Hydrology
CEE 440, CEE 545, GLG 471
Arizona State University

Lecture 7:

1. Water in Soils: Infiltration and Redistribution

Precipitation leads to a soil hydrologic response. Infiltration is the movement of water from the soil surface into the soil. Redistribution is the subsequent movement of infiltrated water in a soil column. Infiltration and redistribution are important hydrologic processes. As infiltration is estimated to be 76% of rainfall over the land-surface area, an appropriate understanding of unsaturated zone processes is essential.

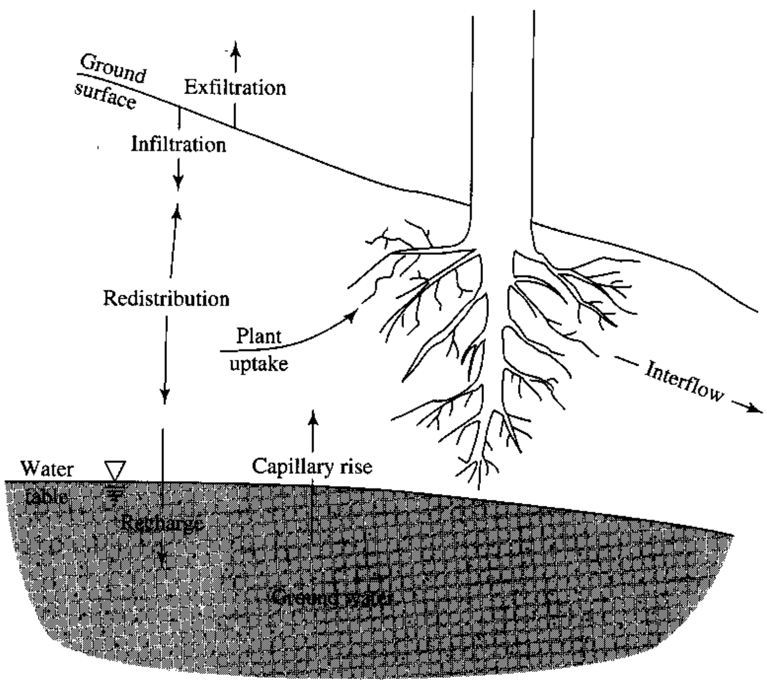
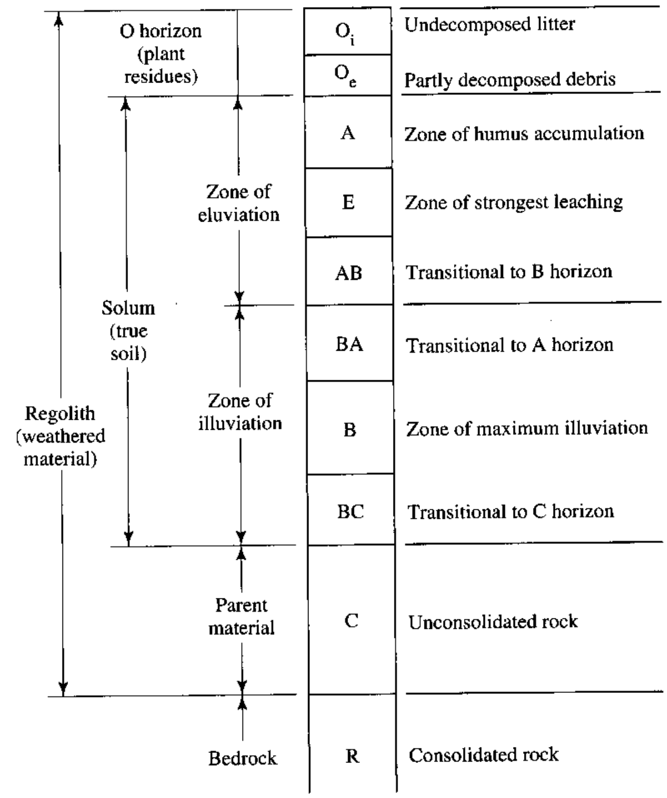


Diagram of Infiltration and Redistribution in Unsaturated (Vadose) Zone

Definition of Terms:

(1) Infiltration:	Downward flux from soil surface into soil profile.
(2) Exfiltration:	Upward flux from soil to atmosphere due to evaporation.
(3) Redistribution:	Downward (or lateral) flux in soil profile.
(4) Interflow:	Lateral downslope flux in the unsaturated zone.
(5) Percolation:	General term for downward flux in unsaturated zone.
(6) Recharge:	Unsaturated zone flux into saturated zone.
(7) Capillary Rise:	Saturated zone flux into unsaturated zone.
(8) Plant Uptake:	Root water uptake for plant consumption and transpiration.



Pedologic Soil Profile Horizons

The properties of a soil profile are important to understand infiltration. A soil profile consists of various pedologic units:

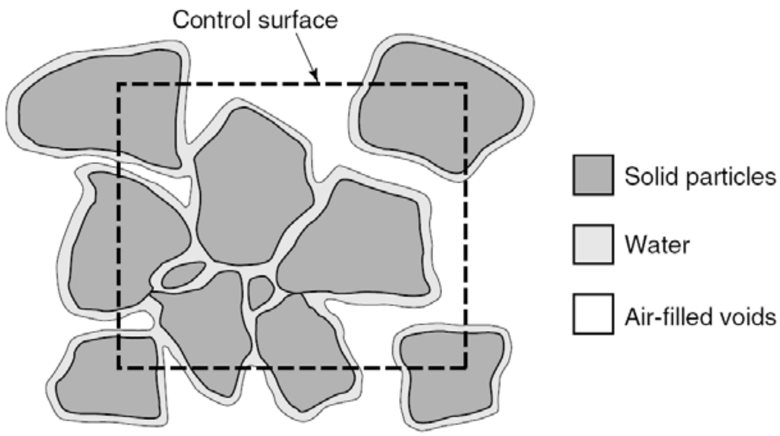
(1) These are distinguished by the proportion of organic matter, and the degree to which material has been removed (eluviated) or deposited (illuviated) by chemical, physical and biological processes.
(2) Each soil horizon is identified by the color, texture and structure of the material composing the soil.
(3) Horizons above the C-horizon constitute the solum (or true soil).
(4) Soil horizon development is determined by climate, topography, effects of erosion and deposition, parent material and time of development.

2. Material Properties of Soil

We will treat a soil column as a homogeneous soil consisting of a matrix of individual soil grains that are interconnected by pore spaces (air or water filled):

(1) Size of the soil pore spaces is approximately equal to the grain size.
(2) The grain size distribution determines the amount of available porosity.
(3) Soil texture is typically used to determine grain (or particle) size distribution.
(4) Soil texture consists of the weight fractions of silt, clay and sand.

The properties of soil will provide a quantitative description of unsaturated zone processes, including infiltration. For a soil column, we can define:



Soil Control Volume with Air, Water and Solid Phases

(1) Soil particle density (ρ_m):

$$\rho_m = \frac{M_m}{V_m} \qquad (1)$$

where M_m is the mass of soil grains and V_m is the volume of the soil grains. Typically, most soil is approximated crudely as a quartz sand with a density ρ_m = 2650 kg/m^3.

(2) Bulk density (ρ_b):

$$\rho_b = \frac{M_m}{V_s} = \frac{M_m}{V_a + V_w + V_m} \qquad (2)$$

where V_s is the volume of the soil sample and V_a, V_w and V_m are the volumes of the air, water and soil grains in the soil sample.

(3) Soil Porosity (ϕ):

$$\phi = \frac{V_a + V_w}{V_a + V_w + V_m} = \frac{V_a + V_w}{V_s} \qquad (3)$$

We can use the particle density and bulk density to obtain the relationship:

$$\phi = 1 - \frac{V_m}{V_s} = 1 - \frac{\rho_b}{\rho_m} \qquad (4)$$

(4) Volumetric Water Content (θ):

$$\theta = \frac{V_w}{V_s} \qquad (5)$$

where $0 \le \theta \le \phi$ since water can only occupy up to the porosity (void space available).

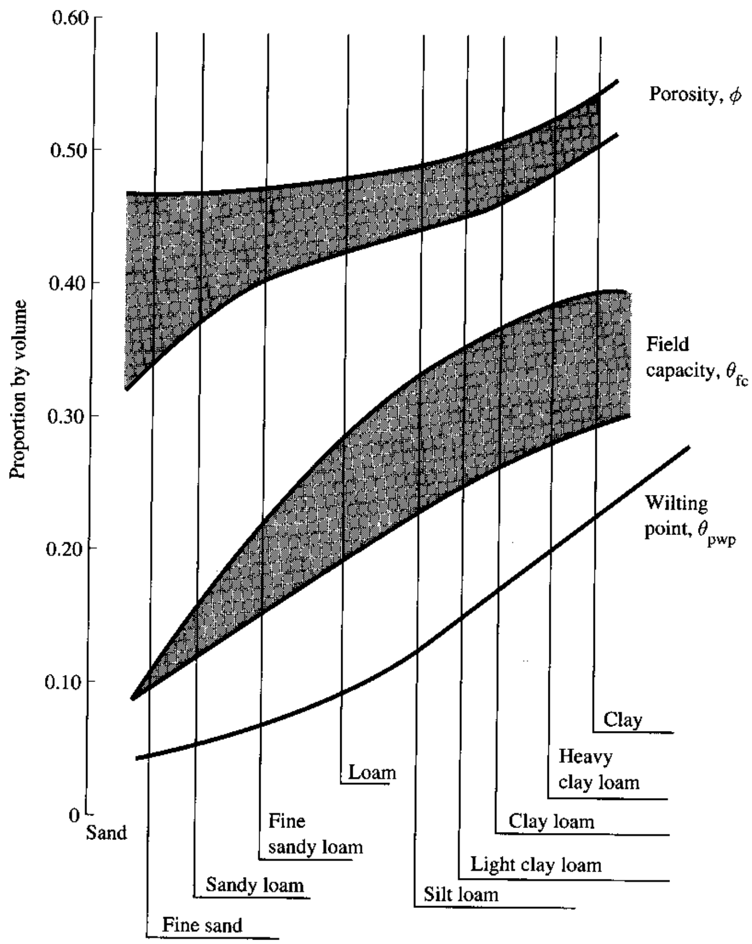
(5) Degree of Saturation (S):

$$S = \frac{\theta}{\phi} \qquad (6)$$

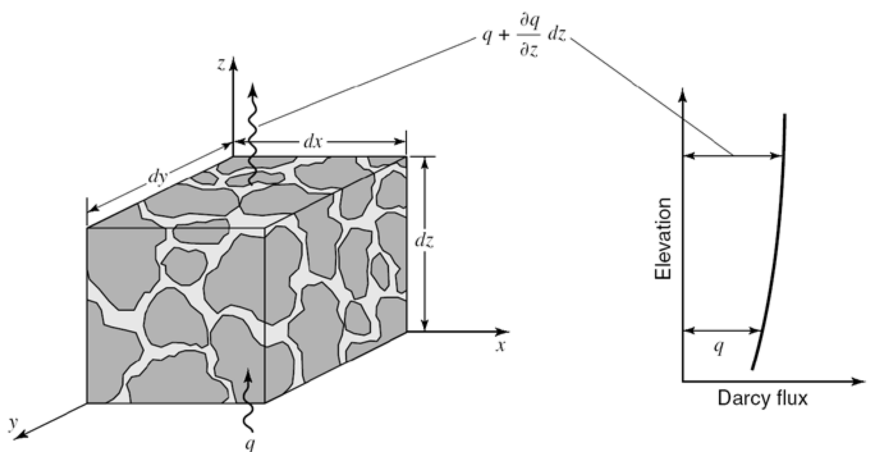
(6) Relative Saturation (s):

$$s = \frac{\theta - \theta_r}{\phi - \theta_r} \qquad (7)$$

which varies $0 \le s \le 1$ and where θ_r is the specific retention, a value of water content retained in the pore spaces due to strong hygroscopic forces.



Range of Soil Porosities, Field Capacities and Wilting Points for Various Textures



Control Volume Approach for Defining Darcy's Law in Unsaturated Soil.

3. Unsaturated Water Flow – Darcy's Law

Unsaturated porous media flow can be described using Darcy's Law. We can begin with the flow Q per unit cross-sectional area A at a pore velocity v:

$$Q = \phi v A \tag{8}$$

where ϕ is the soil porosity. If we define the darcy velocity, $q = \phi v$, we can write:

$$q = Q / A \tag{9}$$

Darcy's Law states that the unsaturated flow in the x, y and z direction is proportional to the gradient in total head. Total head (Φ) is the sum of the pressure head (ψ) and elevation head (z):

$$\Phi = \psi + z \tag{10}$$

where each term has dimensions of length. The elevation head represents the gravitational forces on water in soil. The pressure head is the pressure due to capillary forces that hold water within pore spaces:

$$\psi = \frac{p}{\rho_w g} \tag{11}$$

where g is the acceleration of gravity, p is the water pressure and ρ_w is the water density. The pressure (or matric) head is a function of matrix geometry and structure as well as liquid properties such as temperature and salinity. The matric head is near zero when the pore spaces are saturated and negative for unsaturated soils and since $p \le 0$ then $\psi \le 0$.

Darcy’s Law expresses the flux (darcy velocity) as proportional to a change in total head:

$$q_x \propto -\frac{\partial \Phi}{\partial x}, \quad q_y \propto -\frac{\partial \Phi}{\partial y}, \quad q_z \propto -\frac{\partial \Phi}{\partial z} \qquad (12)$$

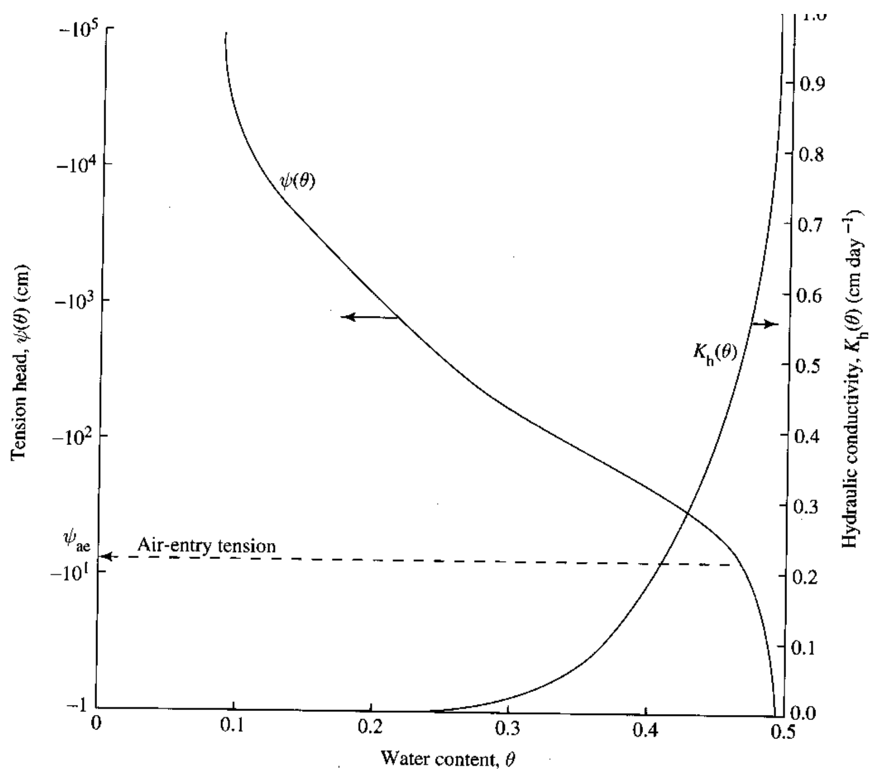
We can express Darcy’s Law as:

$$q_x = -K_h(\theta)\frac{\partial \psi(\theta)}{\partial x}, \quad q_y = -K_h(\theta)\frac{\partial \psi(\theta)}{\partial y}, \quad q_z = -K_h(\theta)\left(\frac{\partial \psi(\theta)}{\partial z} + 1\right) \qquad (13)$$

where $K_h(\theta)$ is the unsaturated hydraulic conductivity and $\psi(\theta)$ is the matric head. For unsaturated conditions, both the hydraulic conductivity and matric head are a function of water content, θ.

(1) Air-filled pores become an obstacle for water flow (as if part of the soil matrix) and thus the low water content (θ) significantly reduces $K_h(\theta)$.

(2) Water is held onto the soil particles with greater capillary force as the soil dries and thus the matric head $\psi(\theta)$ becomes larger (negative units) for low θ.



Typical Forms of the $K_h(\theta)$ and $\psi(\theta)$ Relationships for $\phi = 0.5$

Vertical Infiltration (1-dimensional):

For vertical infiltration, we consider primarily the vertical component of Darcy's Law:

$$q_z = -K_h(\theta)\left(\frac{\partial\psi(\theta)}{\partial z} + 1\right) \tag{14}$$

The moisture characteristic curve $\psi(\theta)$ and the hydraulic conductivity $K_h(\theta)$ relation can be approximated analytically via a number of methods (e.g. Brooks/Corey relation, van Genutchen relation). The power-law methods of Campbell (1974) are one such example:

$$|\psi(\theta)| = |\psi_{ae}|\left(\frac{\phi}{\theta}\right)^b \tag{15}$$

where b is the pore-size distribution index, ψ_{ae} is the air entry tension which defines the inflection point of the $\psi(\theta)$ relation (when large amounts of air occupy the pore spaces).

$$K_h(\theta) = K_h^*\left(\frac{\theta}{\phi}\right)^c \tag{16}$$

where c is pore-disconnectedness index (c = 2*b+3) and K_h^* is the saturated conductivity.

Soil Texture	ϕ	K_h^* (cm s^{-1})	$\lvert\psi_{ae}\rvert$ (cm)	b
Sand	0.395 (0.056)	1.76×10^{-2}	12.1 (14.3)	4.05 (1.78)
Loamy sand	0.410 (0.068)	1.56×10^{-2}	9.0 (12.4)	4.38 (1.47)
Sandy loam	0.435 (0.086)	3.47×10^{-3}	21.8 (31.0)	4.90 (1.75)
Silt loam	0.485 (0.059)	7.20×10^{-4}	78.6 (51.2)	5.30 (1.96)
Loam	0.451 (0.078)	6.95×10^{-4}	47.8 (51.2)	5.39 (1.87)
Sandy clay loam	0.420 (0.059)	6.30×10^{-4}	29.9 (37.8)	7.12 (2.43)
Silty clay loam	0.477 (0.057)	1.70×10^{-4}	35.6 (37.8)	7.75 (2.77)
Clay loam	0.476 (0.053)	2.45×10^{-4}	63.0 (51.0)	8.52 (3.44)
Sandy clay	0.426 (0.057)	2.17×10^{-4}	15.3 (17.3)	10.4 (1.64)
Silty clay	0.492 (0.064)	1.03×10^{-4}	49.0 (62.1)	10.4 (4.45)
Clay	0.482 (0.050)	1.28×10^{-4}	40.5 (39.7)	11.4 (3.70)

Soil Properties as a function of Soil Texture

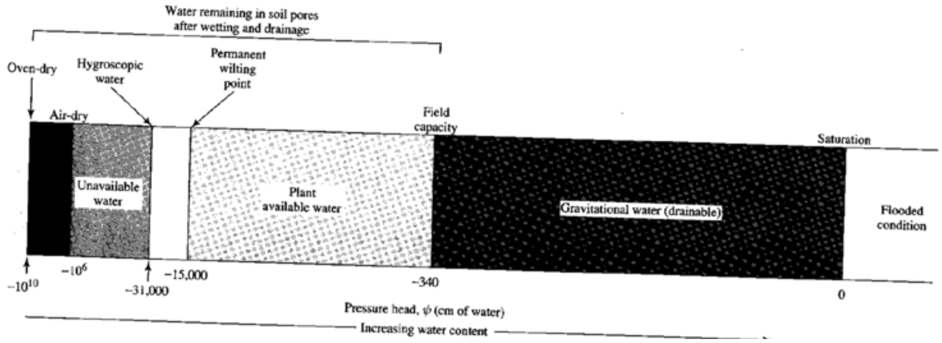


Diagram of Water Contents and Matric Head in a Soil Column. Note the Field Capacity, Wilting Point and Hygroscopic Point

<u>Field Capacity, Wilting Point and Available Water in a Soil Column:</u>

(1) Soil field capacity (θ_{fc}) is the water content retained in a soil against gravity. It can be computed by defining a reference pressure head at -340 cm (-33 kPa):

$$\theta_{fc} = \phi \left(\frac{|\psi_{ae}|}{340} \right)^{1/b} \qquad (17)$$

The field capacity is a function of soil texture. For sands, θ_{fc} ~ 0.1, while for clays θ_{fc} ~ 0.3. This quantity is also related to soil texture and can be measured experimentally.

(2) The permanent wilting point (θ_w) is the water content below which a plant will wilt. Wilting is a loss of turgor pressure inside the plant (water content within a plant is not sufficient to sustain plant stiffness).

The wilting point water content can be computed by defining a reference pressure head at -15000 cm (-1470 kPa):

$$\theta_w = \phi \left(\frac{|\psi_{ae}|}{15000} \right)^{1/b} \qquad (18)$$

The wilting point soil is a function of soil texture, soil profile properties and vegetation characteristics. For sands, θ_w ~ 0.05, while for clays θ_w ~ 0.25.

(3) Available water for plant use:

$$\theta_a = \theta_{fc} - \theta_w \qquad (19)$$

(4) Residual or hygroscopic water content is the water remaining in the soil after drainage and evapotranspiration. It is a function of soil texture/type.