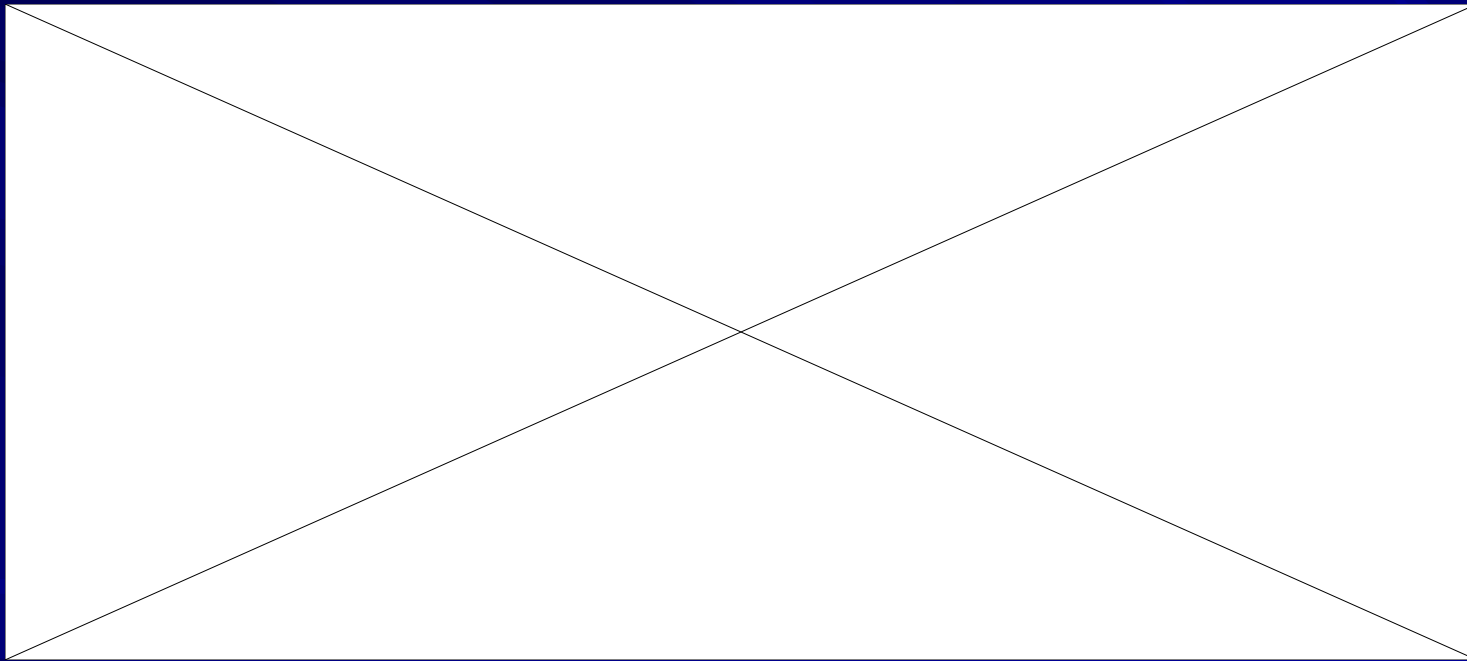


Water Flow Through Soils

Satish Gupta
Department of Soil, Water, & Climate
University of Minnesota
St. Paul, MN

Water Flow Thru Different Soil Types

<http://tecalive.mtu.edu/meec/module06/Permeability.htm>



Michigan Environmental Education Curriculum

Topics

- Soil Water Properties
- Soil Wetness
- Energy Status of Soil Water
- Soil Water Retention Characteristics
- Darcy's Law-Steady State Water Flow
 - Saturated Flow
 - Unsaturated Flow
- Richards Equation-Non-steady State Water Flow

Soil Water Properties

- How much water there is?
 - Soil wetness
- What is the energy or force with which it is held?
 - Where does this water reside?
 - How tightly is this water held?

Soil Wetness

Soil Wetness

■ Water Content by Weight, W

- Mass wetness,
- g of water/g of oven dry soil

■ Water Content by volume, θ

- Volume wetness,
- cm^3 of water/ cm^3 of soil volume

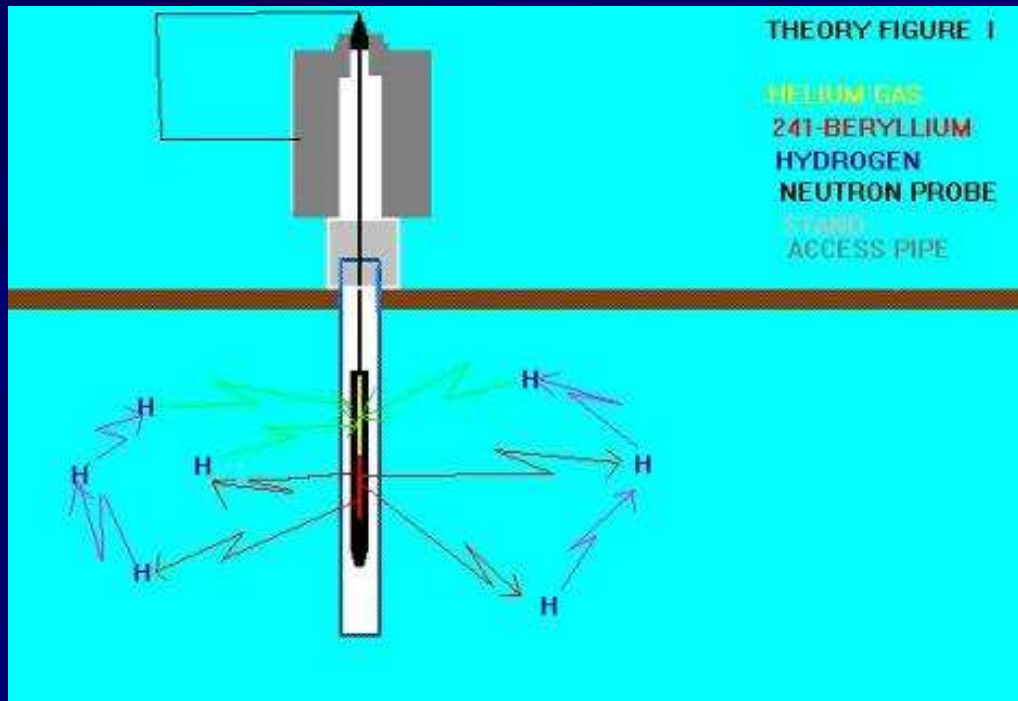
Relationship Between Volume and Mass Wetness

$$\theta = W \frac{\rho_b}{\rho_w}$$

Methods of Measuring Soil Wetness

- Gravimetric Method.
- Neutron scattering.
- Time domain reflectometry.
- Gypsum Block.

Neutron Scattering



- Fast neutron collide with H atom and are slowed. We measure slowed neutron. Since most H atoms are associated with water, we characterize soil wetness.

Time Domain Reflectometry (TDR)

- Measures the dielectric properties of the soil.
- Dielectric property reflects the ability of a material to store electric charge.
- Dielectric constant is the ratio of the capacitance of a material to the capacitance of air.

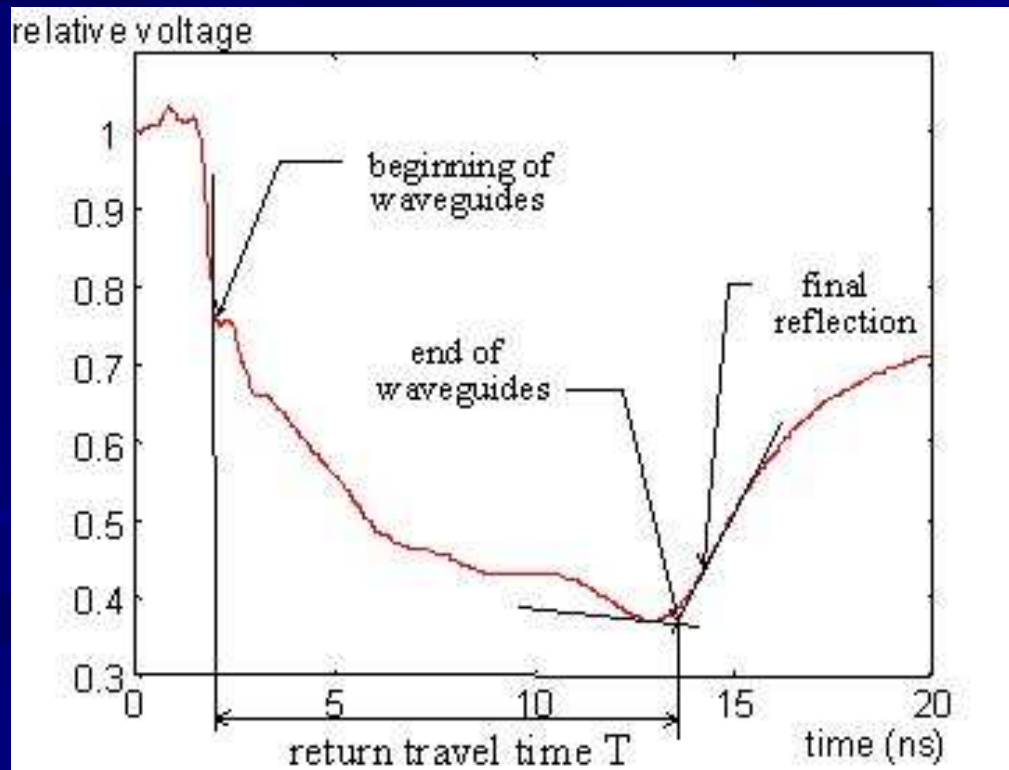


Dielectric Constant, K_a

- Dielectric constant of liquid water is 80, and soil is 4.
- Therefore, changes in dielectric constant reflect water content changes.

$$\theta = -0.053 + 0.029K_a - 5.5 \times 10^{-4} K_a^2 + 4.3 \times 10^{-6} K_a^3$$

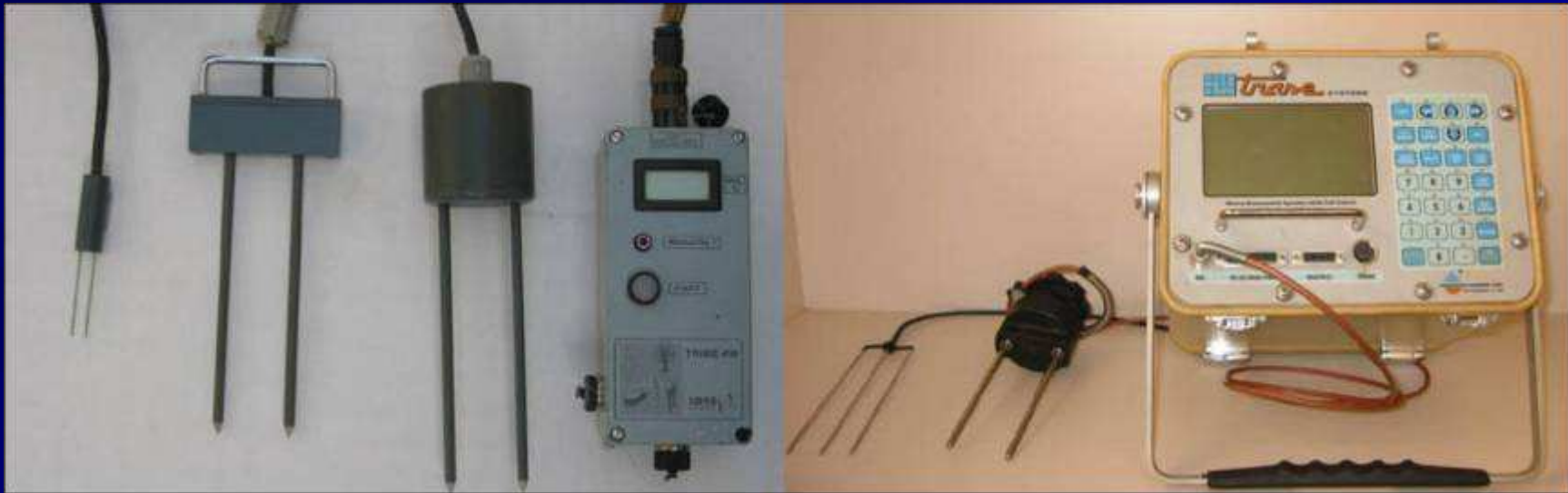
TDR Trace



$$K_a = \left(\frac{CT}{2L} \right)^2$$

- $C = 3 \times 10^8 \text{ m s}^{-1}$
- Speed of Light

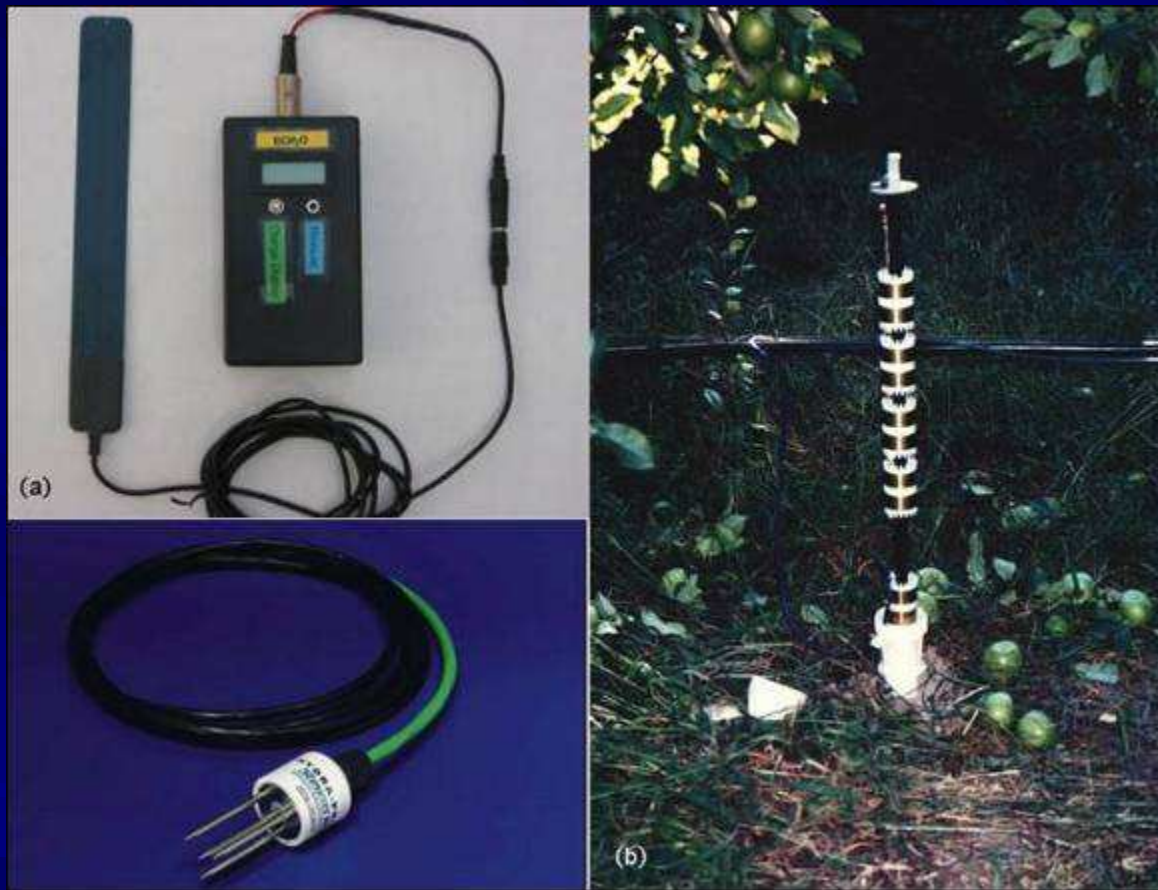
Various Types of TDR probes



Munzo-Capena et al., 2005, Field methods of measuring soil water status, In Soil-Water Solute Process Characterization (Alvarez-Bendi and Munzo-Capena, eds.), CRC press

<http://edis.ifas.ufl.edu/EDISImagePage?imageID=1199206555&dINumber=AE266&tag=FIGURE%204&credits=>

Capacitance Probes

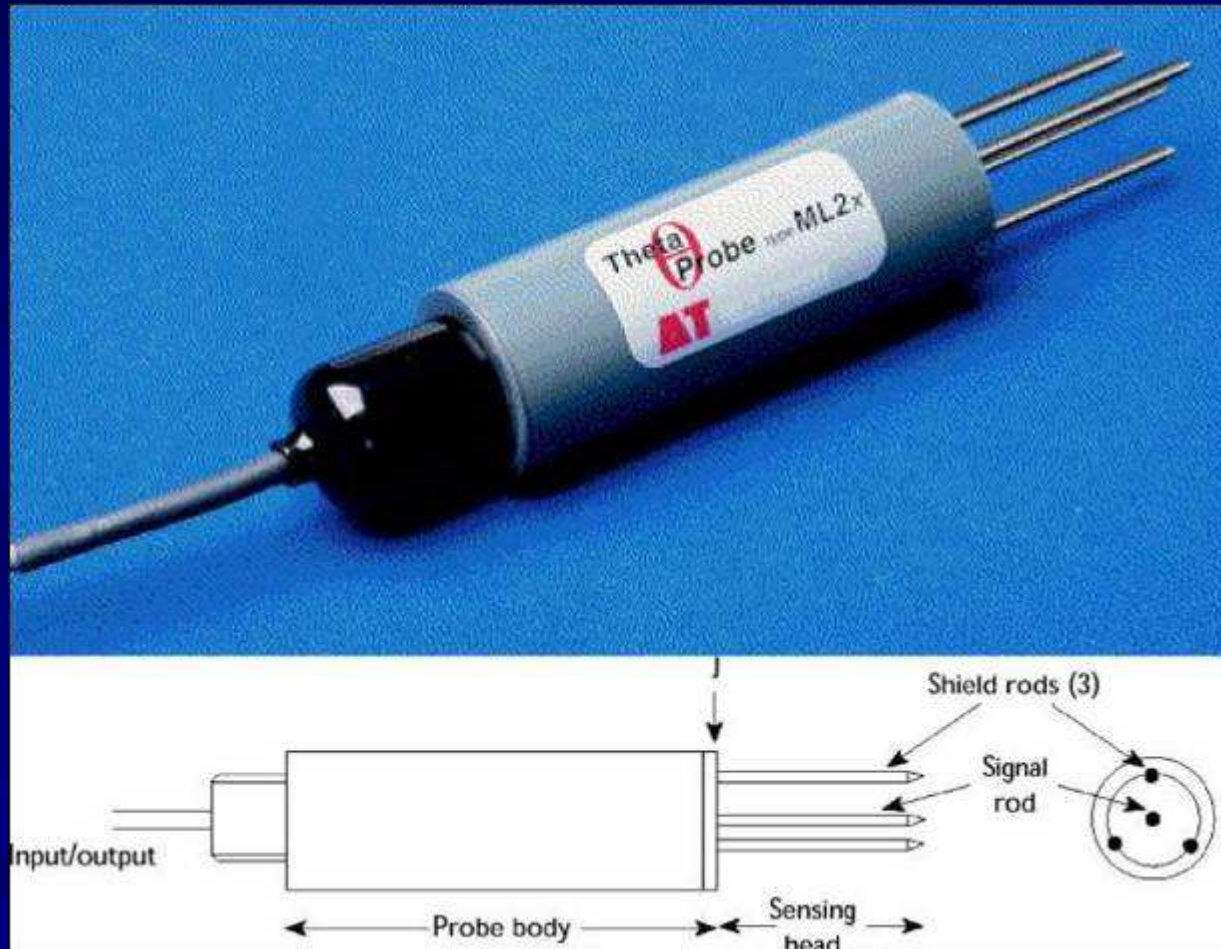


Also called Frequency Domain probes

Munzo-Capena et al., 2005, Field methods of measuring soil water status, In Soil-Water Solute Process Characterization (Alvarez-Bendi and Munzo-Capena, eds.), CRC press

<http://edis.ifas.ufl.edu/EDISImagePage?imageID=1519031495&dINumber=AE266&tag=FIGURE%205&credits=>

Impedance Probes



Munzo-Capena et al., 2005, Field methods of measuring soil water status, In Soil-Water Solute Process Characterization (Alvarez-Bendi and Munzo-Capena, eds.), CRC press

<http://edis.ifas.ufl.edu/EDISImagePage?imageID=751887005&dINumber=AE266&tag=FIGURE%206&credits=>

Phase Transmission Probes



Munzo-Capena et al., 2005, Field methods of measuring soil water status, In Soil-Water Solute Process Characterization (Alvarez-Bendi and Munzo-Capena, eds.), CRC press

<http://edis.ifas.ufl.edu/EDISImagePage?imageID=1978188387&dINumber=AE266&tag=FIGURE%207&credits=>

Time Domain Transmission Probes



Munzo-Capena et al., 2005, Field methods of measuring soil water status, In Soil-Water Solute Process Characterization (Alvarez-Bendi and Munzo-Capena, eds.), CRC press
<http://edis.ifas.ufl.edu/EDISImagePage?imageID=66639424&dINumber=AE266&tag=FIGURE%208&credits=>

Resistance Block

- Measures the electrical conductivity of the soil.
- Higher moisture content, higher is the electrical conductivity.



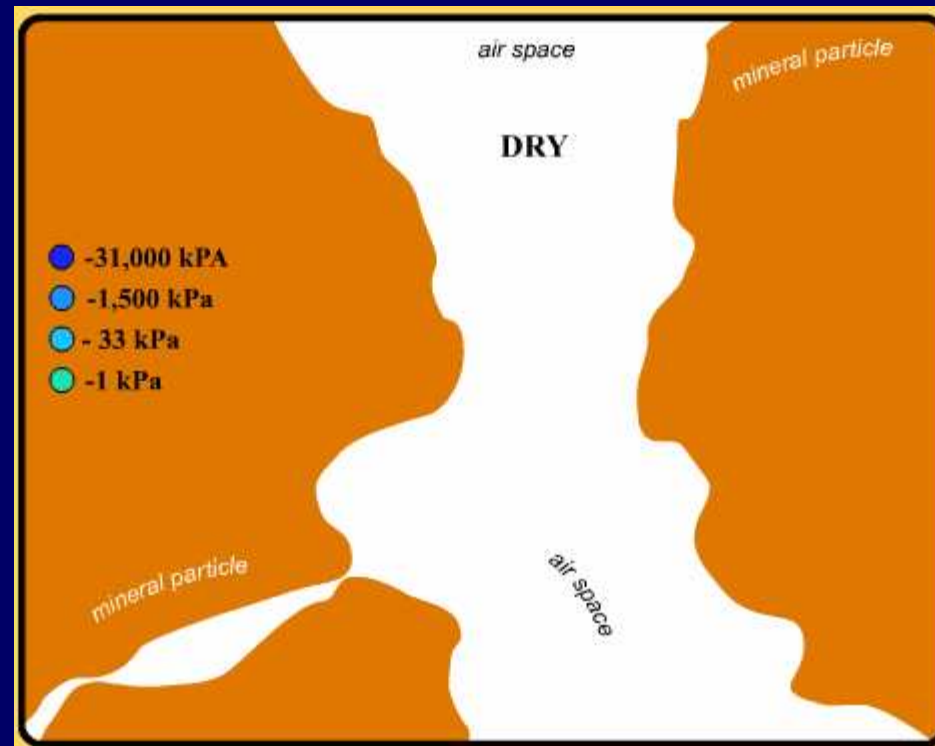
Resistance Probe- Water Mark Sensor



Munzo-Capena et al., 2005, Field methods of measuring soil water status, In Soil-Water Solute Process Characterization (Alvarez-Bendi and Munzo-Capena, eds.), CRC press
<http://edis.ifas.ufl.edu/EDISImagePage?imageID=1786970386&dINumber=AE266&tag=FIGURE%2011&credits=>

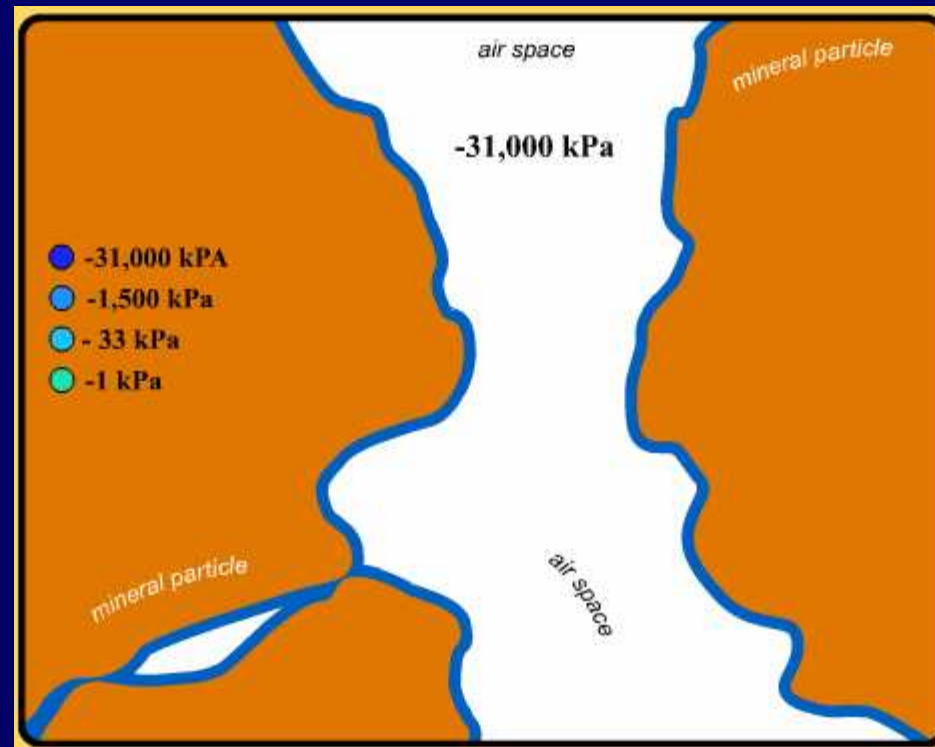
Energy of Soil Water

Energy of Soil Water

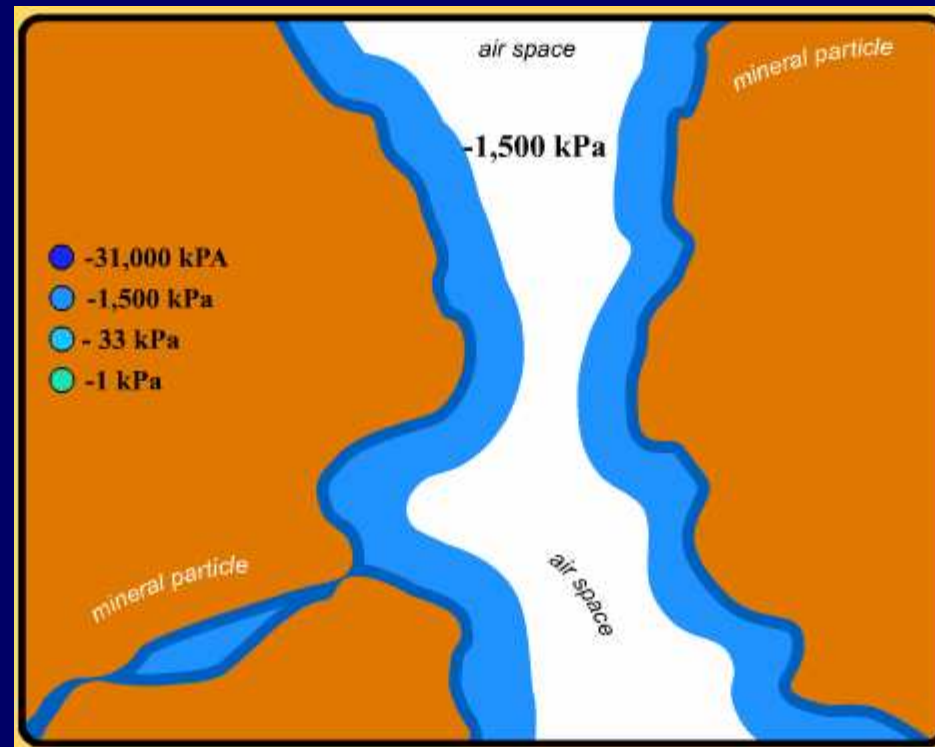


- It tells us where does water resides in soil.
- Big pores, medium size pores, or small pores.

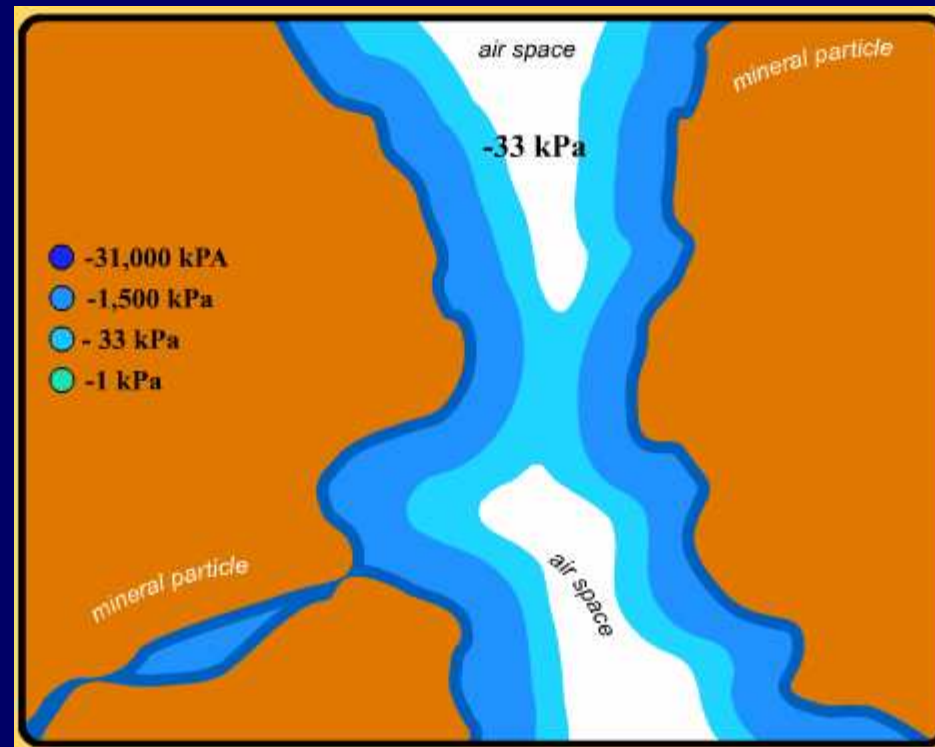
Energy of Soil Water



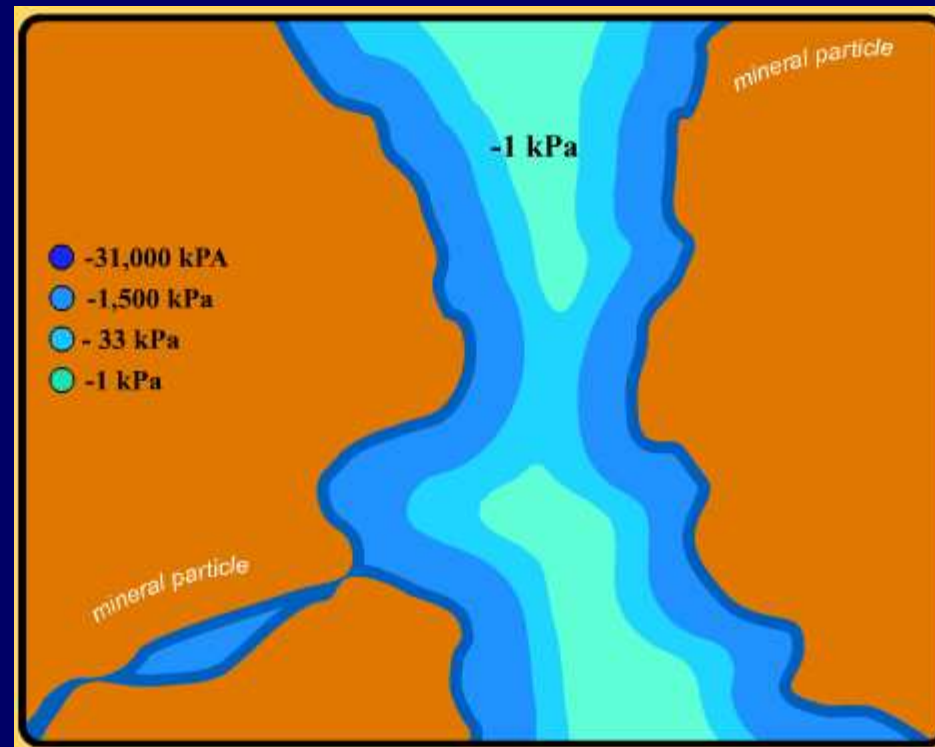
Energy of Soil Water



Energy of Soil Water



Energy of Soil Water



Types of Energy

■ Kinetic Energy

- due to velocity
- Not important in soil water

$$KE = \frac{1}{2}mv^2$$

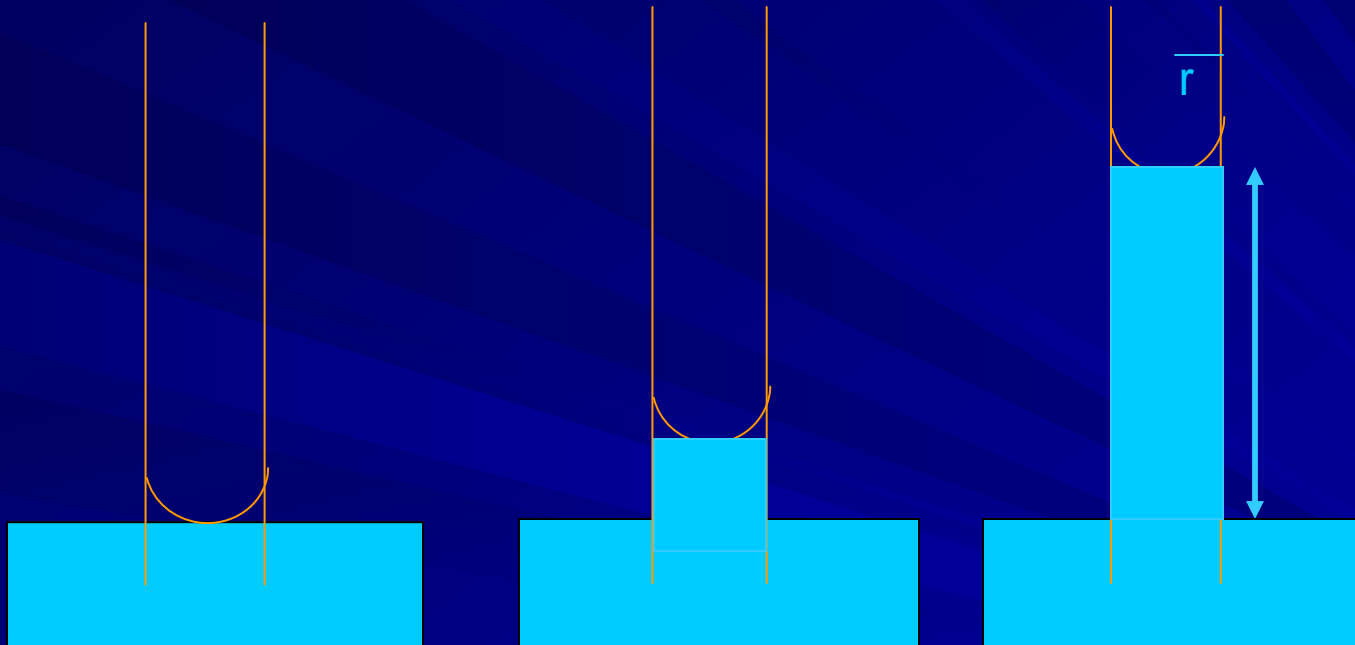
■ Potential Energy

- due to position or internal make-up of soil water
- very important in soil water
- it controls water flow

$$E_P = mgh$$

$$E_P = h$$

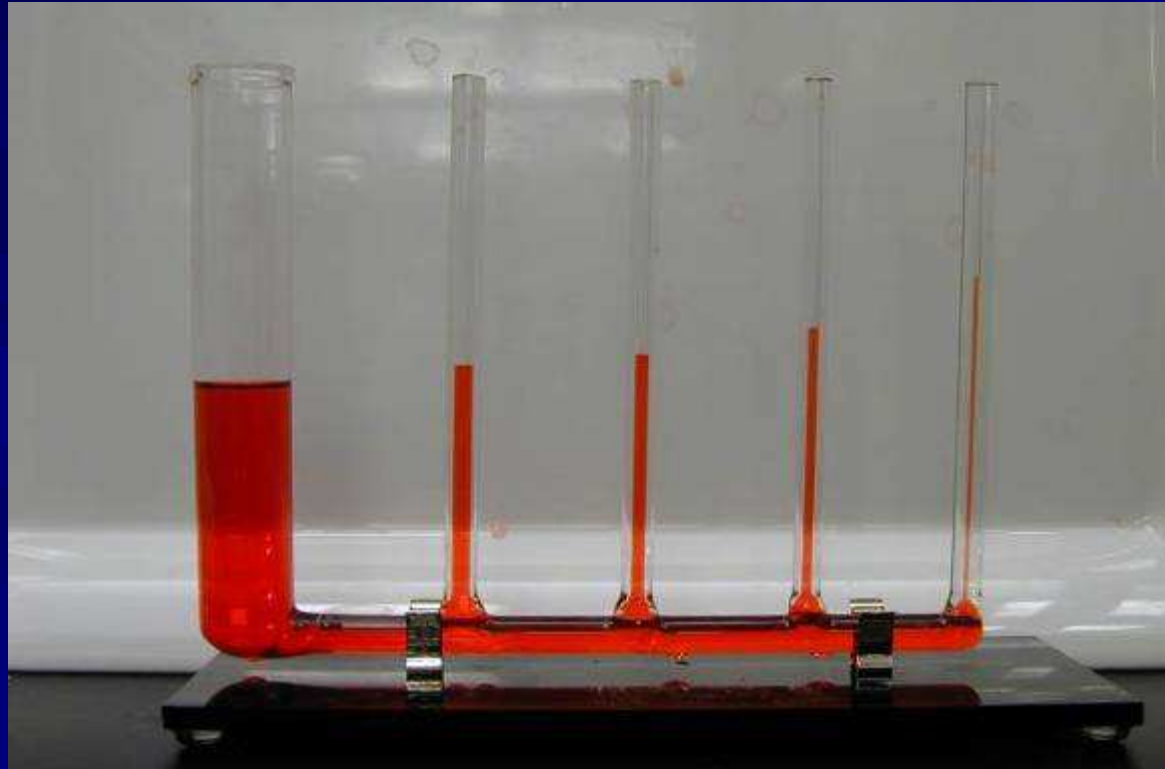
Concept of Capillarity



$$h = \frac{2\sigma \cos\beta}{\rho g r}$$

$$h = \frac{0.15}{r}$$

Capillary Rise

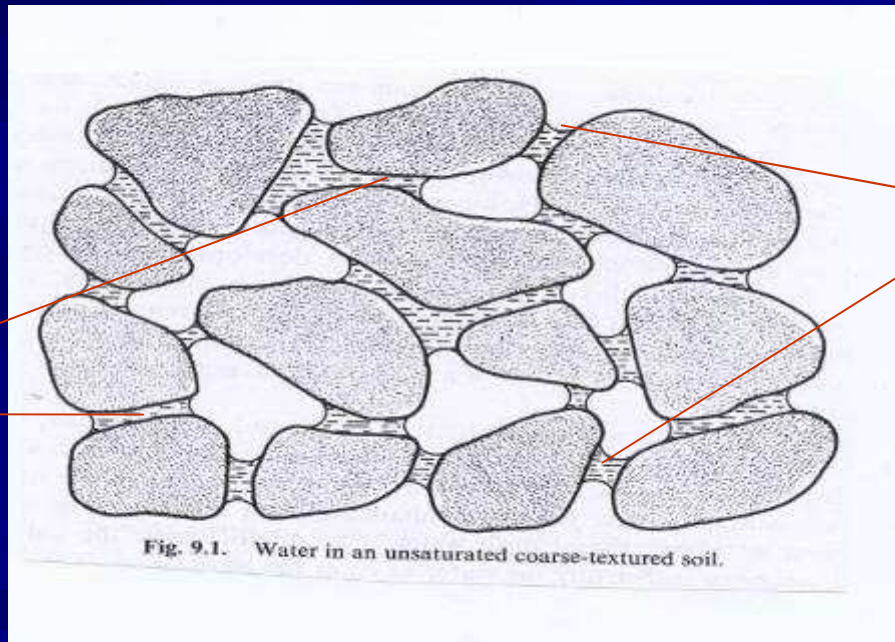


In smaller capillaries, curvature of water meniscus is much higher.

Water Retention

Where is water residing?

What is the force with which it is Held?



Small pore,
greater is the
curvature and
thus more
tightly is the
water held

Large pore,
smaller is the
curvature and
thus less
tightly is water
held

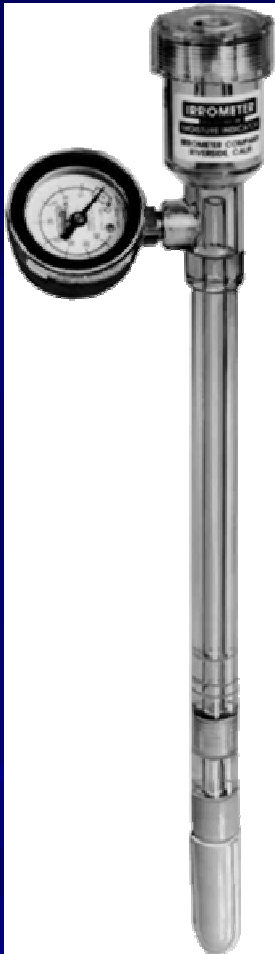
Matric Potential

- Energy holding the water in soil is called matric potential energy or simply matric potential.
- It is synonymous to vacuum and thus is also called suction.

Methods of Measuring Matrix Potential

- Tensiometers
- Heat Dissipation Unit
- Thermocouple Psychrometer

Tensiometer



<http://www.irrometer.com/agcat.htm#Irrometer>

<http://www.irrometer.com/agcat.htm#Irrometer>

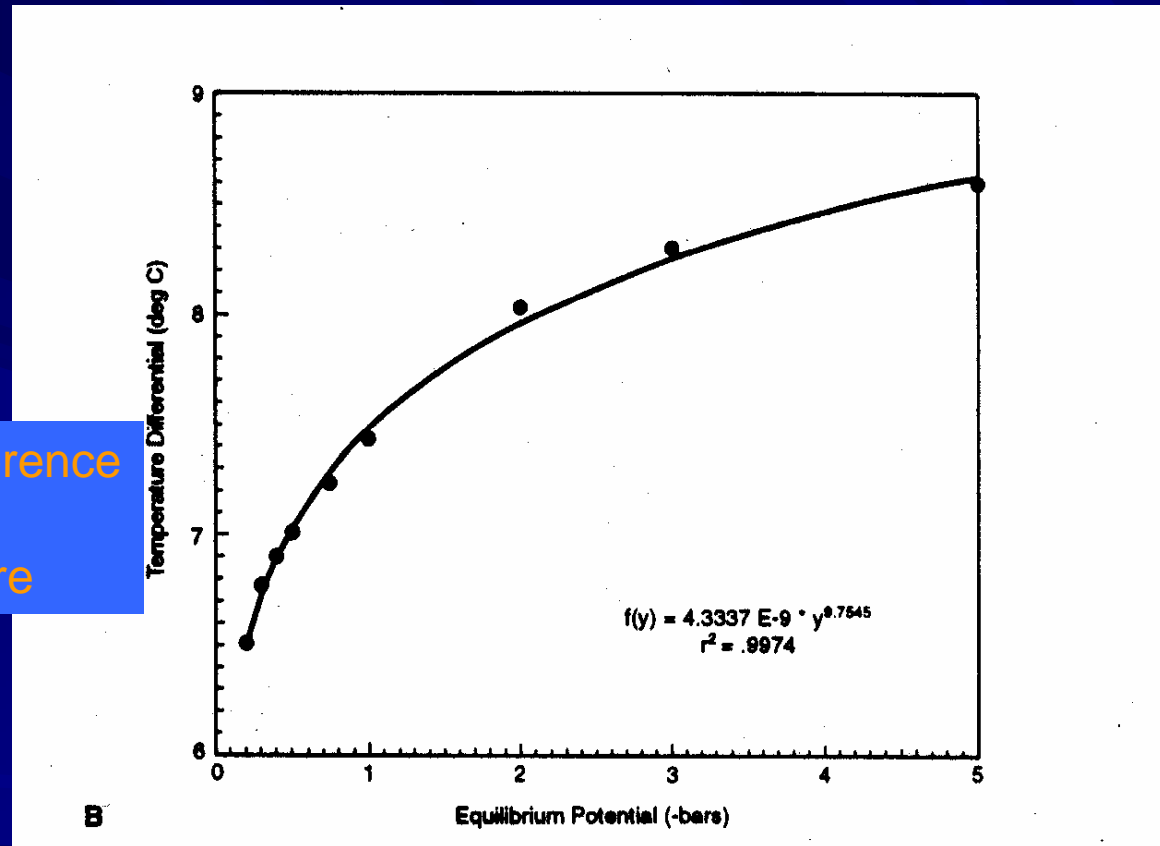
Heat Dissipation Unit



- Measures the rate of heat dissipation.
- Higher the water content, higher is the rate of heat dissipation and less is the temperature rise.

Calibration Curve for Heat Dissipation Unit

Temperature Difference
or
Rise in temperature

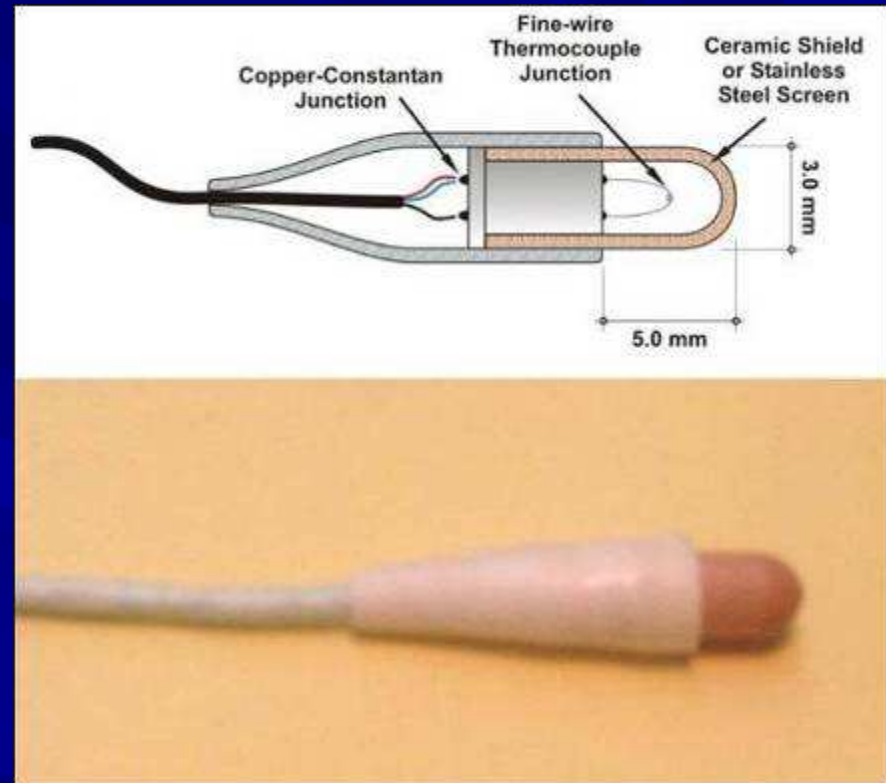


Equilibrium Potential

Stephan, D., 1996. Vadose Zone Hydrology, CRC Press

Thermocouple Psychrometer

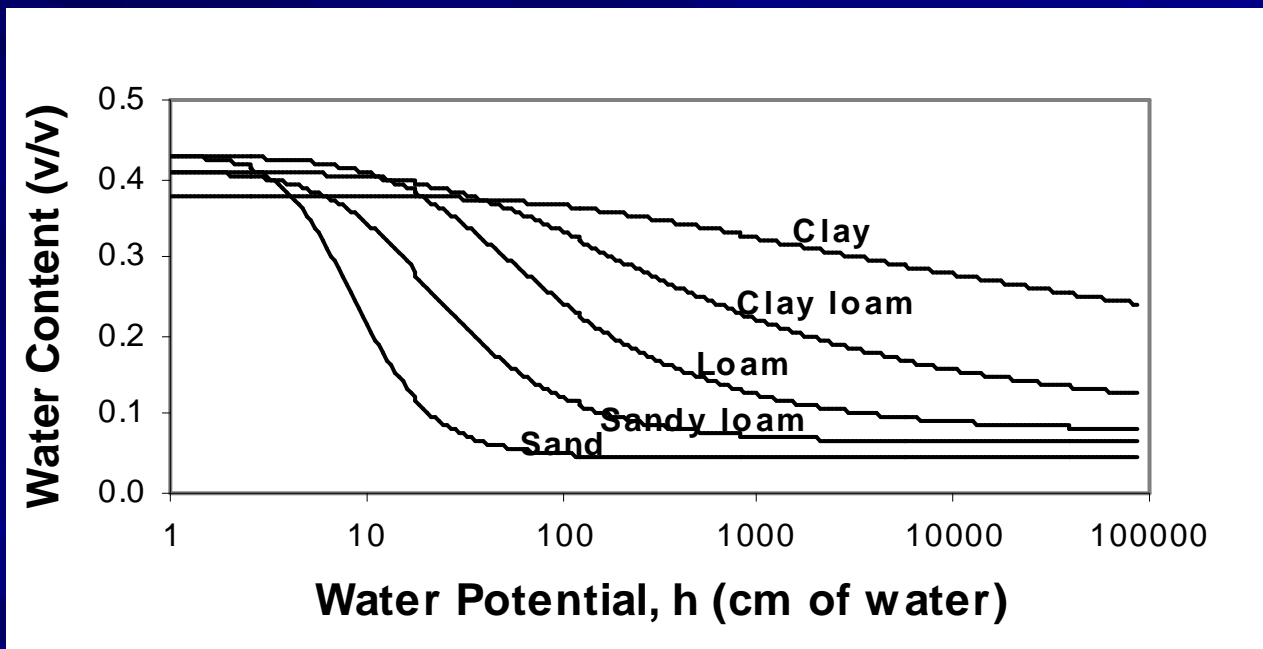
- It measures the relative humidity of soil air.
- It can measure soil matric potential up to -100 bars and above.



Water Retention Characteristics

Soil Water Retention Characteristics

- Relationship between quantity of water and energy with which it is held.



It is also an indication of how much water is held in what size pores.

Gupta & Wang

Characterization of Water Retention Curve

- Hanging water column
- Tempe Cell
- Pressure plate chambers

Hanging Water Column



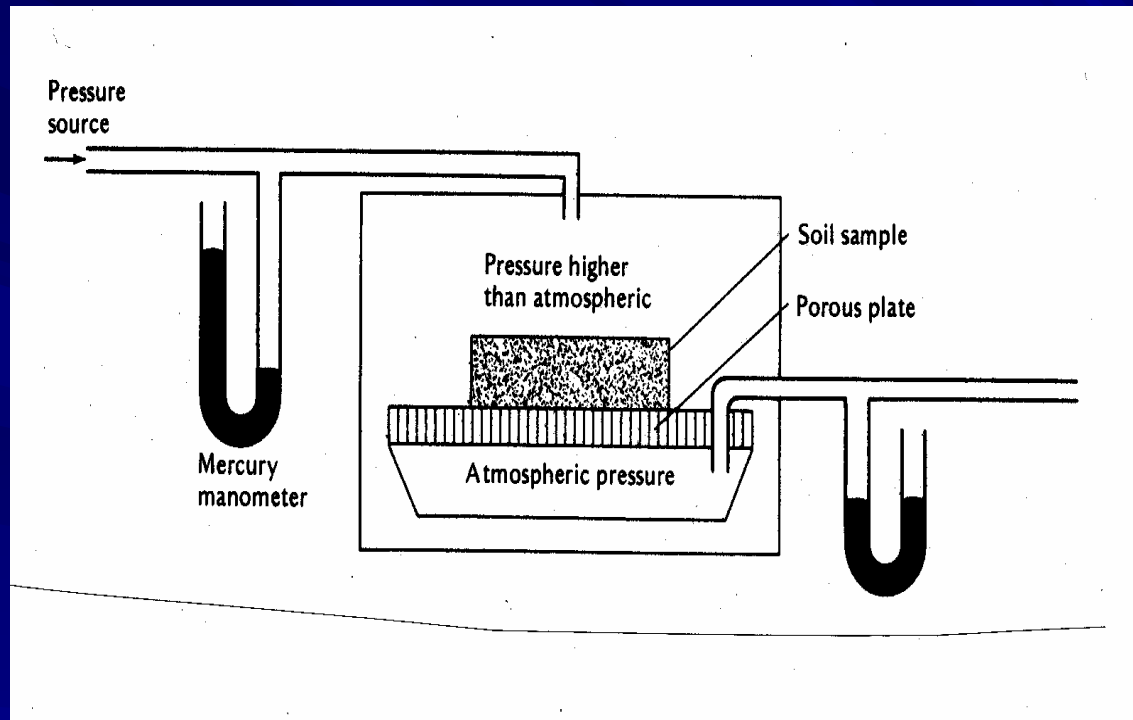
- It can characterize water retention up to soil matric potential up to 0.8 bar.

Tempe Cell



- It can characterize water retention up to soil matric potential up to 1.0 bar.

Pressure Plate Apparatus



- It can characterize water retention up to soil matric potential up to 15 bars.

Pressure Plate Apparatus



Estimating Water Retention curves

- Pedo-transfer Function

- Input needed are the particle size distribution, organic matter content and bulk density.

- $\theta_p = a + b \text{ sand (\%)} + c \text{ silt (\%)} + d \text{ clay (\%)} + e \text{ OM (\%)} + f \text{ bulk density (g cm}^{-3}\text{)}$

Pedo-Transfer Functions

- Gupta and Larson (1979)
 - Based on controlled lab studies
- Rawls and Brakensiek (1982)
 - Based on large NRCS data base
- Arya and Paris (1986)
 - Semi-physical/semi-empirical

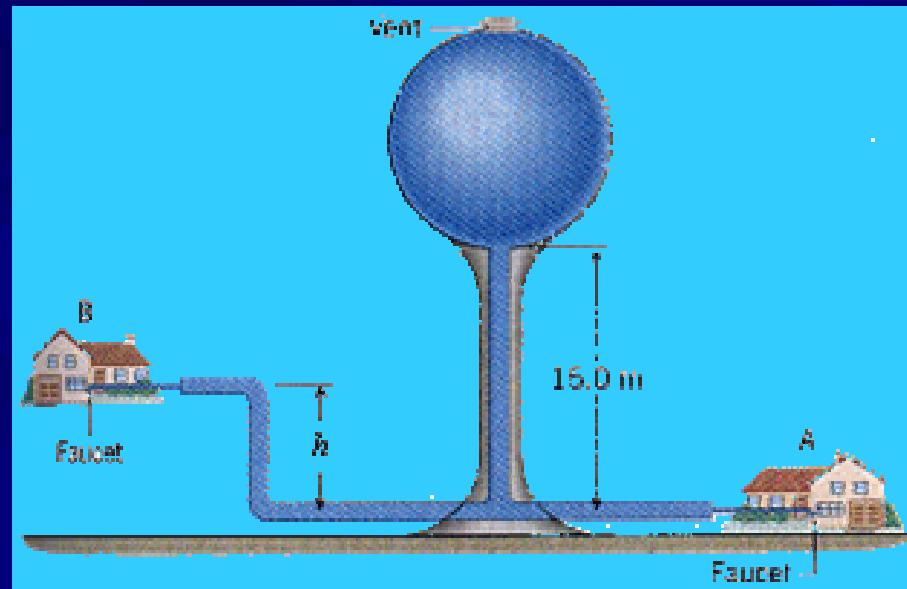
Estimating Water Retention Curves

Gupta & Larson (1979), WRR 15: 1633-1635

ψ_p	$ax10^3$	$bx10^3$	$cx10^3$	$dx10^3$	$ex10^2$
-0.04	7.053	10.242	10.070	6.333	-32.120
-0.07	5.6780	9.228	9.135	6.103	-26.960
-0.1	5.018	8.548	8.833	4.966	-24.230
-0.2	3.890	7.066	8.408	2.817	-18.780
-0.33	3.075	5.886	8.039	2.208	-14.340
-0.6	2.181	4.557	7.557	2.191	-9.276
-1.0	1.563	3.62	7.154	2.388	-5.759
-2.0	0.0932	2.643	6.636	2.717	-2.214
-4.0	0.483	1.943	6.128	2.925	-0.204
-7.0	0.214	1.538	5.908	2.855	-1.530
-10.0	0.076	1.334	5.802	2.653	2.145
-15.0	-0.059	1.142	5.766	2.228	2.671

■ $\theta_p = a \text{ sand (\%)} + b \text{ silt (\%)} + c \text{ clay (\%)} + d \text{ OM (\%)} + e \text{ bulk density (g cm}^{-3}\text{)}$

Water Flow Through Soils



- Liquid water always moves from higher hydraulic head to lower hydraulic head

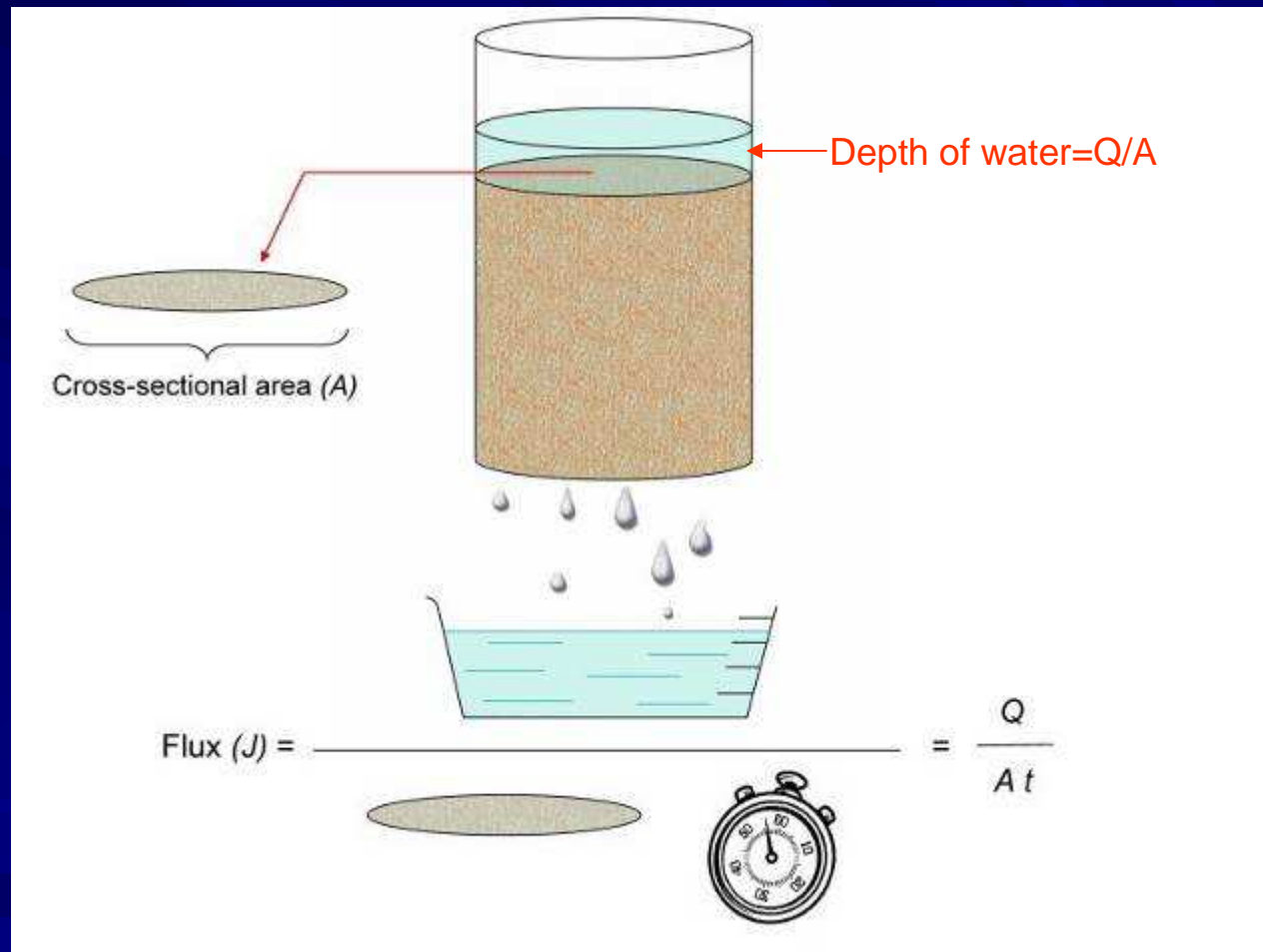
Steady State Water Flow- Darcy's Law

$$J_w \propto \frac{\Delta H}{\Delta z}$$

$$J_w = -K_s \frac{\Delta H}{\Delta z}$$

- Where H=Hydraulic Head, K_s is Saturated Hydraulic Conductivity, Δz =length

Darcy's Flux, J_w

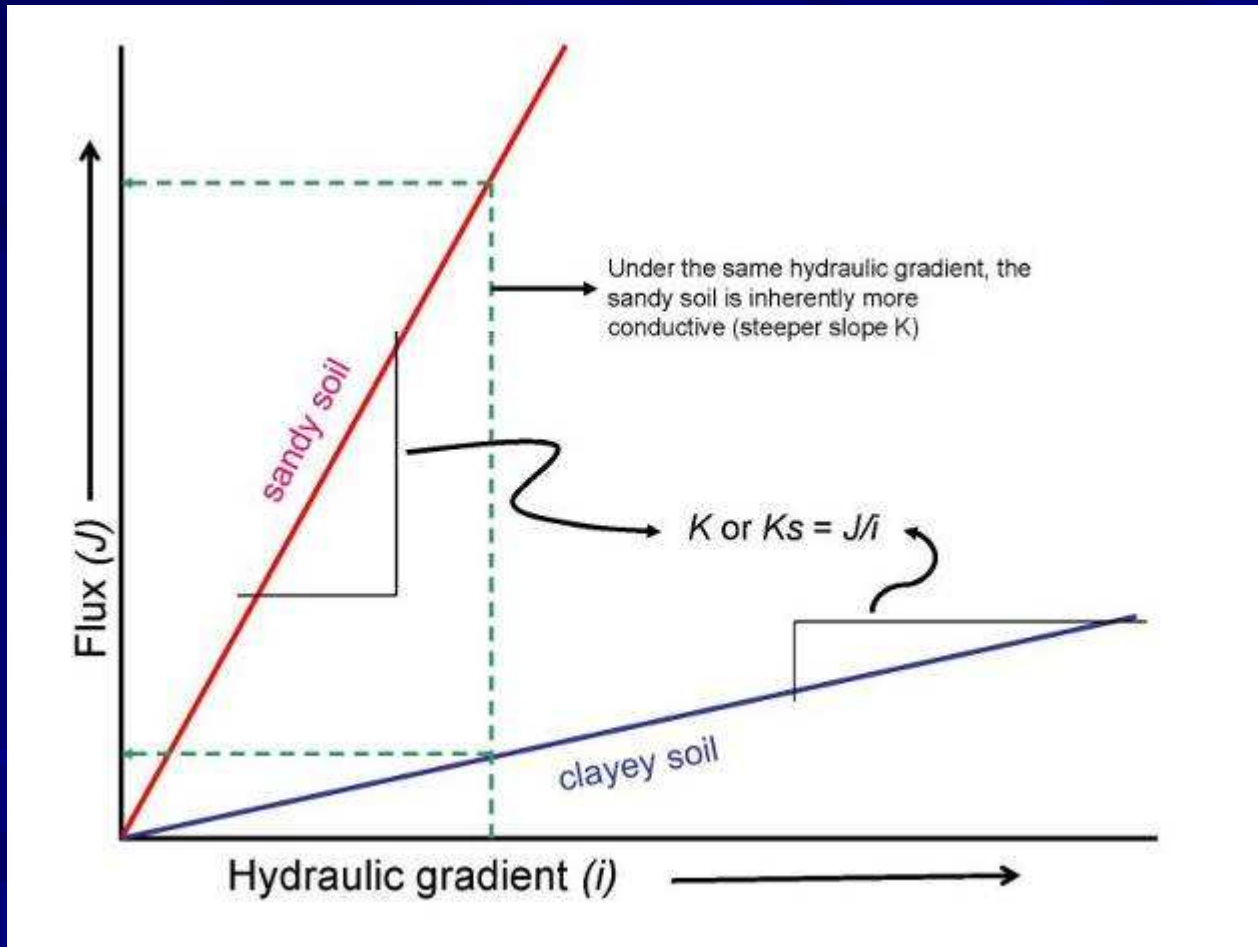


Hydraulic Head (H)

$$H = h + z$$

- h = pressure head, z =gravitational head
- Difference in hydraulic head (ΔH) is causing the water to move.
- Higher is the hydraulic head gradient, greater is water flow rate.

Hydraulic Conductivity, K



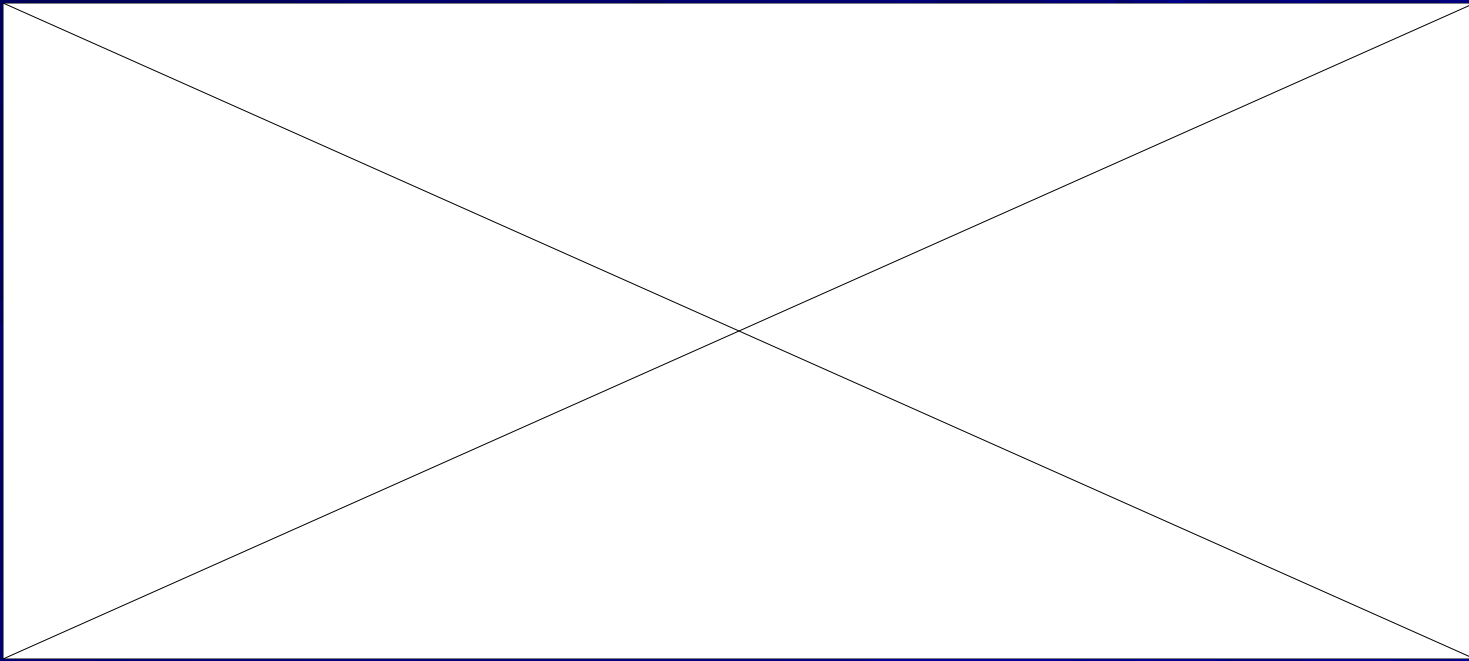
$$J_w = -K \frac{\Delta H}{\Delta z}$$

$$J_w = -Ki$$

Hydraulic Conductivity, K

- Hydraulic conductivity (K)-defines the size of pores through which water flows.
- Larger the pores, higher is the hydraulic conductivity.
- Sandy soils have large pore and thus higher hydraulic conductivity than the clay soils.

Hydraulic Conductivity



Hydraulic conductivity (K)-defines the size of pores through which water flows.

Larger the pores, higher is the hydraulic conductivity.

Darcy's Law-Saturated Flow

$$J_w = -K_s \frac{\Delta H}{L}$$

$$J_w = -K_s \left(\frac{\Delta h}{L} + \frac{\Delta z}{\Delta z} \right)$$

$$J_w = -K_s \left(\frac{\Delta h}{L} + 1 \right)$$

- Flux has two components
 - Flux due to pressure head gradient
 - Flux due to gravitational head gradient







Darcy's Law-Unsaturated Flow

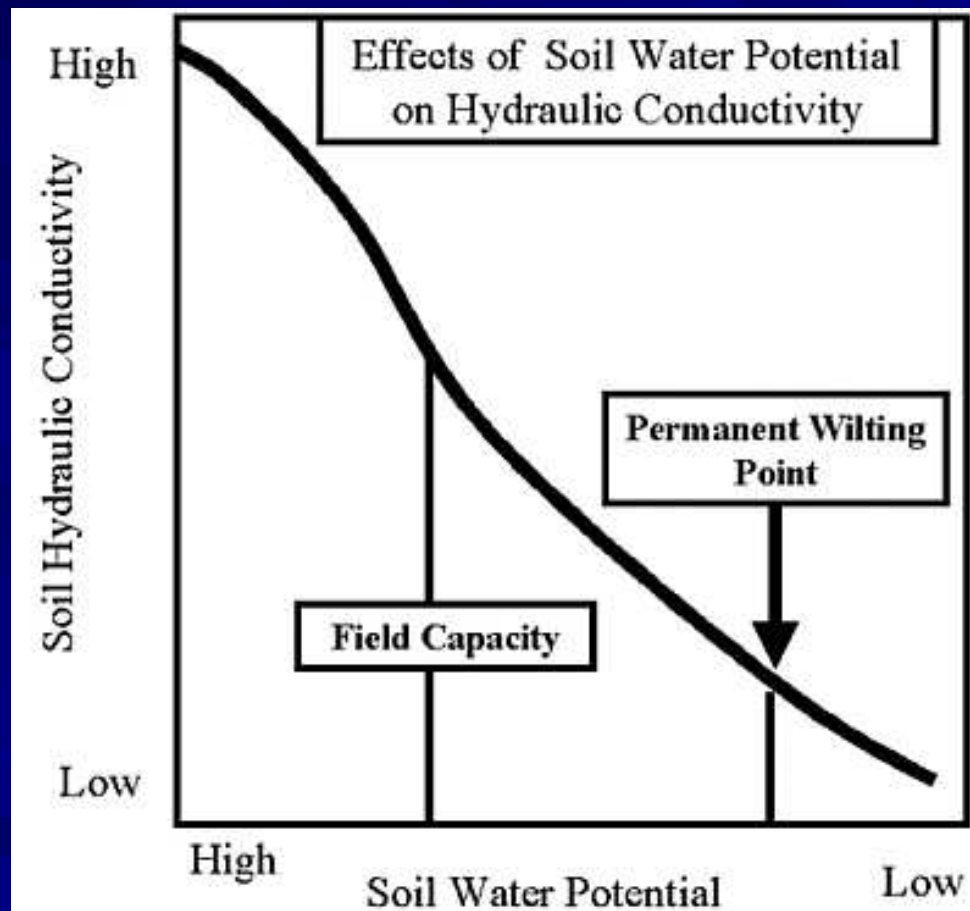
$$J_w = -K(h) \left(\frac{\Delta h}{\Delta z} + 1 \right)$$

$$J_w = -K(\theta) \left(\frac{\Delta h}{\Delta z} + 1 \right)$$

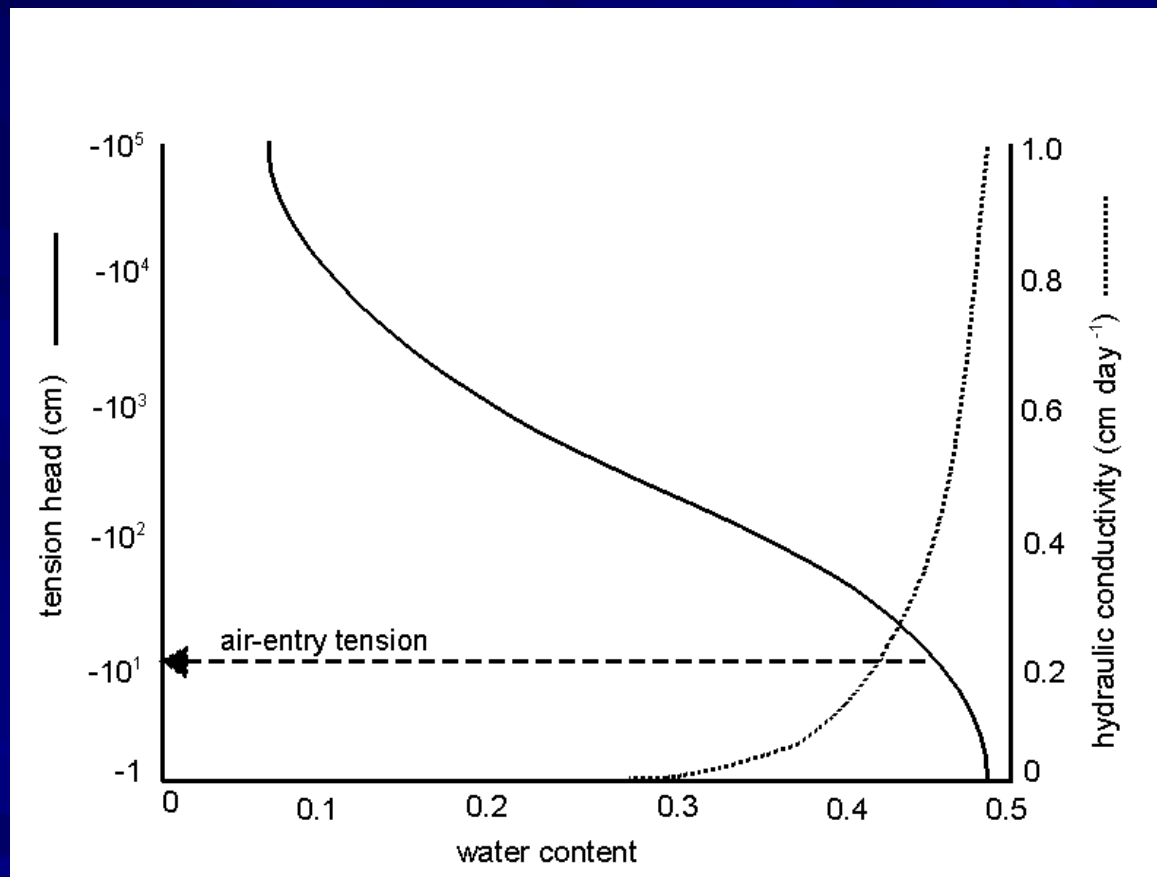
- Flux still has two components
 - Flux due to matric head gradient
 - Flux due to gravitational head gradient
- Hydraulic conductivity is now function of soil wetness



Hydraulic Conductivity Water Content Relationship



Water Retention and Hydraulic Conductivity Functions



<http://uregina.ca/~sauchyn/geog327/moisture.gif>

Water Retention and Hydraulic Conductivity Functions

■ Van Genuchten Function

$$\Theta(h) = \left[1 + \alpha(-h)^n \right]^{-m}$$

$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r}$$

$$m = 1 - 1/n$$

$$K(\theta) = K(\theta_s) \Theta^{0.5} \left[1 - \left(1 - \Theta^{\frac{1}{m}} \right)^m \right]^2$$

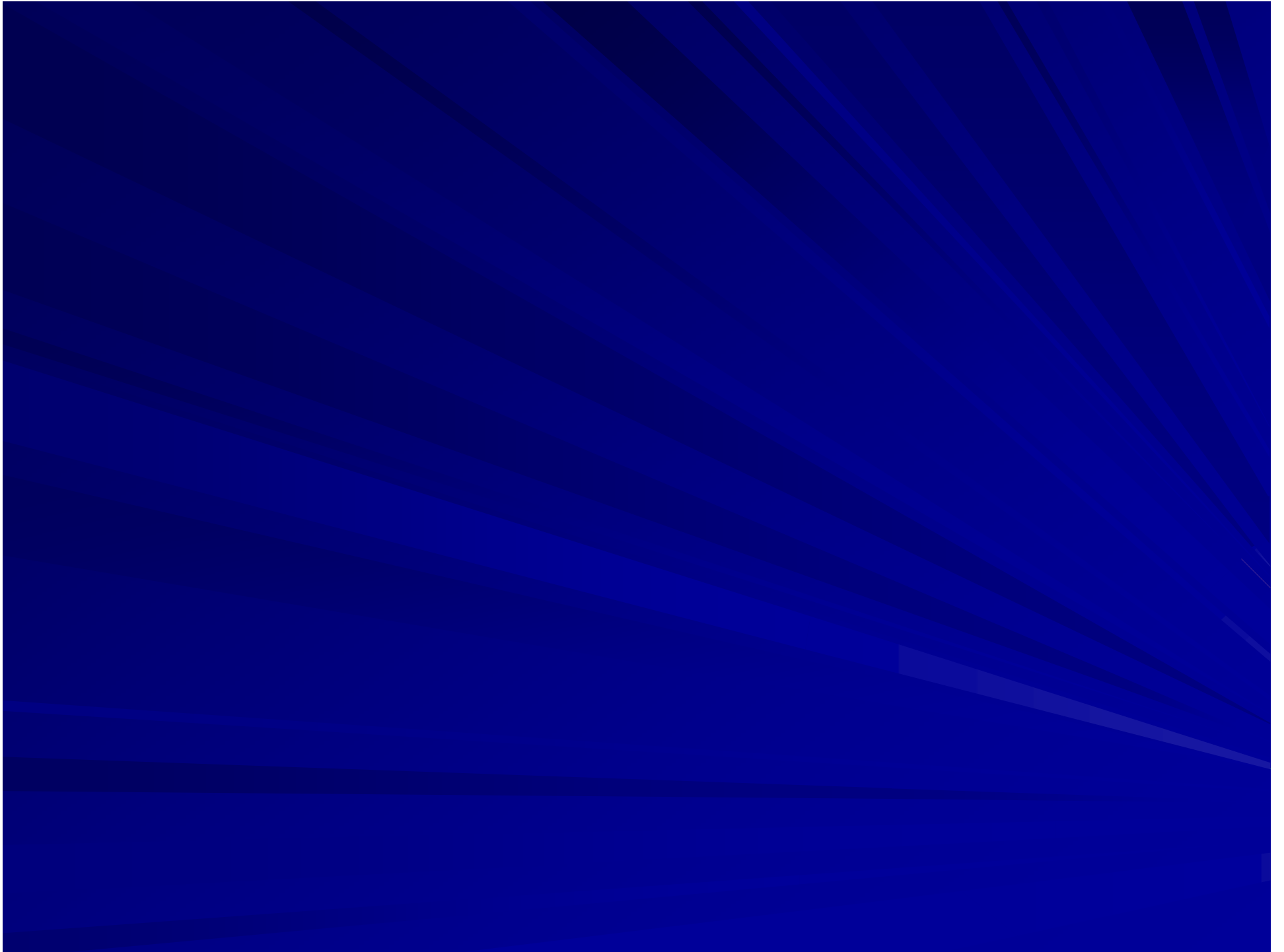
Estimating Hydraulic Conductivity Function Parameters

$$\theta_r = 0.015 + 0.005Clay + 0.014Carbon$$

$$\log \alpha = -2.486 + 0.025Sand - 0.023Clay - 0.351Carbon - 2.617BD$$

$$\log n = 0.053 - 0.009Sand - 0.031Clay + 0.00015Sand^2$$

$$m = 1 - 1/n$$





Richards Equation

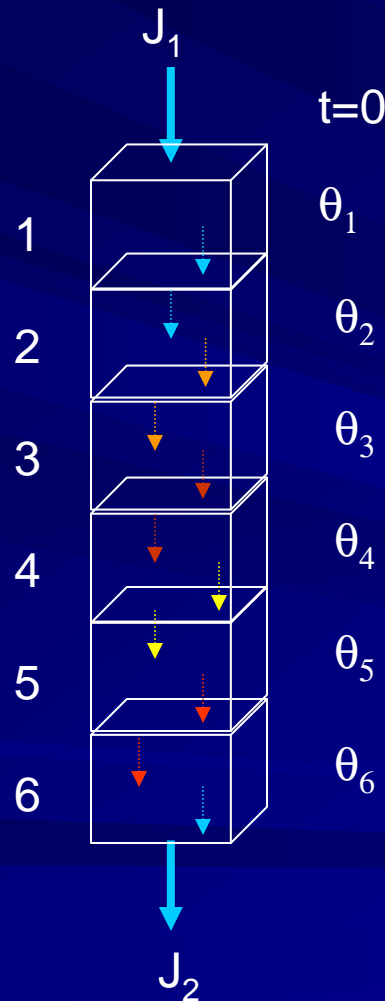
Non-steady State Flow

$$\frac{\partial \theta}{\partial t} = - \frac{\partial J_w}{\partial z}$$

$$\frac{\partial \theta}{\partial t} = - \frac{\partial J_w}{\partial z} = - \frac{\partial}{\partial z} \left(- K(\theta) \frac{\partial H}{\partial z} \right)$$

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left(K(\theta) \frac{\partial H}{\partial z} \right) = \frac{\partial}{\partial z} \left(K(\theta) \left(\frac{\partial h}{\partial z} + 1 \right) \right)$$

Application of Richards Eq.



Initial and Boundary value problem and one can solve it for water contents with depth and time.

This is the basis for many computer models simulation water content in soil over time.

Thank you





Darcy's Law Calculations

■ $H=h+z$

■ Inlet

– $h=20$ cm

– $z=20$ cm

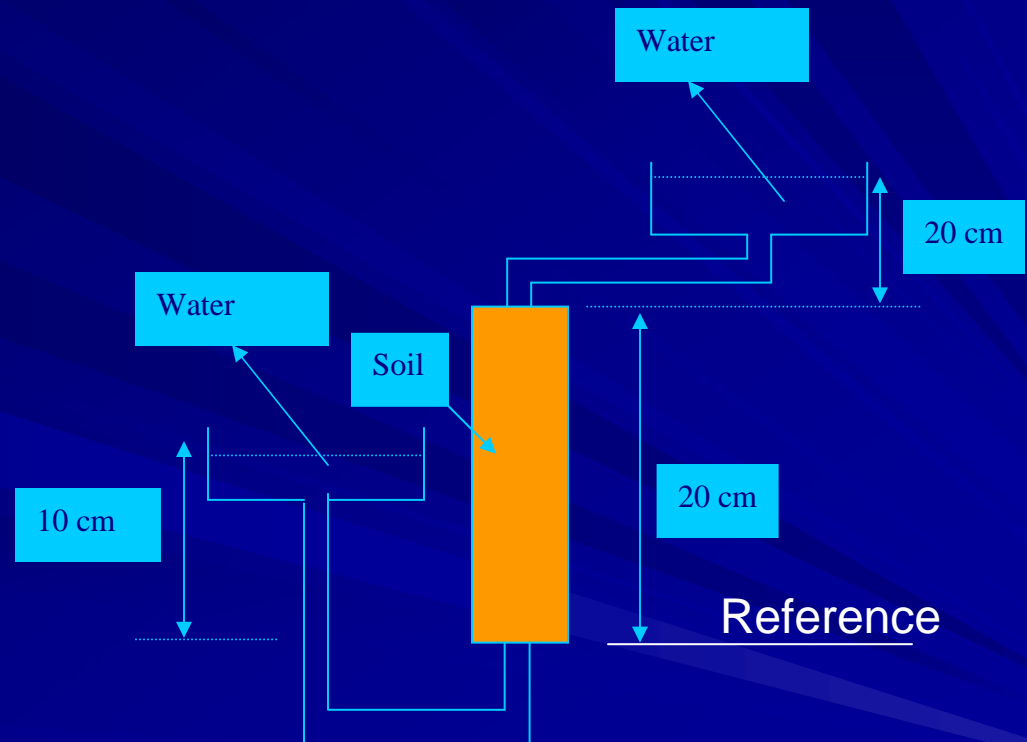
– $H_1=20+20=40$

■ Outlet

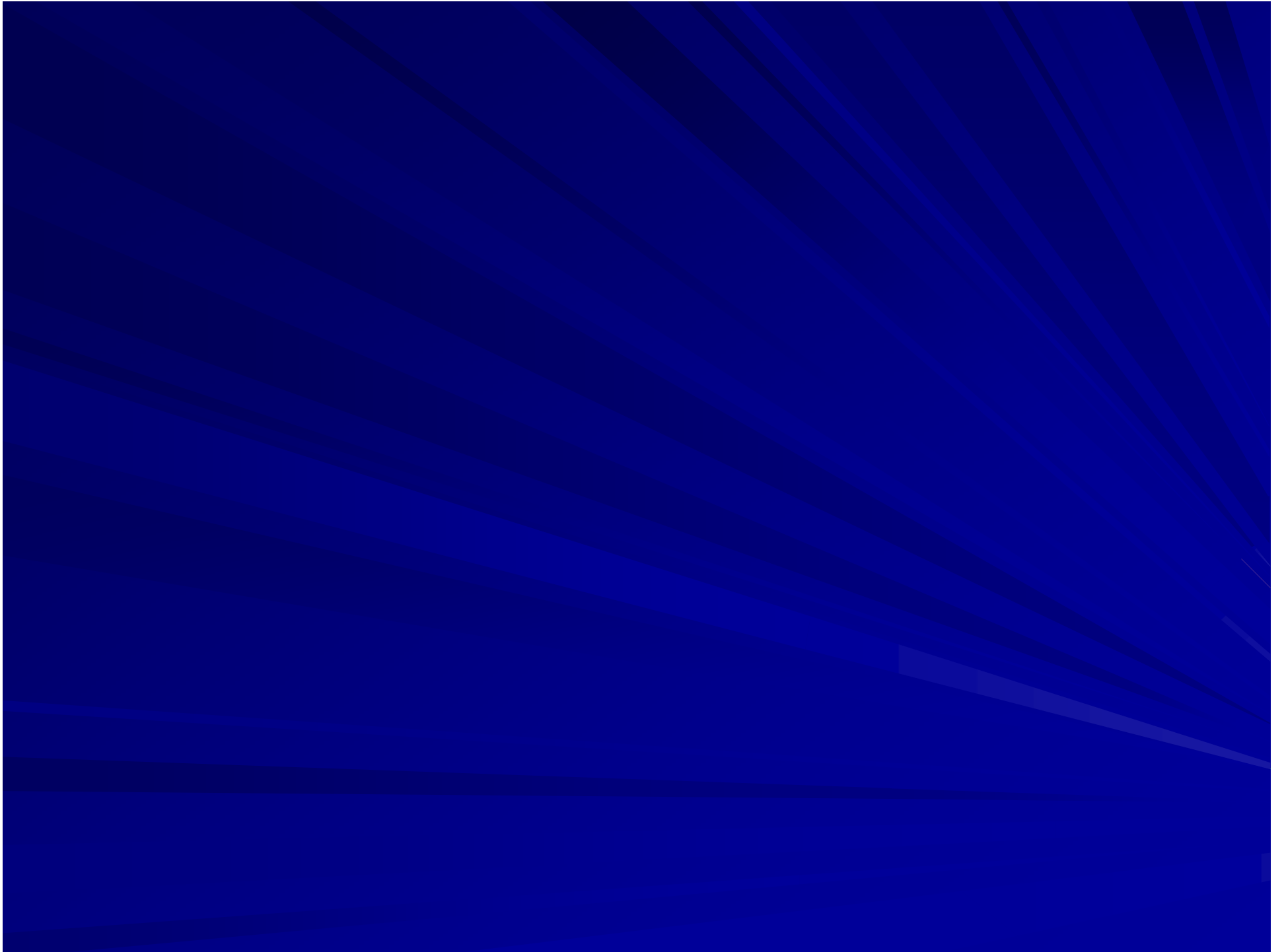
– $h=10$ cm

– $z=0$

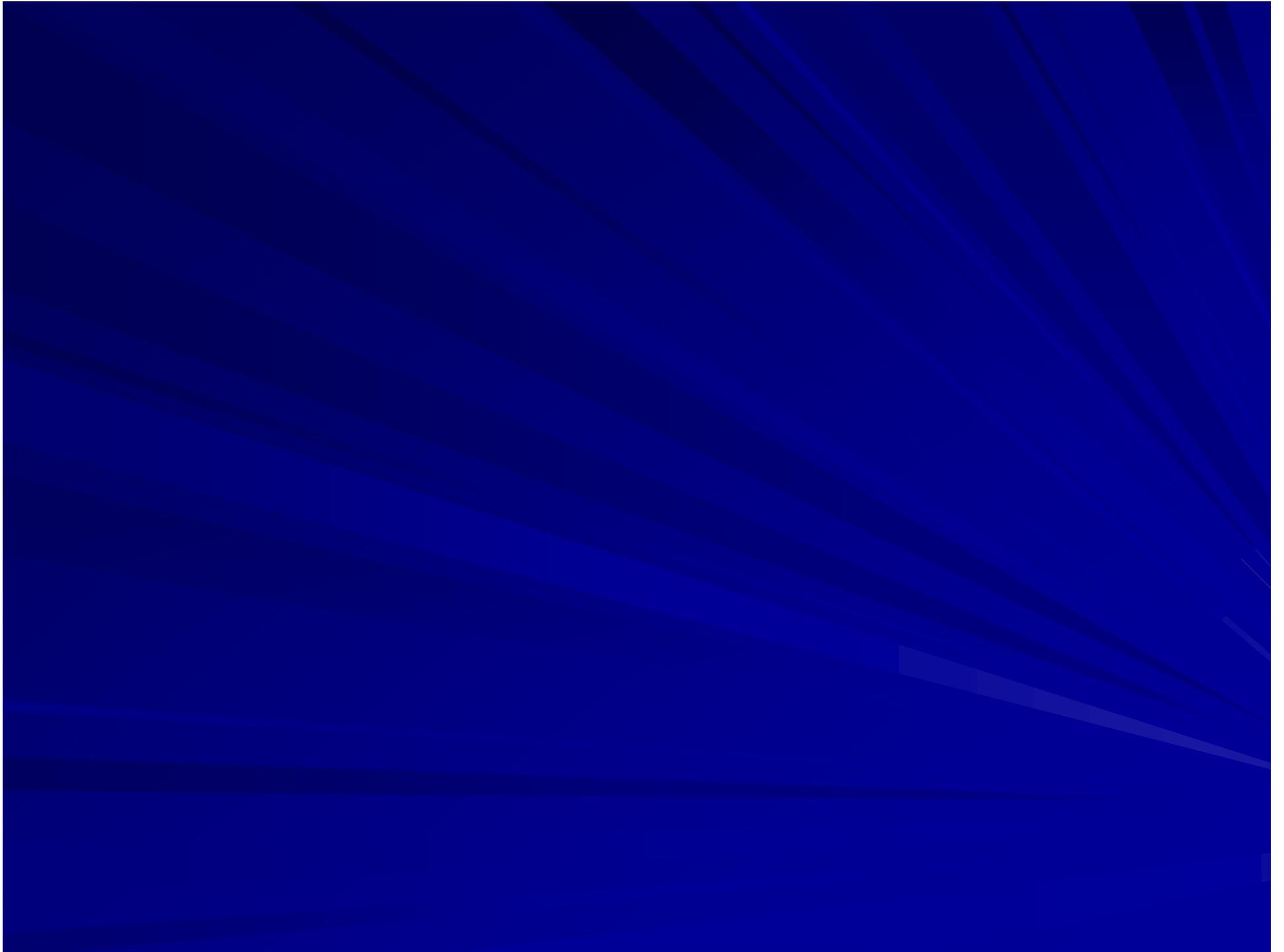
– $H_2=10+0=10$



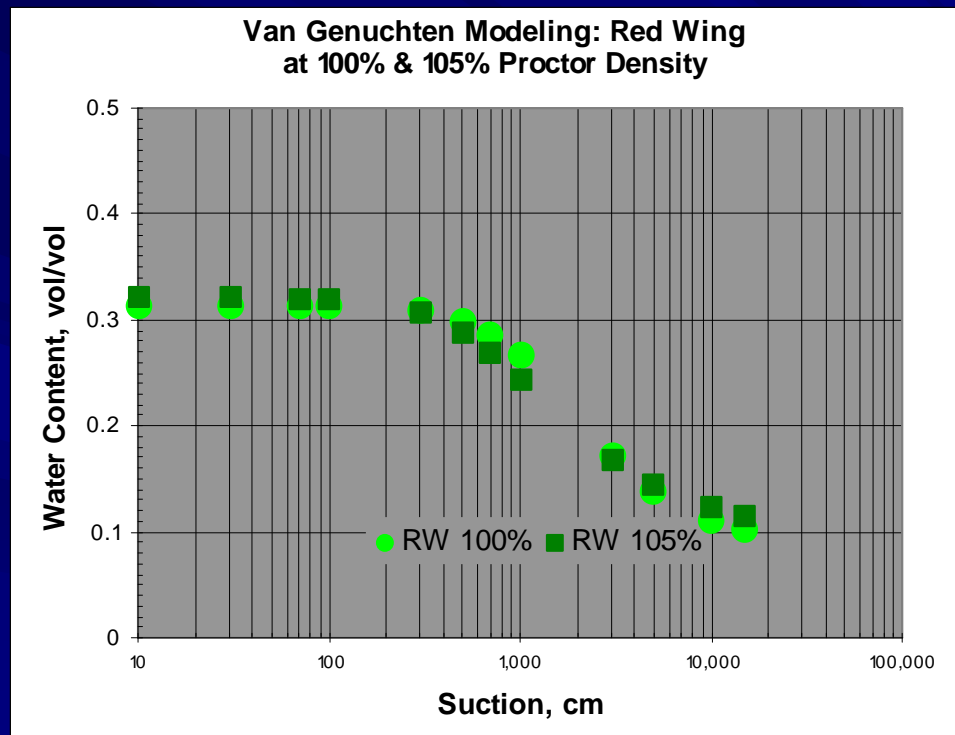
$$J_w = -K \frac{\Delta H}{L} = -5 \frac{cm}{hr} \left(\frac{40-10}{20-0} \right) \frac{cm}{cm} = -7.5 \frac{cm}{hr}$$







Water Retention Fit of Van Genuchten's Function



Density	θ_s	θ_r	α	n
100%	0.31	0.10	0.0007	2.044
105%	0.32	0.11	0.0012	1.852



Hydraulic Conductivity Function

$$K(\theta) = K(\theta_s) \Theta^{0.5} \left[1 - \left(1 - \Theta^{\frac{1}{m}} \right)^m \right]^2$$

$$K(\theta) = K(\theta_s) \left(\frac{\theta - 0.1}{0.21} \right)^{0.5} \left[1 - \left(1 - \left(\frac{\theta - 0.1}{0.21} \right)^{1.96} \right)^{0.511} \right]^2$$