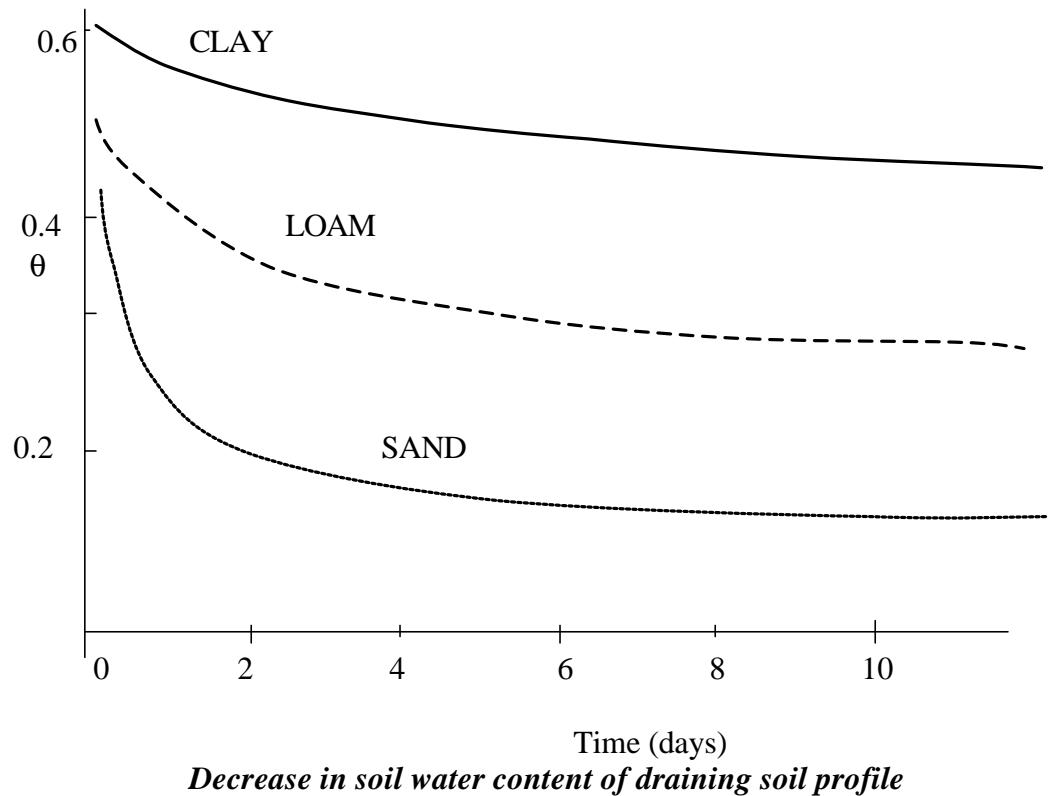
Redistribution



The changing soil moisture profile during redistribution following an irrigation.

- Sharp front during infiltration gradually dissipates during redistribution
- Sublayers wet and then drain
- If initial wetting depth small and the underlying soil is dry, then redistribution will be rapid
- If initial wetting depth is large and the underlying soil is moist, then redistribution is slow

AFTER FULLY WETTING SOIL PROFILE:



Decrease in soil water content of draining soil profile

- K of sand decreases more rapidly than K of clay for decreasing soil-water content.
- Redistribution lasts longer in clay than in sand

Also:

- Rate of redistribution decreases with time
- Initial rate depends on initial wetting depth, dryness of lower depths, and K versus θ relationship of the soil

Decrease of redistribution with time is caused by:

1. $\frac{\Delta h}{\Delta X}$ decreases with time as wet zone loses water and dry zone gains water
2. K decreases with time as wet zone θ decreases, so both $\frac{\Delta H}{\Delta X}$ and K are decreasing with time.

Therefore, J_w (redistribution rate) is decreasing with time as well

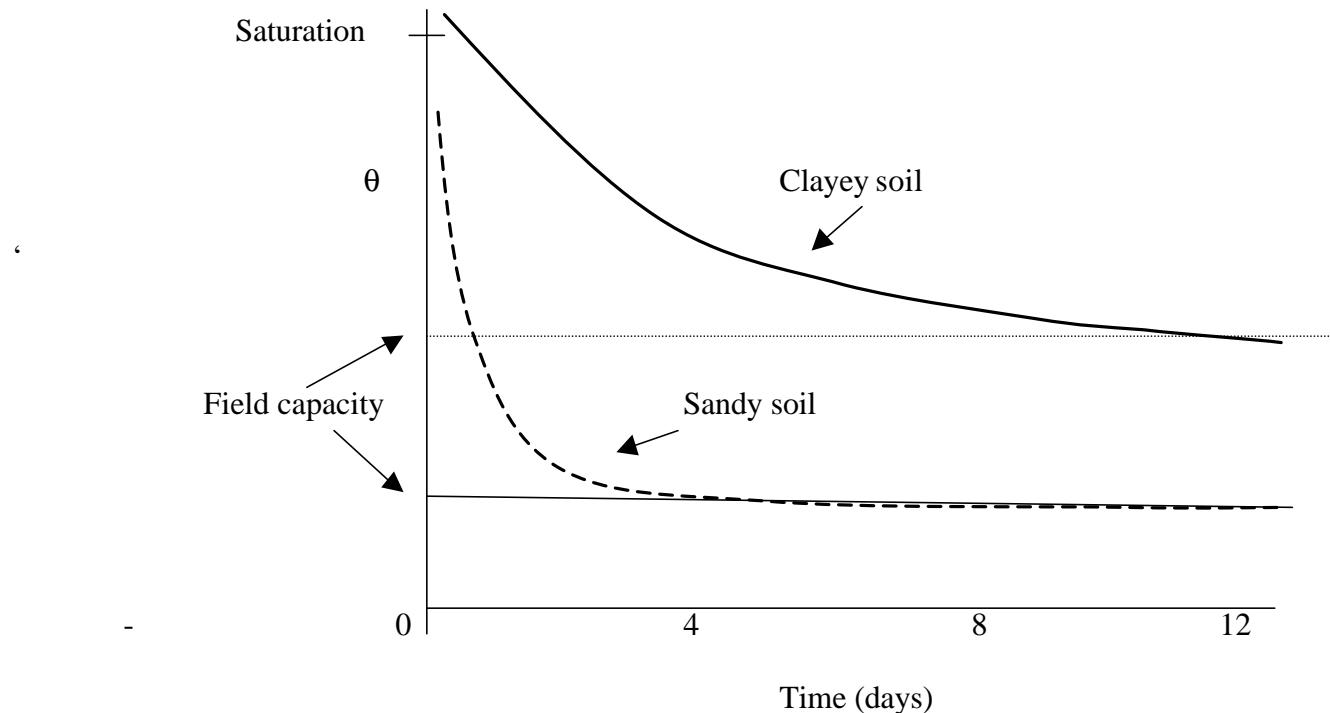
Also, redistribution results in drying of the surface soil and wetting of the subsurface soil:

- Soil is both wetting and drying (hysteresis)
- θ versus h becomes complicated
- Net effect of simultaneously wetting and drying within soil profile is to retard water redistribution

Field Capacity (only applies to field soils)

FORMAL DEFINITION:

"The amount of water held in soil after excess water has drained away and the rate of downward movement has materially decreased, which usually takes place within 2 - 3 days after a rain or irrigation in pervious soils of uniform structure and texture".



- Above curves differ somewhat for different amounts of infiltration, depth of wetting, and θ at the end of infiltration
- Rate of drainage from any given layer depends not only on the hydraulic characteristics of that layer, but also on the characteristics of the entire profile
- Field capacity is not a unique value

Factors affecting field capacity

1. Texture

The finer the texture of the soil particles, the higher is the apparent field capacity and the slower it is attained. Also its value will be less distinct

$$\text{Field capacity} \quad \begin{cases} = 0.04 \text{ sands} \\ = 0.45 \text{ clay} \end{cases}$$

2. Type of Clay

Soils high in montmorillonite have higher field capacity values

3. Organic Matter

Increases field capacity (as high as 100% in organic soils)

4. Depth of initial wetting

In general (but not always),

The wetter the lower soil profile at the beginning of redistribution, and the greater the depth of wetting, the slower the rate of redistribution, and the greater the value of field capacity

5. Impeding layers

Inhibit redistribution and increase field capacity

6. Evapotranspiration

Modifies redistribution and affects field capacity

★ How will evaporation affect field capacity?

Redistribution - mathematical solution

Transient state (Richards equation)

$$\frac{\partial \bar{q}}{\partial t} = \frac{\partial}{\partial z} \left(D \frac{\partial q}{\partial z} \right) + \frac{\partial K}{\partial z}$$

Gardner et al. (1970) solved for $D = c \theta^m$, $K = B\theta^m$

to give an equation with a form like

$$\bar{q} \approx a(b+t)^{-c}$$

with a and b related to K & D

b was found to be small after a couple of days, so can be simplified to:

$$\text{Hence: } \bar{q} = at^{-c}$$

Change in θ with time

$$-\frac{d\bar{q}}{dt} = -cat^{-c-1} \quad \text{or} \quad -\frac{d\bar{q}}{dt} = cat^{-(c+1)}$$

Gardner's approximate equation is similar to an empirical equation by Richards (1956)

$$-\frac{d\bar{q}}{dt} = at^{-b}$$

where rate of θ - change is inversely related to time.

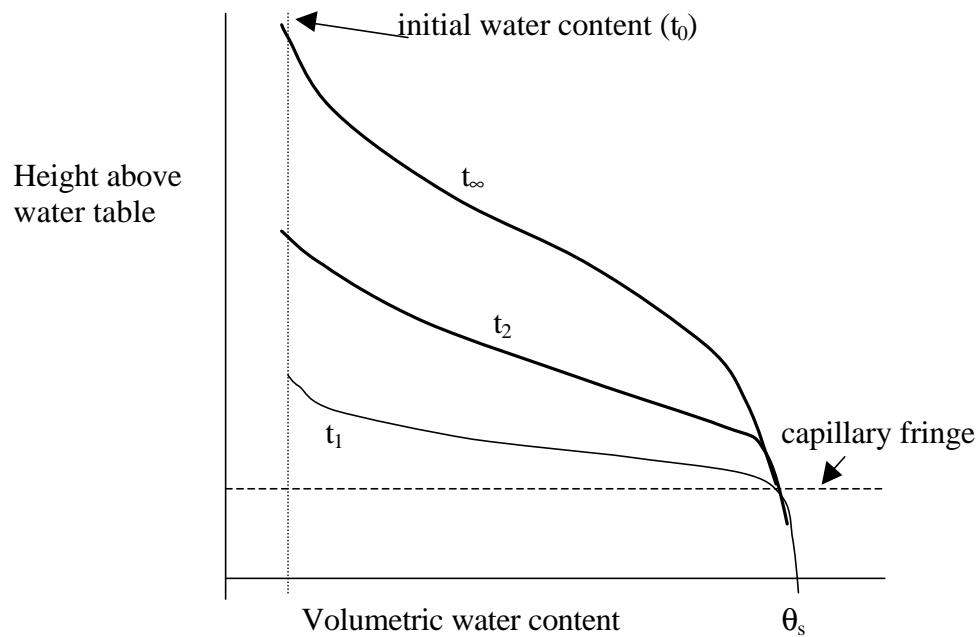
Evaporation - Bare Surface Soil

- Removal of water from the soil by evaporation.
- 3 conditions are necessary for evaporation to occur
 1. Heat supply - 590 cal/g or 2500 J/g H₂O
 2. Vapor pressure gradient between soil and air
 3. Supply of H₂O from underlying soil to surface
- Evaporation situations considered here are:
 1. Situations of shallow groundwater (may be steady flow)
 2. Situations of deep water table (transient flow)
 3. One-dimensional and 2- or 3-dimensional flow (cracks)
 4. Environmental conditions constant or fluctuating

1. Steady state evaporation, with a shallow water table (capillary rise)

- Upward flow possible because of capillary rise from water table
- Water moves upward from water table into initially dry soil because of total soil water potential decreasing upwards.
- Rate of upward water movement decreases with time, as the total water potential gradient approaches zero.

$$\text{at } t \rightarrow \text{infinity}, \frac{\Delta H}{\Delta z} = 0, \quad \text{and} \quad h = -z \quad (\text{if reference level at water table})$$



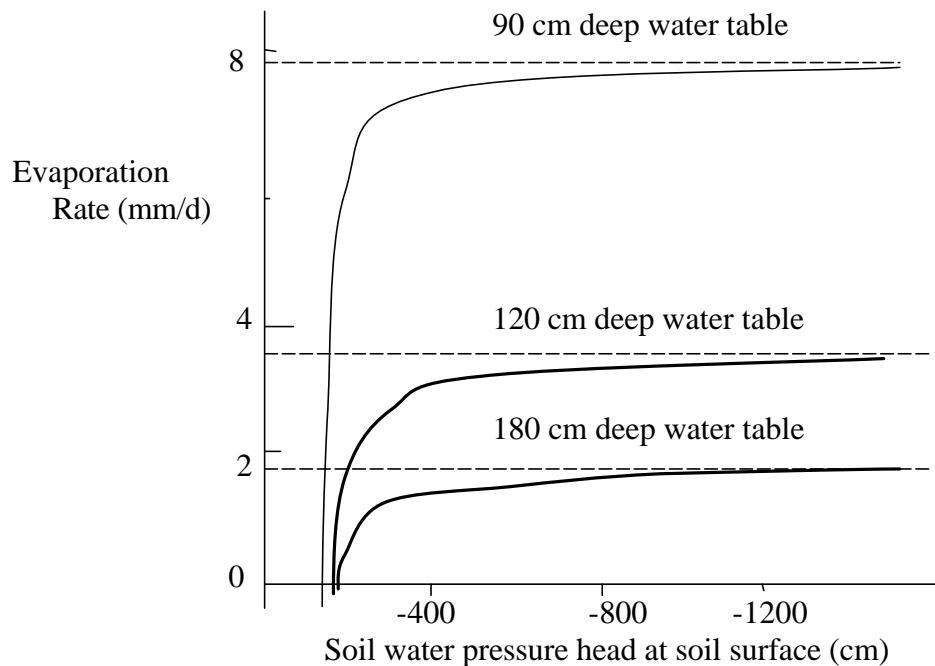
Capillary fringe - that distance above the water table where the soil pores are still full of water but the pressure head is slightly negative (most likely seen in soils with narrow pore size distributions, i.e. very fine sands of uniform particle size at high ρ_b). Even though matric potential is slightly negative the soil is still saturated and K is a constant within the fringe and the water table (equivalent to air-entry value phenomenon of porous cups/plates)

Shallow water tables

1. May supply some crop needs
2. May also transport salt to surface and cause extreme salinization

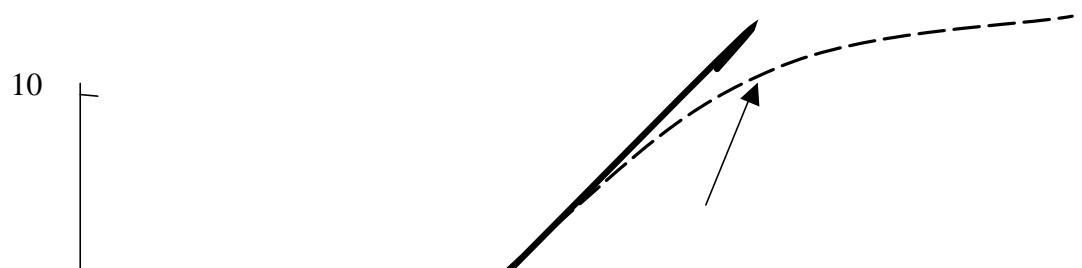
Steady evaporation from water table

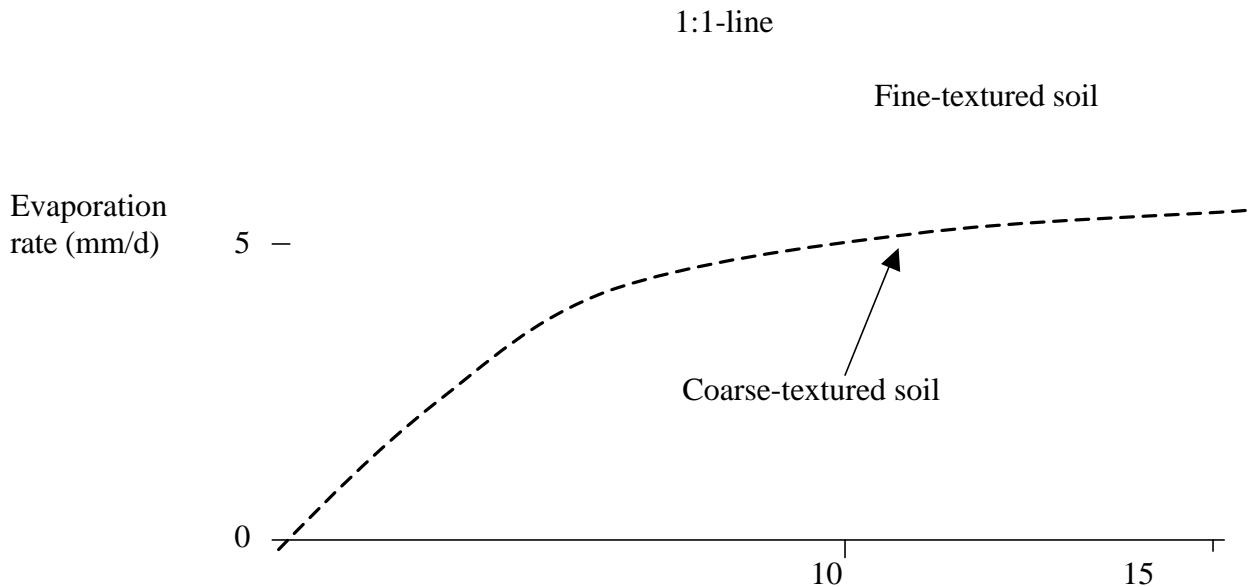
$$q = -K \frac{\Delta H}{\Delta z}$$



Steady-state rate of upward flow (evaporation rate) as a function of water table depth and soil water pressure head at soil surface.

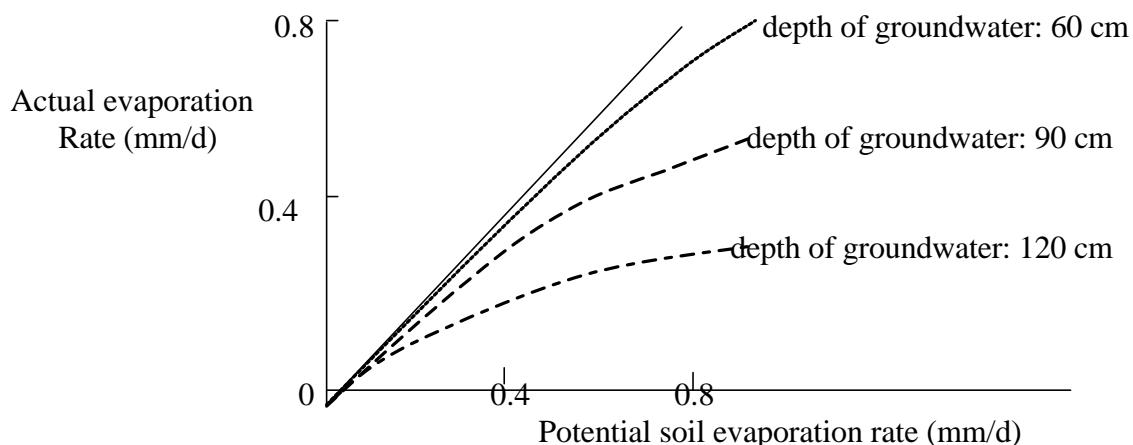
- As the stationary water table is closer to the soil surface, the total hydraulic gradient at steady state is larger. Hence, the maximum possible evaporation rate increases.
- As the soil-water pressure head at the soil surface decreases (become more negative), the steady state evaporation rate increases because the total hydraulic gradient increases.
- However, the steady state evaporation rate reaches an asymptotic value, because the unsaturated hydraulic conductivity decreases as the soil-water pressure head decreases.
- Therefore, the steady evaporation rate will be a function of soil type.





Relationship between soil evaporation rate and maximum possible evaporation rate for a free-water surface (evaporative demand).

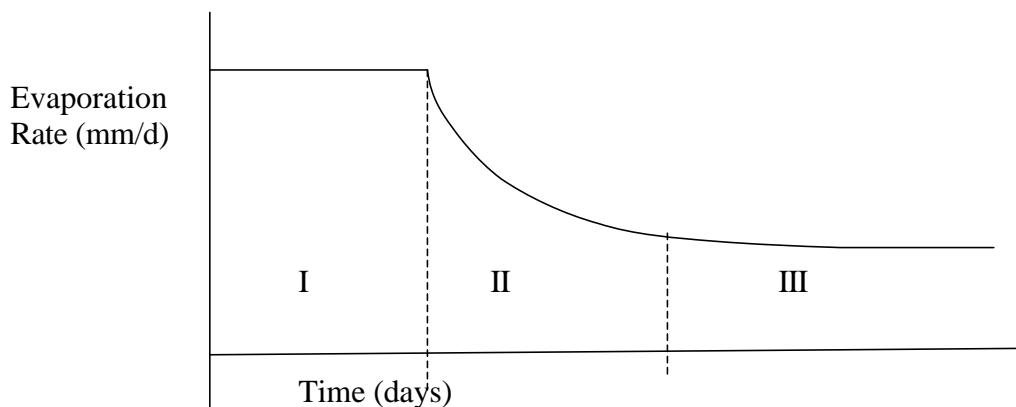
- Relationship of above will be affected by depth of shallow groundwater
- Evaporative demand is controlled by atmospheric conditions (temperature, net radiation, wind speed, vapor pressure)
- Lower soil evaporation rates, as compared to evaporative demand, is controlled by ability of soil to transmit soil water towards the soil surface (e.g. unsaturated hydraulic conductivity).



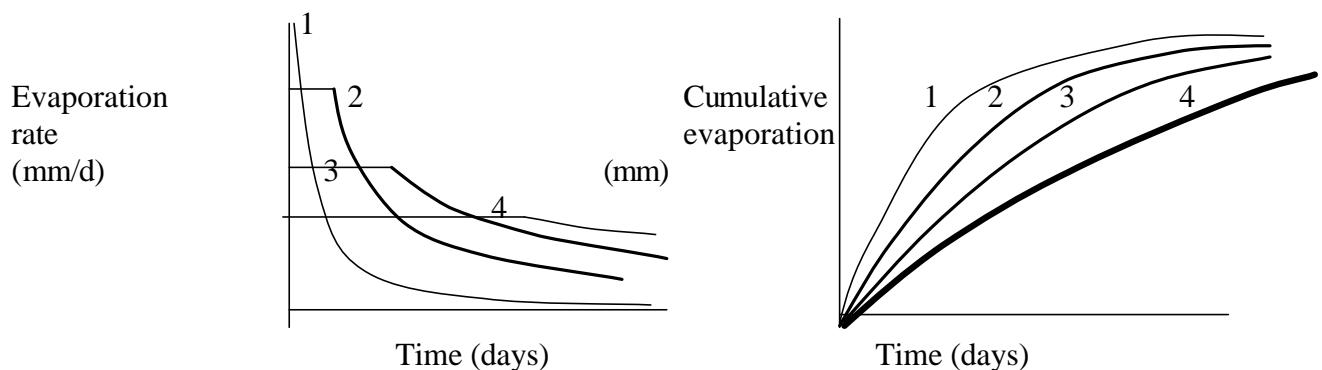
2. Evaporation with very deep water table (transient evaporation)

Characteristics:

- Drying process
- Unsteady flow
- Drying occurs in 3 stages
 1. Constant-rate stage - I
 2. Falling-rate stage - II
 3. Slow-rate stage - III



- Length of drying stages depends on evaporative demand:Evaporative demand decreases from situations 1 to 4.



When evaporative demand is high, initial evaporation rate will be high, but will faster decline as compared to those conditions where the evaporative demand is lower.

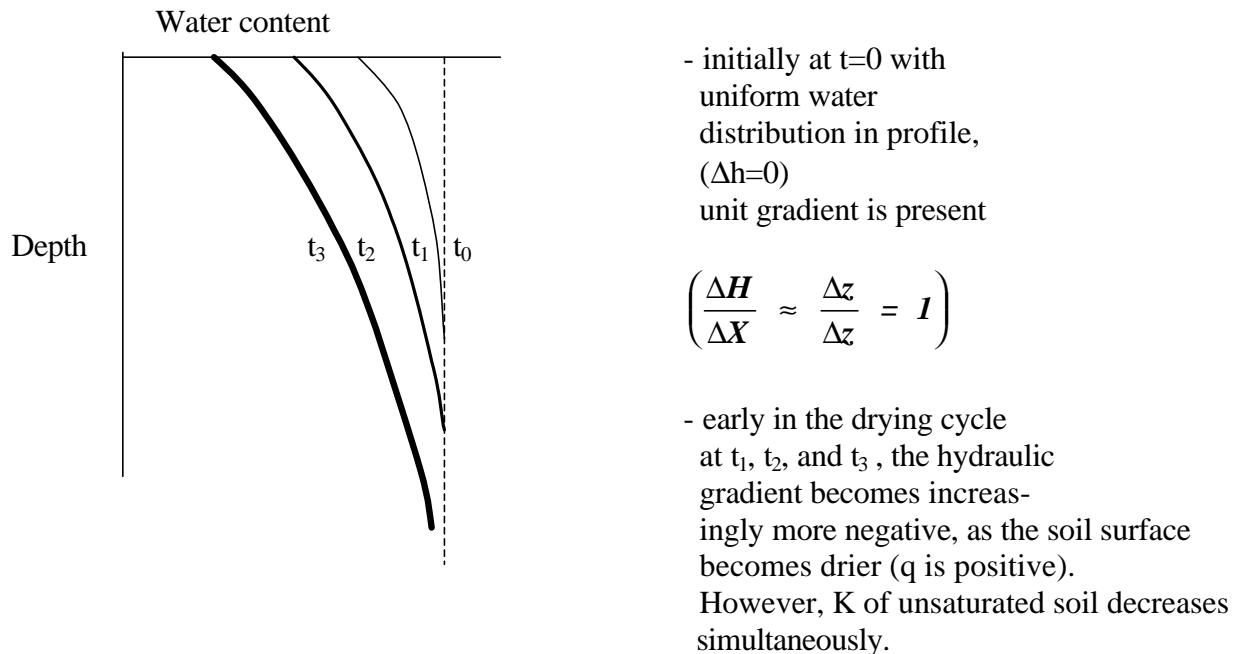
The fast decline of evaporation rate is caused by the lower hydraulic conductivity

of the soil as the near soil decreases in water content.

However, given it enough time, all curves will eventually approach the same amount of cumulative evaporation (mm).

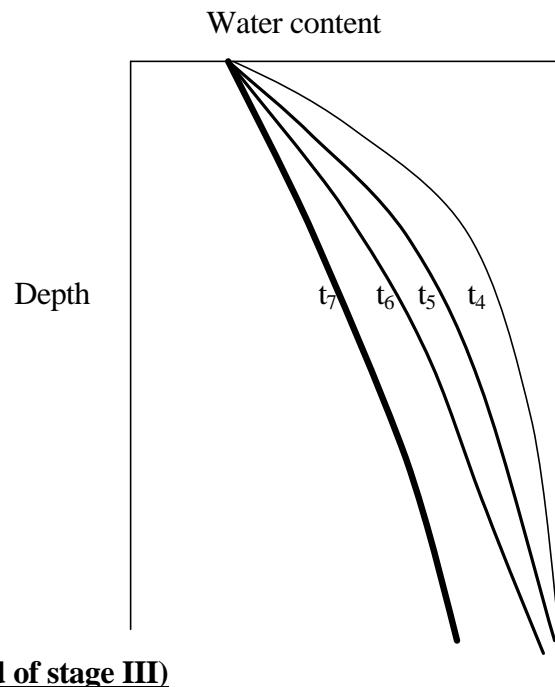
Constant-Rate Stage - I

- Soil is wet
- Soil can supply enough H₂O to surface to meet evaporative demand
- May last a few hours to a few days



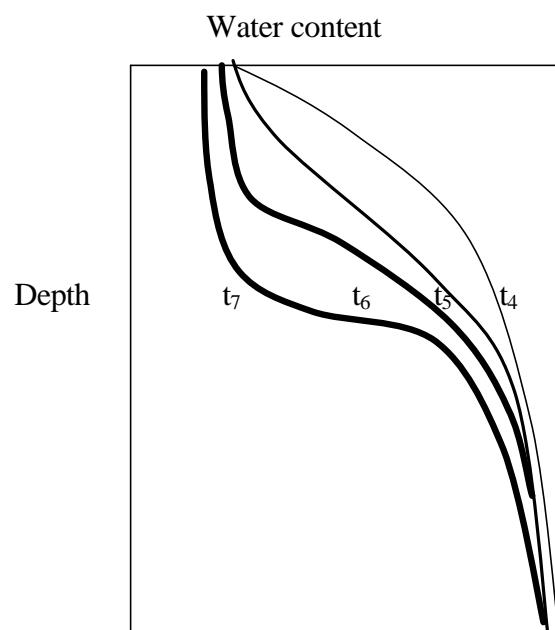
Falling- and Slow-Rate Stages - II and III

- Rate drops below evaporative demand
- Soil limits water transport to surface
- Surface is air-dry
- Gradients are decreasing less negative
- K decreases
- J_w or evaporation rate drops
- Drying front moves down

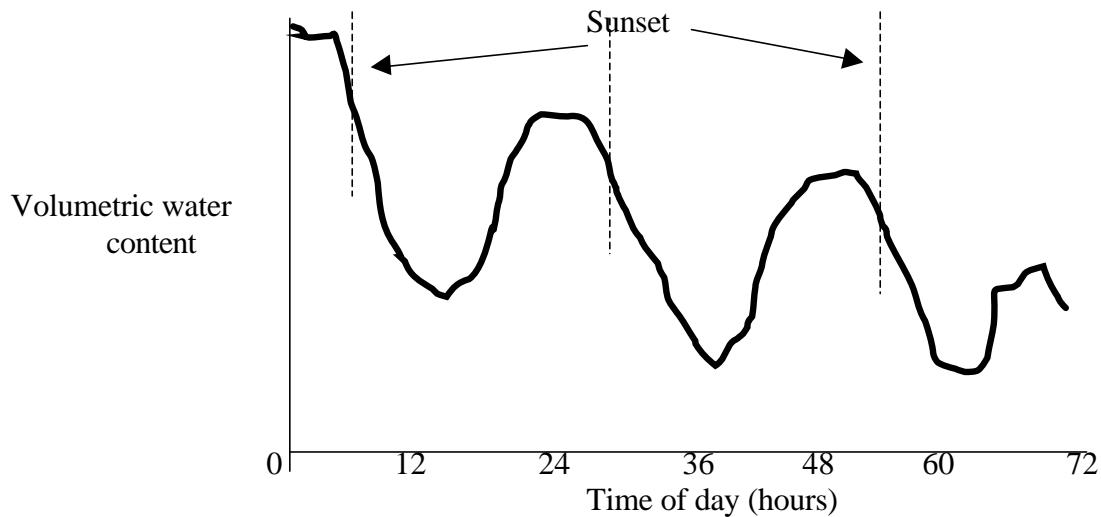


Drying Front (end of stage III)

- Air-dry soil zone increases
- Water must move across air-dry zone by vapor diffusion
- Vapor flow follows diffusion equation
- Thermal gradients tend water to move from hot to cold soil, which tends to somewhat reverse flow when surface hot



3. Fluctuating Evaporative Demand



- Soil surface dries during day and tends to rewet at night
- Three stages of drying may not have much meaning in field

Reduction of Evaporation

Flux modified by

1. Controlling energy supply
 - changing color
 - shading
2. Reducing soil-water pressure head gradients
 - lowering water table
 - surface heating which sets up downward-acting thermal gradient
3. Decreasing K in profile especially in surface
 - tillage
 - mulches

Tillage is generally effective only if it creates a coarse layer of stable aggregates