Soil Water (I)

Prof. Gabriele Manoli
gabriele.manoli@epfl.ch

Today's Lecture

- **Methods of measuring water saturation in soil**
- **Water in the soil profile**
- **Potential of soil water**

See pages 2-13 of Notes 2.pdf

Characterization of the liquid phase

The characterization of the soil's liquid phase is based on two types of information:

- The quantity of water present in the soil (notion of **water content**)
- The energy state of the soil water (notion of **water potential**)

https://education.nationalgeographic.org

Water content

Water content (teneur en eau du sol):

- Gravimetric water content (teneur en eau massique): $w = \frac{M_w}{M_s}$
- Volumetric water content (teneur en eau volumique): $\theta = \frac{V_w}{V_t} = \frac{\rho_d}{\rho_w} w$
- Degree of saturation (degré de saturation): $S_w = \frac{V_w}{V_v} = \frac{\theta}{n}$

Where M_w is the mass of water in the soil, M_s is the mass of dry soil, V_w is the volume of water in the soil, V_t is the total volume, n is the porosity, $\rho_d = M_s/V_t$ is the dry bulk density, $\rho_d = (M_s + M_w)/V_t$ is the wet bulk density, $\rho_s = M_s/V_s$ is the solid density, and $\rho_w = M_w/V_w$ is the water density.

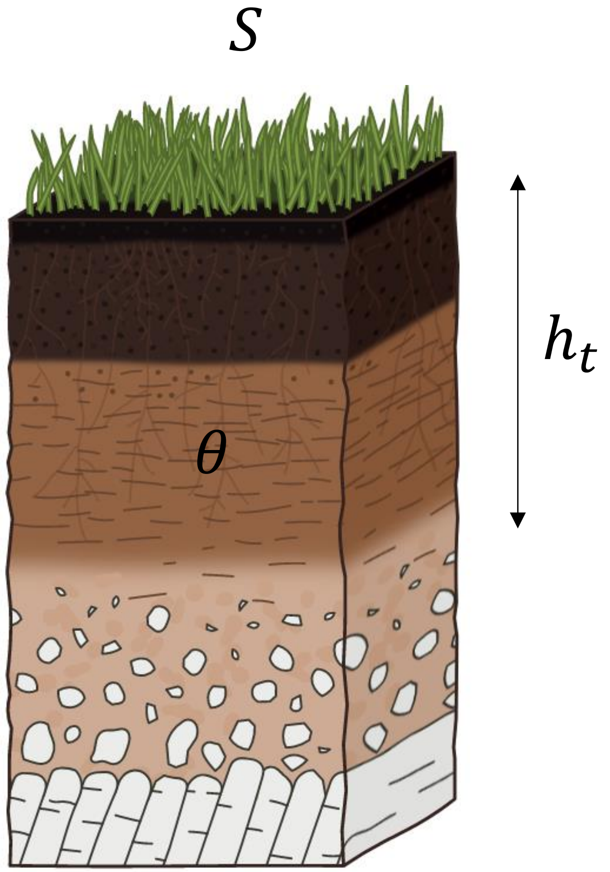
Equivalent water height

From the water content by volume we can calculate the equivalent water height stored in a soil of height h_t :

$$\theta = \frac{V_w}{V_t} \longrightarrow V_w = \theta\, V_t = \theta\, S\, h_t = S\, h_w$$

$$\longrightarrow h_w = \theta\, h_t$$

equivalent water height



Exercise

A litre of dry soil from a farm needs 300 g of water to bring it to full saturation.

a) What is the soil's porosity?
b) What is the total volume of water needed to saturate the top 20 cm of 1 hectare of farmland (assuming it is initially dry)?
c) What is the equivalent height of water in the top 20-cm layer of soil after it becomes saturated?

a) Porosity $n = V_w/V_t = (300\ \mathrm{g}/(1\ \mathrm{g/cm^3}))/1000\ \mathrm{cm^3} = 0.3\ \mathrm{m^3/m^3}$
b) Volume $= n\, h_t A = 0.3 \times 0.2\ \mathrm{m} \times 10^4\ \mathrm{m} = 600\ \mathrm{m^3}$
c) Height $h_w = \theta\, h_t = n\, h_t = 0.3 \times 0.2\ \mathrm{m} = 0.06\ \mathrm{m} = 6\ \mathrm{cm}$ ($\theta = n$ since the soil is saturated)

Self-Study

Characterization of the liquid phase

The two most important characteristics of the liquid phase (soil water) are:

- the amount of water in the soil: **soil water content θ**
- the force by which water is held in the soil matrix: **matric potential ψ**

These soil water attributes are related to each other through a function known as the soil water characteristic (SWC) curve. Changes in soil water content and matric potential affect many of the soil's mechanical properties including strength, compactibility, and penetrability, and may cause changes in the soil bulk density in swelling soils. The liquid phase characteristics affect the soil's gaseous phase and the rates of exchange between these phases, as well as other soil properties such as the hydraulic conductivity

The soil water content can be measured in the **lab** (direct method, e.g., gravimetric) or in **field** (indirect methods, e.g., neutron scattering, TDR)

https://cropaia.com/blog/soil-water-content/

Soil Water content measurements

Gravimetric Soil Water Measurement

A sample may be obtained by digging, augering, or coring into the soil; its volume need not be known. The moist soil sample is weighed and later dried in an oven at 105ºC for at least 24 h to remove interparticle water, but not "structural-water" trapped in clay lattices. The difference between the "wet" and "dry" masses is the mass of water held in the original soil sample.

https://www.montana.edu

https://uta.pressbooks.pub

https://www.winfieldunited.com

http://epicprojects.com.au

Soil Water content measurements

Gravimetric Soil Water Measurement

Gravimetric water content is expressed relative to the mass of oven-dry soil according to:

$$w = \frac{\text{mass of water}}{\text{mass of dry soil}} = \frac{(\text{mass wet soil}) - (\text{mass oven dry soil})}{\text{mass oven dry soil}}$$

And recall that, in terms of volume:

$$\theta = \frac{\text{volume of water}}{\text{bulk volume of soil}} = \frac{\left(\dfrac{\text{mass of water}}{\text{density of water}}\right)}{\text{sample volume}} = w\frac{\rho_d}{\rho_w}$$

An undisturbed sample is needed to find the bulk density

https://www.montana.edu

https://uta.pressbooks.pub

Soil Water content measurements

Neutron scattering method

This method is commonly used for field measurement of volumetric water content. It is based on the propensity of hydrogen nuclei to slow (thermalize) high energy fast neutrons. A typical neutron moisture meter consists of:

- a probe containing a radioactive source that emits high energy (2-4 MeV) fast (1600 km/s!) neutrons as well as a detector of slow neutrons;
- a scaler to monitor the flux of slow neutrons;
- optionally a datalogger for storing and retrieving data

The radioactive source commonly contains a mixture of Americium-241 and Beryllium in 10 to 50 millicurie amounts. The Americium-241 emits alpha particles which strike the Beryllium and result in emission of fast neutrons

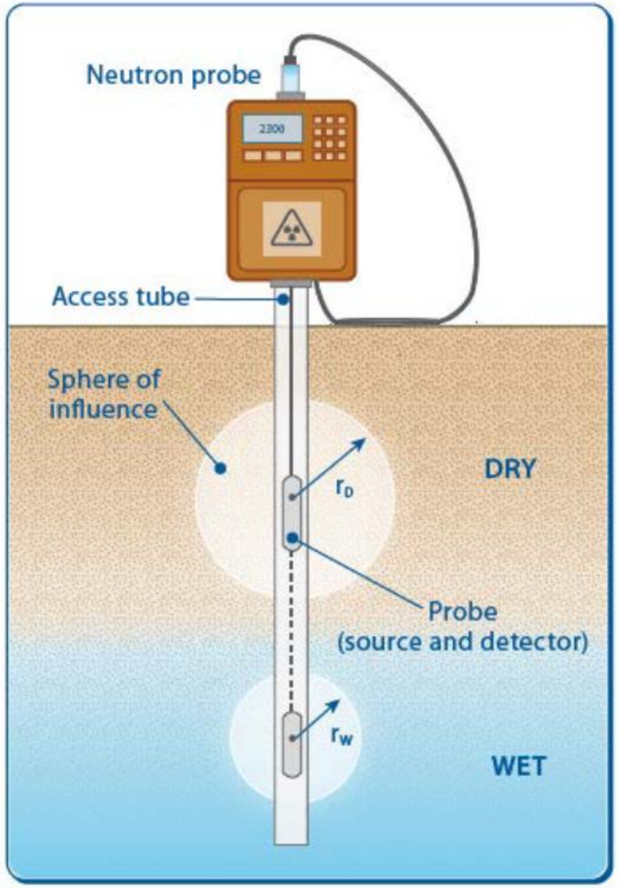


Fig.1-14: An illustration of a neutron probe device for measuring soil water content

Source: Or, Tuller, & Wraith, 1994-2018

Soil Water content measurements

Neutron scattering method

When the probe is lowered into an access tube, fast neutrons are emitted radially into the soil where they collide with various atomic nuclei. Collisions with hydrogen nuclei, which have similar mass to neutrons, cause a significant loss of kinetic energy and slow down the fast neutrons – when their speed diminishes to about 2.7 km/s, neutrons become "thermalized" or "slow". The relative number of slow neutrons is therefore proportional to the amount of hydrogen nuclei in the soil, the primary source of which is water. Several other non-hydrogen substances which may be present in trace amounts in some soils may also effectively thermalize fast neutrons; hence, a soil-specific calibration is needed. The calibration curve is usually linear and relates volumetric water content to **slow neutron counts or count ratio** (CR):

$$\theta_v = a + b\,(CR)$$

Source: Or, Tuller, & Wraith, 1994-2018

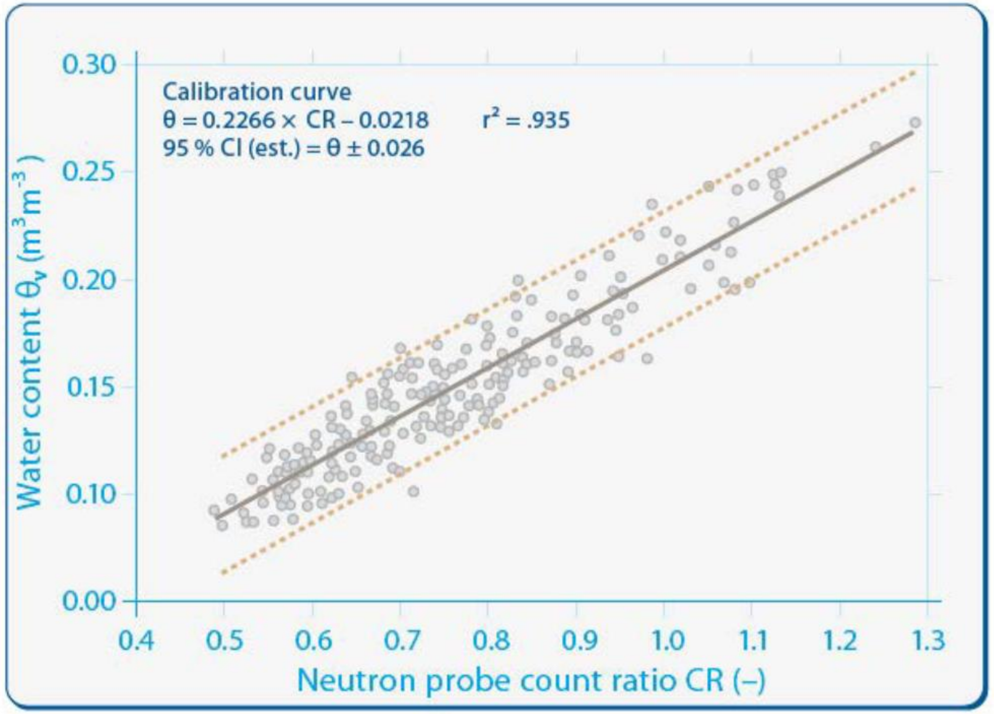


Fig.1-15: A typical calibration curve for neutron probe (Millville silt loam soil, Logan, Utah)

Soil Water content measurements

Neutron scattering method

The sphere of influence about the radiation source varies between about 15 cm (wet soil) to perhaps 70 cm (very dry soil). An approximate equation for the radius of influence (r) in cm as a function of soil wetness is:

$$r\ [\text{cm}] = 15\left(\theta_v\right)^{-1/3}$$

thus, the neutron scattering method is **unsuitable for measurement near the soil surface** because a portion of the neutrons may escape the soil.

Other limitations/disadvantages of this method include the radiation hazard and attendant licensing requirements, relatively poor and uncertain spatial resolution, unsuitability for near-surface measurements, and soil-specific calibration requirement.

Source: Or, Tuller, & Wraith, 1994-2018

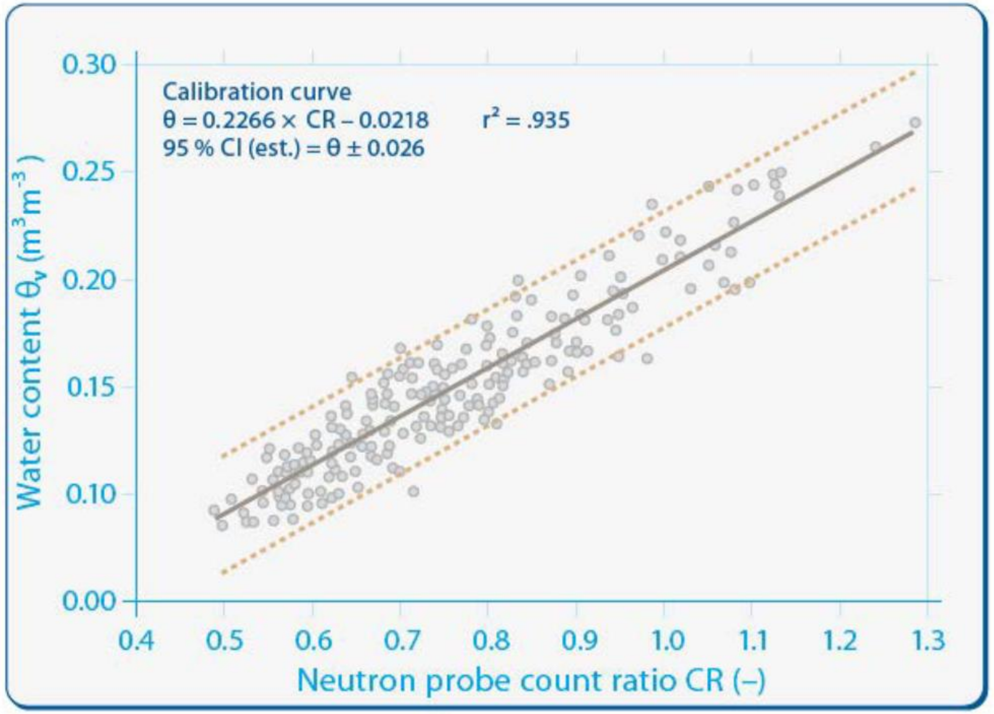


Fig.1-15: A typical calibration curve for neutron probe (Millville silt loam soil, Logan, Utah)

Soil Water content measurements

Time-Domain Reflectometry

The Time Domain Reflectometry (TDR) is a relatively new method for measurement of soil water content. The main **advantages** of the TDR method over other methods for repetitive soil water content measurement such as the neutron moisture meter are:

- superior accuracy to within 1 or 2% of volumetric water content;
- calibration requirements are minimal - in many cases soil-specific calibration is not needed;
- no radiation hazards associated with neutron probe or gamma-attenuation techniques;
- Excellent spatial and temporal resolution;
- measurements are simple to obtain, and the method is capable of providing continuous soil water measurements through automation and multiplexing

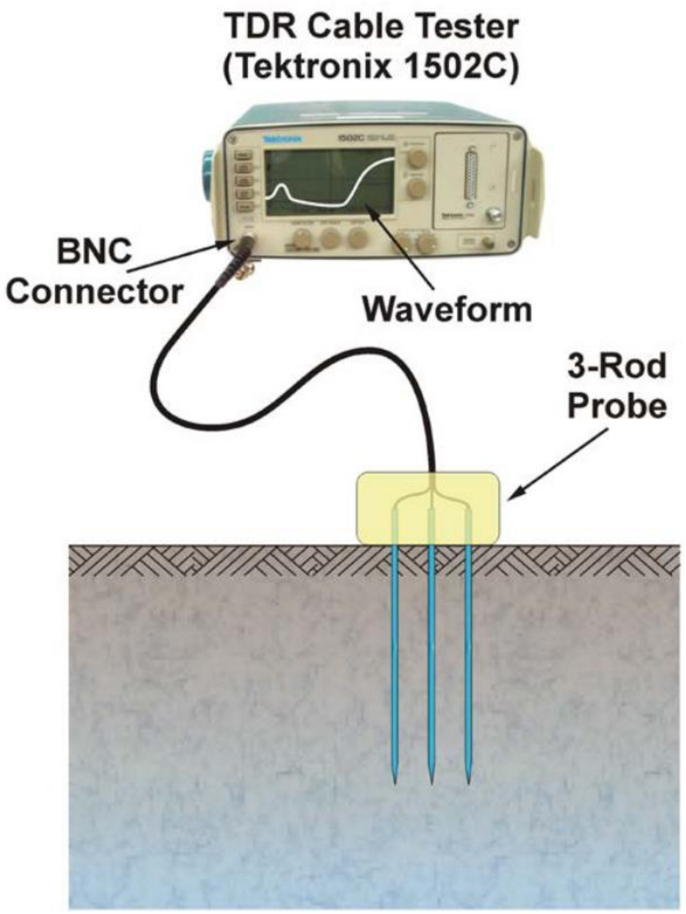


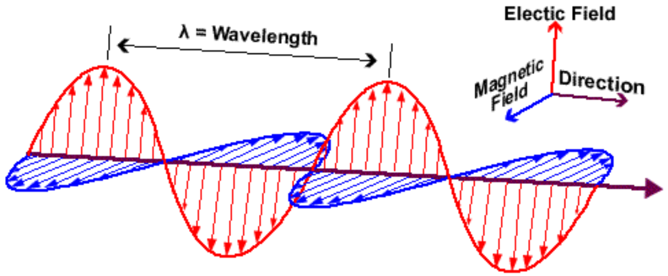
Fig.1-16: TDR cable tester with 3-rod probe embedded vertically in surface soil layer.

Source: Or, Tuller, & Wraith, 1994-2018

Soil Water content measurements

Time-Domain Reflectometry

The propagation velocity (v) of an electromagnetic wave along a transmission line (probe or waveguide) of length L embedded in the soil is determined from the time response of the system to a pulse generated by the TDR cable tester. The propagation velocity (v=2L/t) is a function of the **soil bulk dielectric constant** (ε_b) according to:



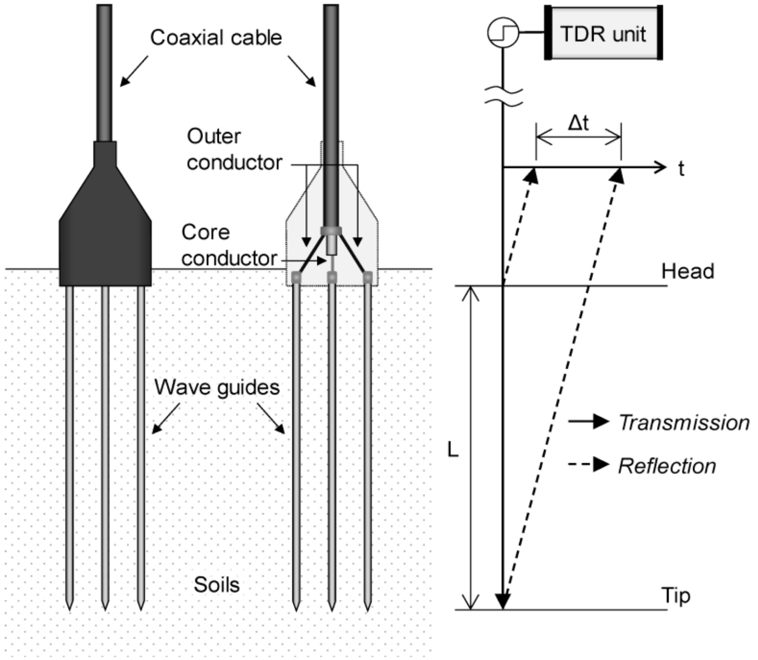
$$\varepsilon_b = \left(\frac{c}{v}\right)^2 = \left(\frac{c\,t}{2L}\right)^2 \longrightarrow v = c \cdot \varepsilon_b^{-1/2}$$

where c is the velocity of electromagnetic waves in vacuum (3×10^8 m/s), and t is the travel time for the pulse to traverse the length of the embedded waveguide (down and back = 2L). The equation simply states that the dielectric constant of a medium is the ratio squared of propagation velocity in vacuum relative to that in the medium. The soil bulk dielectric constant (ε_b) is governed by the dielectric of liquid water **$\varepsilon_w \cong 81$**, as the dielectric constants of other soil constituents are much smaller, e.g., **soil minerals ε_s = 3 to 5**, frozen water (ice) ε_i =4, and air ε_a =1. This large disparity of the dielectric constants makes the method relatively insensitive to soil composition and texture and thus a good method for liquid soil water measurement.

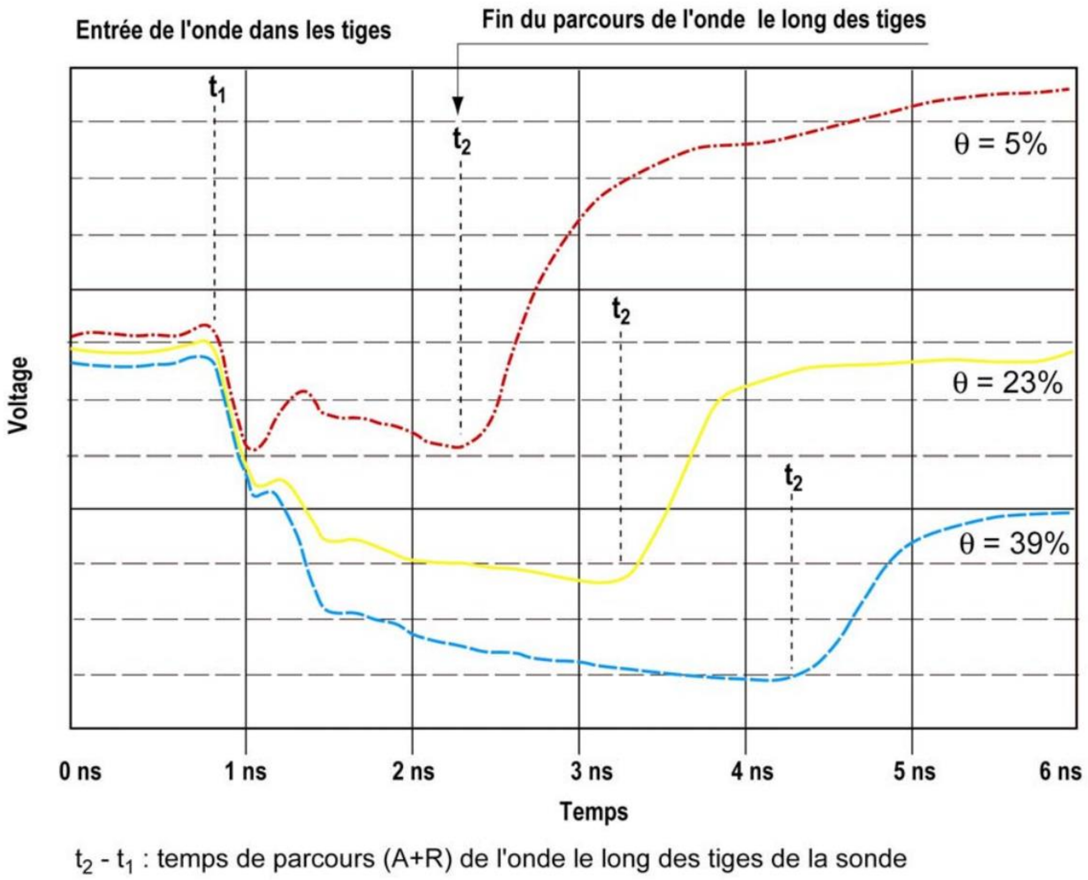
Soil Water content measurements

Time-Domain Reflectometry

$$\varepsilon = \left(\frac{c(t_2 - t_1)}{2L}\right)^2$$



Hong et al. (2019), Sensors



Source: Mermoud (2006)

Soil Water content measurements

Time-Domain Reflectometry

Two basic approaches have been used to establish the relationships between $\boldsymbol{\varepsilon_b}$ and volumetric soil water content ($\boldsymbol{\theta_v}$):

- The first approach is empirical, it was employed by **Topp et al. (1980)** who fitted a third-order polynomial to the observed relationships for multiple soils, i.e.

$$\boxed{\theta_v = -5.3\times10^{-2} + 2.92\times10^{-2}\varepsilon_b - 5.5\times10^{-4}\varepsilon_b{}^2 + 4.3\times10^{-6}\varepsilon_b{}^3}$$

Limitation: fails for $\theta_v > 0.5$ and for organic soils

- The second approach uses a model of the dielectric constants and the volume fractions of each of the soil components. According to the **dielectric mixing model** by Birchak (1974) and Roth et al. (1990), the bulk dielectric constant of a three-phase system is:

$$\varepsilon_b = \left[\theta_v\,\varepsilon_w{}^{\beta} + (1-n)\varepsilon_s{}^{\beta} + (n-\theta_v)\varepsilon_a{}^{\beta}\right]^{\frac{1}{\beta}} \longrightarrow \boxed{\theta_v = \frac{\varepsilon_b{}^{\beta} - (1-n)\varepsilon_s{}^{\beta} - n\,\varepsilon_a{}^{\beta}}{\varepsilon_w{}^{\beta} - \varepsilon_a{}^{\beta}}} \longrightarrow \theta_v = \frac{\sqrt{\varepsilon_b} - (2-n)}{8}$$

n is the soil's porosity and $-1<\beta<1$ summarizes the geometry of the medium in relation to the axial direction of the wave guide: $\beta=1$ for an electric field parallel to soil layering, $\beta=-1$ for a perpendicular electrical field, and $\beta=0.5$ for an isotropic two-phase mixed medium.
Typical values: $\beta=0.5$, $\varepsilon_w=81$, $\varepsilon_s=4$, and $\varepsilon_a=1$

Soil Water content measurements

Time-Domain Reflectometry

Limitations or disadvantages of the TDR method include:

- relatively high equipment expense,
- potential limited applicability under highly saline conditions due to signal attenuation,
- soil-specific calibration may be required for soils having large amounts of bound water or high organic matter contents.

Note: there are several other methods for soil water measurement, including: (i) methods based on electrical resistance or capacitance of a pair of electrodes embedded in porous media and brought to equilibrium with soil water; (ii) gamma ray attenuation methods or x-ray computed tomography; and (iii) miscellaneous methods including fiber optics, nuclear magnetic resonance (NMR), and geophysical methods such as ground-penetrating radar and electrical resistivity sounding

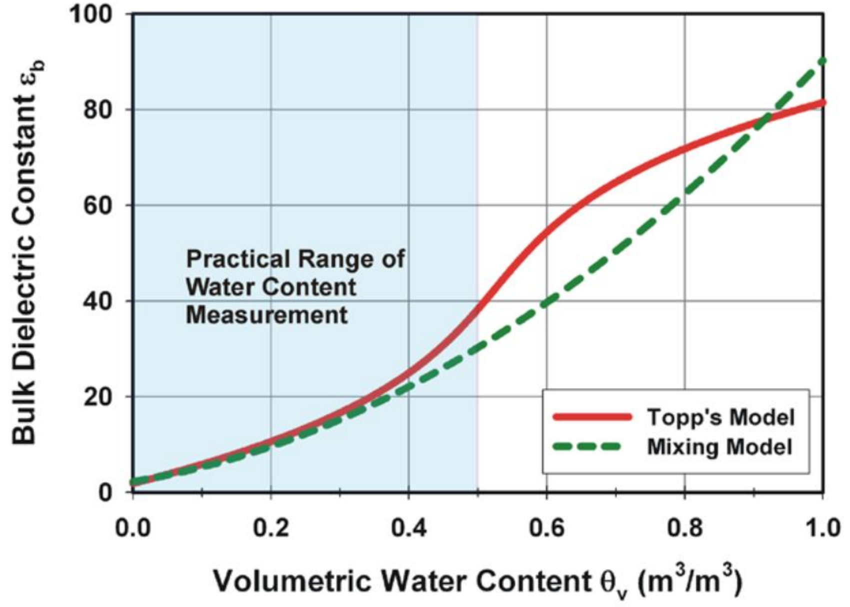


Fig.1-17: Relationships between bulk soil dielectric constant and θ_v expressed by two commonly used TDR calibration approaches

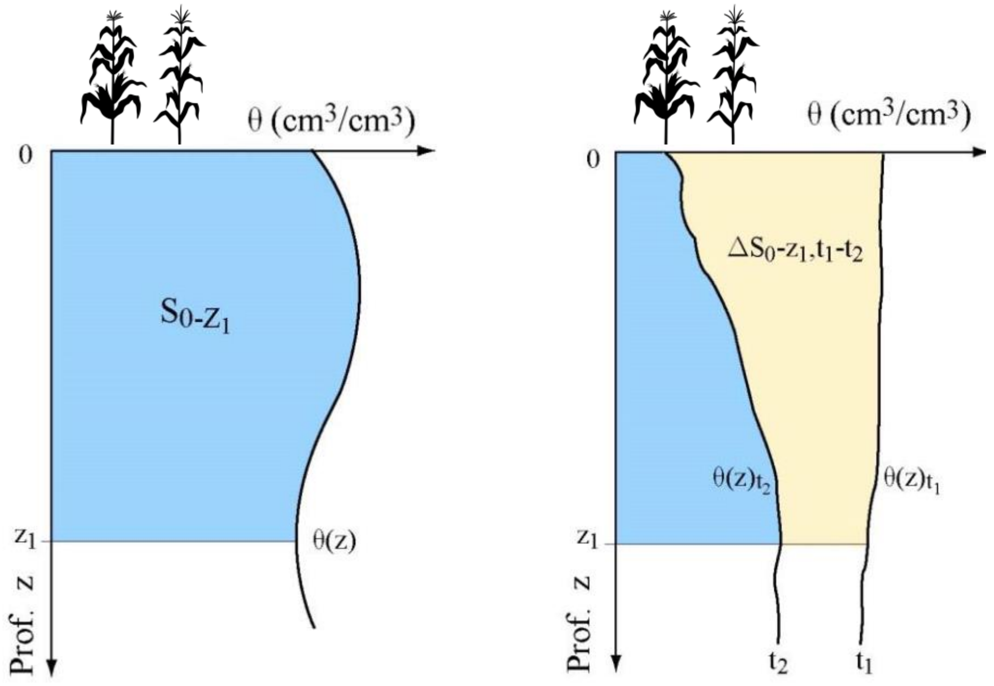
Source: Or, Tuller, & Wraith, 1994-2018

Applications of soil water content measurements

Soil water measurements taken over time are coupled with climatic data including evapotranspiration and precipitation. The resulting information may be used for a wide variety of purposes, for example to assist irrigation scheduling (when to irrigate? how much water to apply?), estimate evapotranspiration or drainage, or help to determine groundwater recharge amounts.

Key applications include:

- Determine the soil water content profile
- Estimate available soil water and its changes over time
- Inform water management and irrigation
- geotechnical and hydrologic applications



$$S_{0\text{-}z_1} = \int_0^{z_1} \theta \, dz \qquad \Delta S_{0-z_1,t_1-t_2} = \int_0^{z_1} \Delta\theta \, dz$$

Important soil moisture levels

- **Saturated water content, θ_S (teneur en eau à saturation):** fully saturated soil, equivalent to porosity

- **Field capacity, θ_{FC} (capacité au champ):** observations of water content changes in the soil profile following irrigation or rainfall show that the rate of change decreases in time. In some cases, water content attains a nearly constant value within 1 to 2 days after irrigation. Field capacity is defined as the water content at which internal drainage becomes essentially negligible

- **Permanent wilting point, θ_{WP} (point de flétrissement permanent):** defined as the water content at which plants can no longer extract soil water at a rate sufficient to meet evaporative demand, and thus irreversibly wilt and die. Though commonly taken as the water content at -1.5 MPa (-15 bar) matric potential, there is substantial variation among plant species in their abilities to resist soil drought.

- **Transient wilting, θ_{TW} (point de flétrissement temporaire):** soil moisture when plants show signs of temporary wilting symptoms during periods of high evaporative demand (e.g., during summer afternoons)

- **Plant-available soil water, PASW (réserve utile).** Soil water storage available for plant use is generally calculated as being between these two limits, PASW = θ_{FC} - θ_{WP}

Source: Or, Tuller, & Wraith, 1994-2018

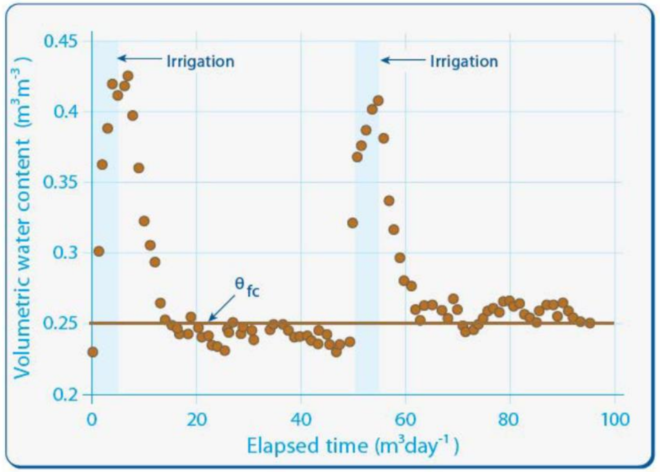


Fig.1-22: Measured soil water content at 0.1 m depth during and after two irrigation events. Field capacity for this silt loam soil is about 0.25

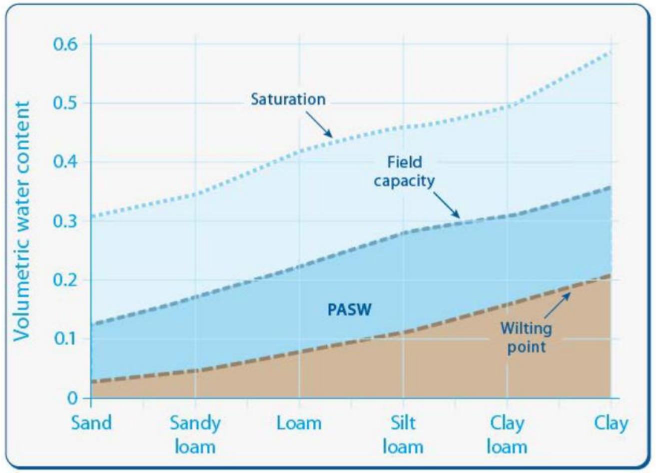
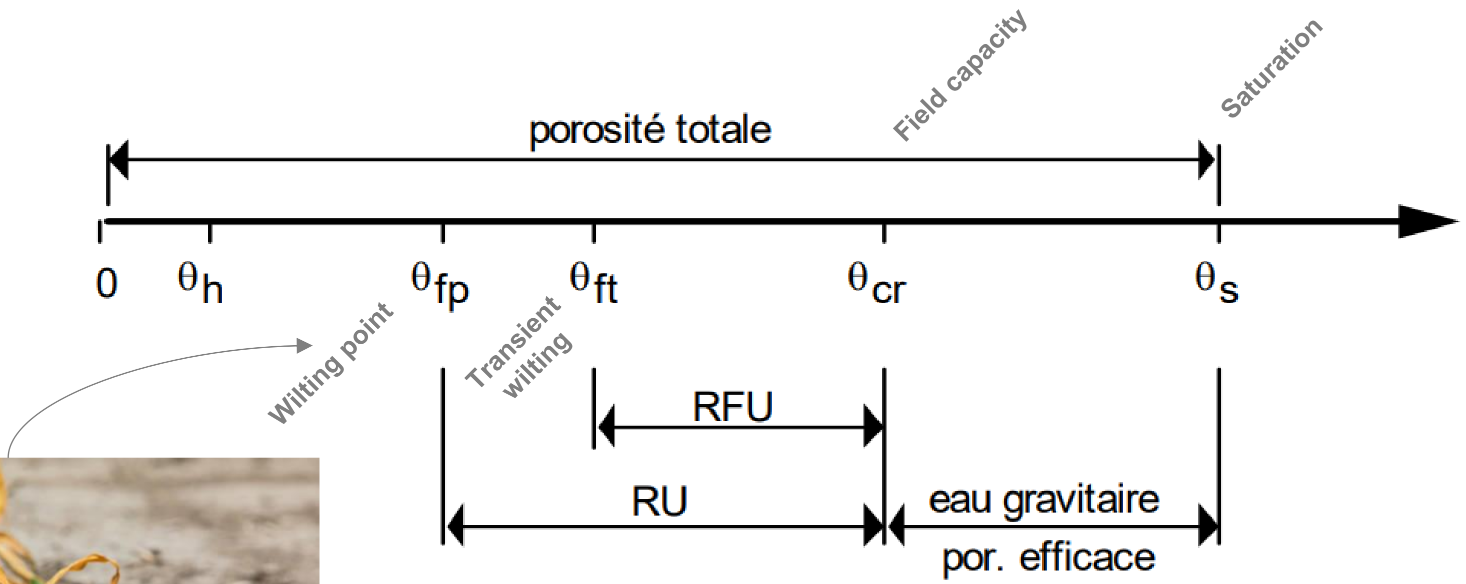


Fig.1-24: Schematic of estimated plant available soil water (PASW) for a range of soil textural classes

Important soil moisture levels



www.istockphoto.com

RU = réserve utile = PASW · d_R = $(\theta_{FC} - \theta_{WP}) \cdot d_R$

RFU = réserve facilement utilisable = $(\theta_{FC} - \theta_{TW}) \cdot d_R$

Where d_R = root depth

Energy state of soil water

An additional critical attribute is the **energy state of soil water**. Soil water contains different forms and quantities of energy, as does any body of matter. The two primary forms of mechanical energy of interest here are **kinetic** and **potential:**

- Kinetic energy is acquired by virtue of motion and is proportional to the velocity squared, i.e., $E_k = mv^2/2$. Since the movement of water in soils is relatively slow, kinetic energy is negligible
- The potential energy, which is determined by a body's position in a force field and by internal conditions, is of primary importance in characterizing the soil water status. Like all other matter, soil water tends to move from where the potential energy is high to where it is lower, in its pursuit of a state known as *equilibrium* with its surroundings (i.e., uniform potential energy throughout). Hence, the driving force behind such spontaneous motion is a difference in potential energy across a distance between two points of interest.

Note: potential energy is defined relative to a **reference** state. The standard state for soil water is defined as pure and free water (no solutes and no external forces other than gravity) at a reference pressure, temperature, and elevation, and is arbitrarily given the value of zero.

Energy state of soil water

Total soil water potential

Definition: total potential of soil water is *"the amount of work that must be done per unit quantity of pure water to transport reversibly and isothermally an infinitesimal quantity of water from a pool of pure water at a specified elevation at atmospheric pressure to the soil water at the point under consideration"* (International Soil Science Society).

In general, soil water is subject to a number of possible forces, each of which may cause its potential to differ from that of pure, free water at a reference elevation. Such force fields result from various factors, i.e.

$$\phi_t = \phi_g + \phi_p + \phi_o + \ldots \tag{6.13}$$

where ϕ_t is the total potential, ϕ_g is the gravitational potential, ϕ_p is the pressure (or matric) potential, ϕ_o is the osmotic potential, and the ellipsis signifies that additional terms are theoretically possible.

Hillel (2003)

Energy state of soil water

EPFL

Gravitational potential

Every body on the earth's surface is attracted toward the earth's center by a gravitational force equal to the weight of the body, that weight being the product of the mass of the body and the gravitational acceleration. To raise a body against this attraction, work must be expended, and this work is stored by the raised body in the form of gravitational potential energy

At a height z above a reference, the gravitational potential energy E_g of a mass M of water occupying a volume V is

$$E_g = Mgz = \rho_w Vgz$$ (Units: ML^2/t^2)

where ρ_w is the density of water and g is the acceleration of gravity. Accordingly, the gravitational potential in terms of the potential energy per unit mass is

$$\phi_{g,m} = gz$$ (Units: L^2/t^2)

and in terms of potential energy per unit volume is

$$\phi_{g,v} = \rho_w gz$$ (Units: $M/L/t^2$)

The gravitational potential is independent of the chemical and pressure conditions of soil water and dependent only on relative elevation.

Hillel (2003)

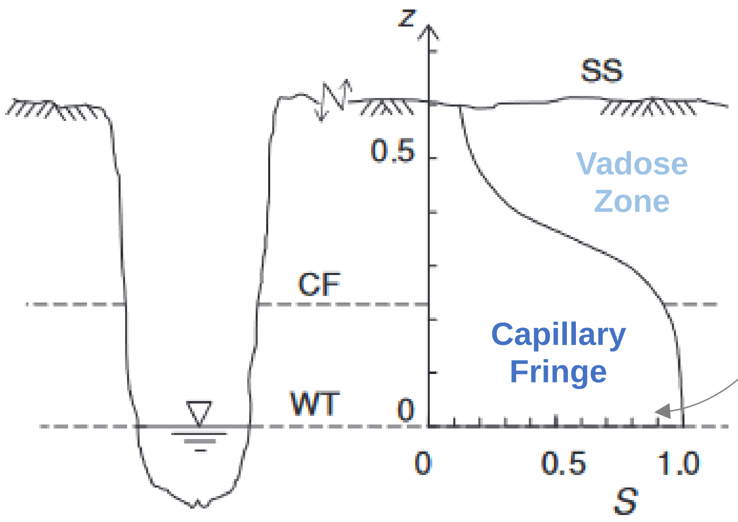
Note: it is customary to set the reference level at the elevation of a pertinent point within the soil or below the soil profile being considered (e.g., at the water table) so that the gravitational potential can always be taken as positive or zero. On the other hand, if the soil surface is chosen as the reference level, as is sometimes done, then the gravitational potential for all points below the surface is negative with respect to that reference level.

Energy state of soil water

Pressure potential

- In **saturated conditions**, soil water is at hydrostatic pressure greater than atmospheric and its pressure potential is considered positive (*submergence potential*).
- At the **water table (WT)**, the pressure head is zero (pressure is 1 atm)
- In **unsaturated conditions**, pressure is lower than atmospheric (a subpressure commonly known as *tension* or *suction*), and the pressure potential is considered negative

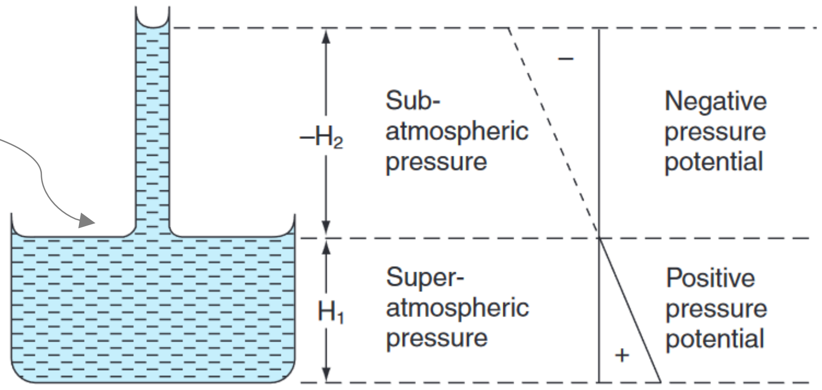
Thus, water at a free-water surface is at a zero pressure potential, water below that surface is at a positive pressure potential, while water that has risen in a capillary tube (or in the pores of the soil) above that surface is at a negative pressure potential.



Brutsaert (2005)

$$\phi_p = 0$$
$$(p = 1atm)$$

$$\phi_p = \phi_m < 0$$



Hillel (2003)

$$\phi_p = \phi_{ps} > 0$$

Energy state of soil water

Pressure potential: submergence potential

The pressure potential below the groundwater level has been termed the *submergence potential*. The hydrostatic pressure P of water in reference to atmospheric pressure is

$$P = \rho g h \tag{6.17}$$

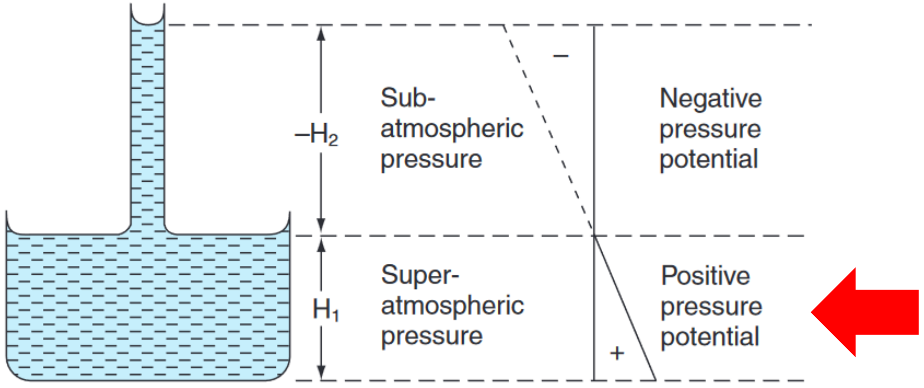
Here h is the piezometric head (submergence depth below the free-water surface). The potential energy of this water is then

$$E = P dV \tag{6.18}$$

and thus the submergence potential, taken as the potential energy per unit volume, is equal to the hydrostatic pressure, P:

$$\phi_{ps} = P \tag{6.19}$$

$$\phi_p = \phi_m < 0$$



Hillel (2003)

$$\phi_p = \phi_{ps} > 0$$

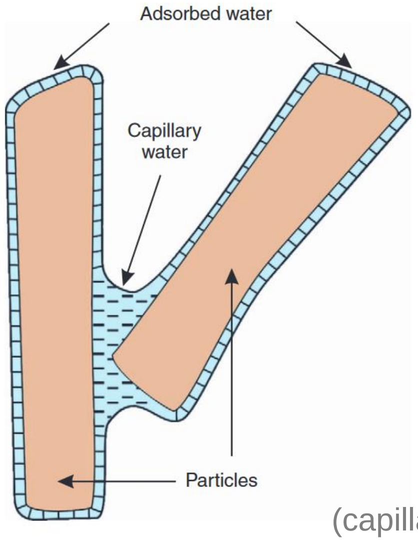
Energy state of soil water

Pressure potential: matric potential (or suction)

Capillarity results from the surface tension of water and its contact angle with the solid particles. If the soil were like a simple bundle of capillary tubes, the equations of capillarity might suffice to describe the relation of the negative pressure potential (tension, or suction) to the radii of the soil pores in which the menisci are contained, i.e.

$$P_0 - P_c = \Delta P = \gamma(1/R_1 + 1/R_2) \qquad (6.20)$$

where P_0 is the reference atmospheric pressure (taken as zero), P_c is the pressure of soil water (which can be smaller than atmospheric), ΔP is the pressure deficit (subpressure) of soil water, γ is the surface tension of water, and R_1, R_2 are the principal radii of curvature of the meniscus.



Matric potential
(capillary + absorptive forces)

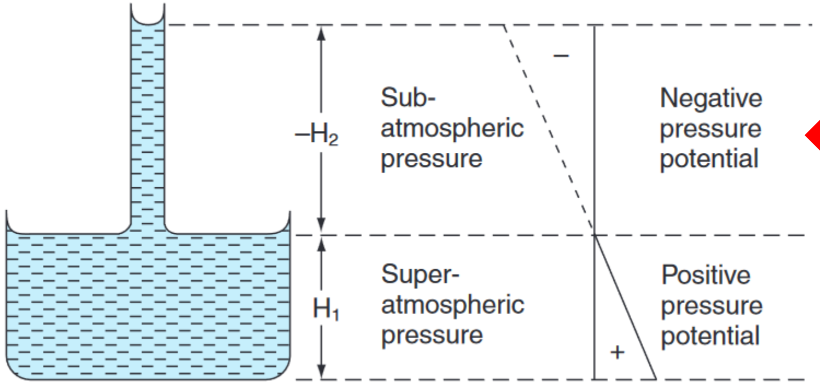
$$\phi_p = \phi_m < 0$$

However, in addition to the capillary phenomenon, the soil alsoo exhibits adsorption, which forms hydration envelopes over the particle surfaces.

In the absence of solute effects, the liquid and vapor phases in an unsaturated porous medium are related at equilibrium by

$$\phi_m = RT \ln(p/p_0) \qquad (6.21)$$

where R is the gas constant for water vapor, T is the absolute temperature, and p/p_0 is the relative humidity (i.e., the ratio of the atmosphere's vapor pressure at equilibrium with the unsaturated medium to the "saturated" vapor pressure at equilibrium with a body of pure free water).



Hillel (2003)

$$\phi_p = \phi_{ps} > 0$$

Energy state of soil water

Solute or Osmotic potential

The presence of solutes in soil water lowers its potential energy and its vapor pressure. Thus,

$$\phi_m + \phi_o = RT \ln(p/p_0)$$

Where ϕ_o is the osmotic potential. The effect of ϕ_o is important when (1) there are appreciable amounts of solutes in the soil; and (2) in the presence of a selectively permeable membrane or a diffusion barrier which transmits water more readily than salts. The effects are otherwise negligible. The two most important diffusion barriers in the soil are:

- soil-plant root interfaces, because cell membranes are selectively permeable
- soil water-air interfaces, when water evaporates salts are left behind.

In dilute solutions of non-dissociating solutes the solute potential, also called the osmotic pressure, is proportional to the concentration and temperature according to the van't Hoff relationship:

$$\phi_o = -RTC_s \qquad \text{(Units: kPa, } M/L/t^2\text{)}$$

where R is the universal gas constant [8.314×10^{-3} kPa m^3/(mol K)], T is absolute temperature (K), and C_s is solute concentration (mol/m^3).

Quantitative expressions of soil water potential

Table 1-5: Units, Dimensions and Common Symbols for Potential Energy of Soil Water

Units	Symbol	Name	Dimensions	SI Units	cgs Units
Energy/Mass	μ	Chemical Potential	L^2/t^2	J/kg	erg/g
Energy/Volume	ψ	Soil Water Potential, suction, or tension	$M/(Lt^2)$	N/m^2(Pa)	erg/cm^3
Energy/Weight	h	Soil Water Head	L	m	cm

(*From:* Jury et al., Soil Physics, 5th Ed. 1991; reprinted by permission of John Wiley & Sons, Inc.)

↔ ϕ Energy per unit volume

Specific relationships between the three potential energy expressions are derived from the relationship between volume and mass of water ($M_w = \rho_w \cdot V_w$ where ρ_w is the density of water), and between mass and weight ($W_w = g \cdot M_w$ where g is acceleration of gravity). The relationships may be summarized by:

$$\mu = \frac{\phi}{\rho_w} = gh \longrightarrow h = \frac{\phi}{g\rho_w}$$

Quantitative expressions of soil water potential

It is common to characterize the state of soil water in terms of the total potential head, the gravitational potential head, and the pressure potential head, which are usually expressible in meters. Accordingly, instead of

$$\phi_{t,v} = \phi_{p,v} + \phi_{g,v}$$

We can write

$$H = H_p + H_g = \frac{\phi_{p,v}}{g\rho_w} + z$$

The sum of the pressure (matric) and gravitational (elevation) heads is generally called the **hydraulic head** (or hydraulic potential). The hydraulic head is useful to evaluate soil water movement and is often written as:

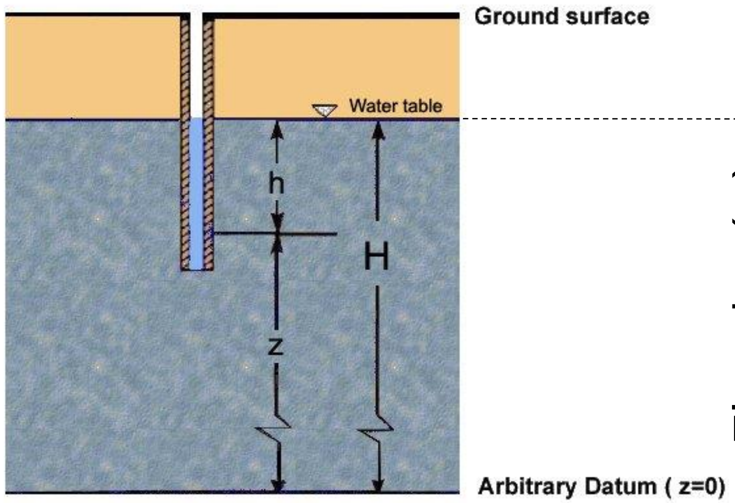
$$\boxed{H = h + z}$$

$h > 0$ in saturated conditions
$h < 0$ in unsaturated conditions

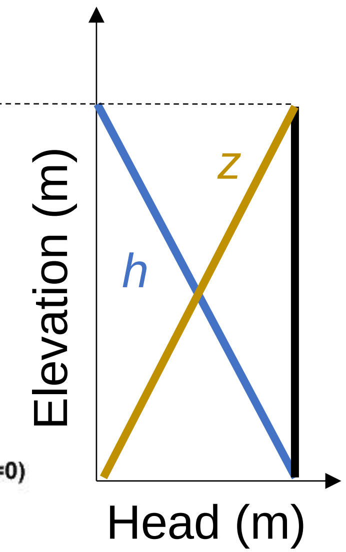
Suction is defined as $\psi = |h|$ (always positive)

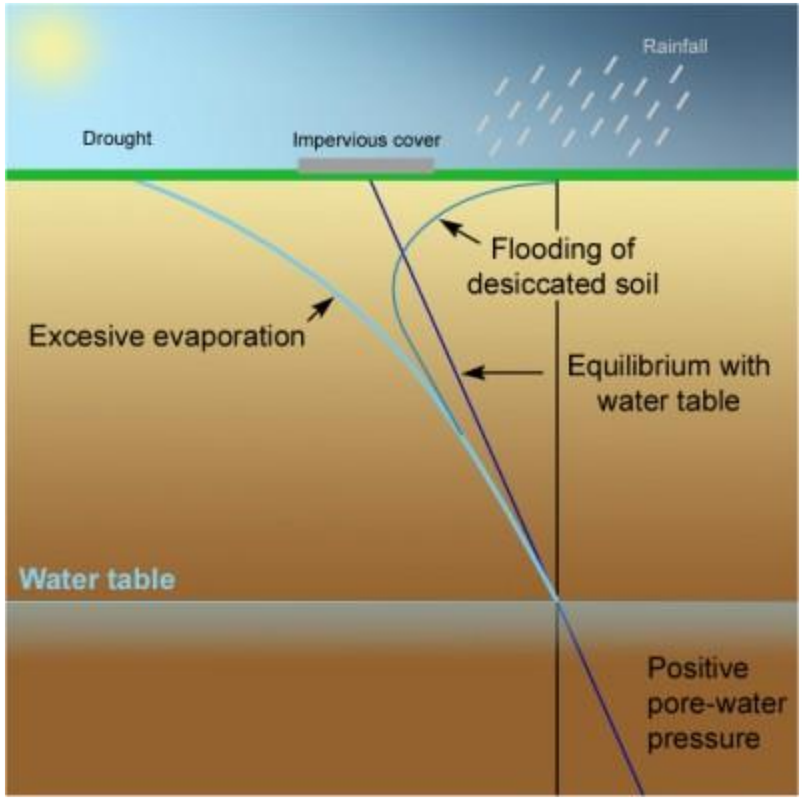
Note: notation may change in different books

Quantitative expressions of soil water potential



$H = h + z = const$





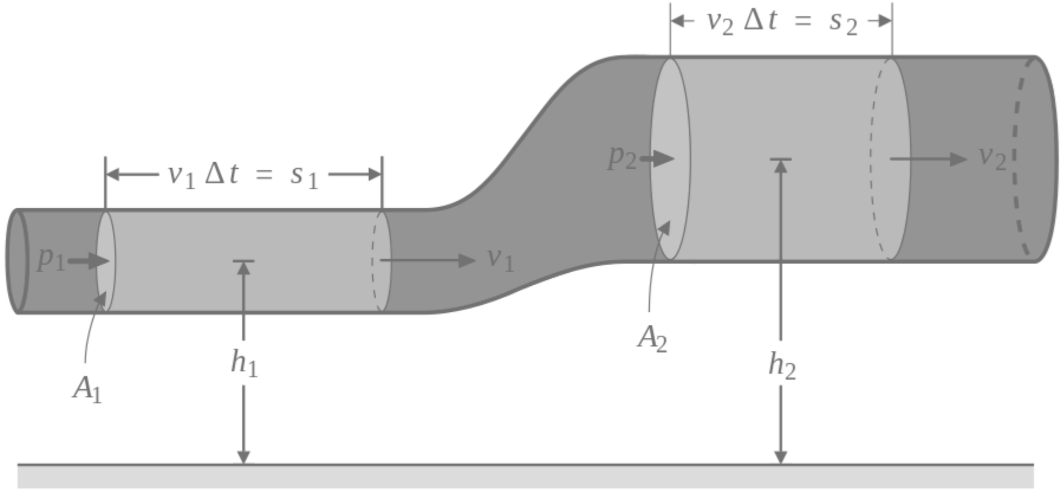
https://echo2.epfl.ch/VICAIRE/mod_3/chapt_4/main.htm

Remark

The expression of the total hydraulic head can be obtained directly by the **Bernoulli's equation** in which the kinetic energy term is neglected:

$$\cancel{\frac{v^2}{2g}} + \frac{P}{g\rho_w} + z = constant$$

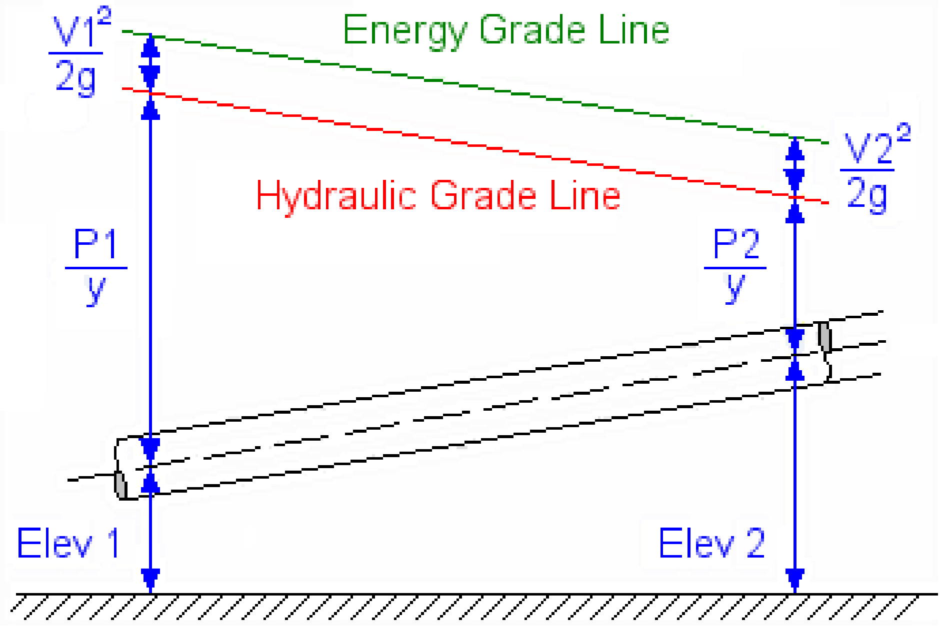
$$\boxed{H = \frac{P}{g\rho_w} + z = \psi + z}$$



Wikipedia

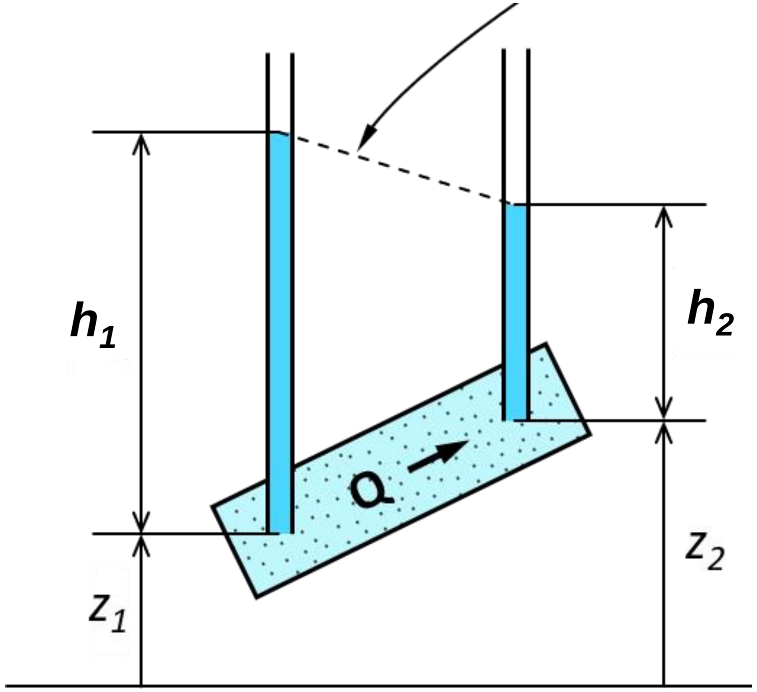
Remark

Hydraulics (pipe)



Energy and Hydraulic Grade Lines (pipeflow.com)

Soil science (porous medium)



Hydraulic Head and Groundwater Flow (gw-project.org)

Exercise

1.8 Water Potentials Under Equilibrium Conditions (Hanks, 1992 - pp. 31-37)

Under equilibrium conditions where the total water potential is equal everywhere in the system, flow is zero or negligible (consider: if water was flowing, the soil wouldn't yet be at equilibrium!). For situations where the solute potential is small or zero we may define a *hydraulic potential*, ψ_h, (applicable to liquid flow only) as:

$$\psi_h = \psi_m + \psi_z + \psi_p \qquad \textbf{(30)}$$

Note that for ψ_s=0 the hydraulic potential is equal to the *total potential*.

<u>1.8.1 Constructing Potential Diagrams under Equilibrium Conditions</u>

In the following examples (Hanks 1992, Examples 2.7 - 2.8) we show how the various components of the potential may be calculated under equilibrium conditions. The main steps for solving this type of problem are: (i) identify a convenient reference level, e.g., water table, soil surface; (ii) draw a diagram of the system - use energy per unit weight to obtain head units - and find the total potential at any point in the system. *Remember:* ***under equilibrium conditions the total potential is constant everywhere***; (iii) draw a 1:1 line for the gravitational potential (ψ_z) vs. depth through the reference point; (iv) use Eq.(30) to identify the value of other components and remember that ψ_p and ψ_m cannot be simultaneously nonzero.

Note that the notation here is as follows:

ψ_h = hydraulic potential
ψ_m = matric potential
ψ_z = gravitational potential
ψ_p = pressure potential (submergence)
ψ_s = solute/osmotic potential

ψ_p is always positive below the water table, or zero if the point of interest is at or above the water table (in this sense ψ_p and ψ_m are "mutually exclusive")

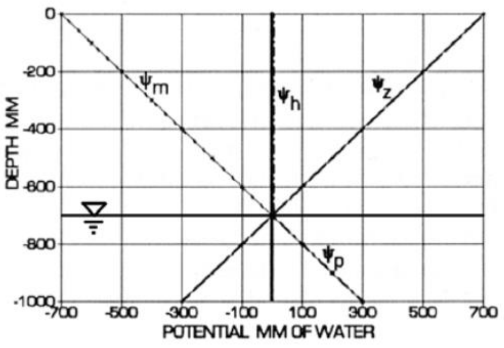
Source: Or, Tuller, & Wraith, 1994-2018

Example 2.7

Given: A soil in which the liquid water is in equilibrium with a water table at -700 mm and the reference level is chosen as -700 mm.
Find: The values of ψ_p, ψ_m, ψ_z, and ψ_h throughout the soil profile to -1100 mm.

Solution:

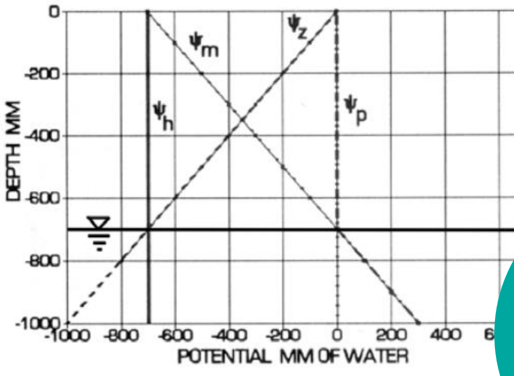
ψ_p	ψ_m	ψ_z	ψ_h	depth
0	-700	700	0	0
0	-600	600	0	-100
0	-500	500	0	-200
0	-400	400	0	-300
0	-300	300	0	-400
0	-200	200	0	-500
0	-100	100	0	-600
0	0	0	0	-700
100	0	-100	0	-800
200	0	-200	0	-900
300	0	-300	0	-1000



Example 2.8

Given: The conditions of Example 2.7 except the reference level is the soil surface.
Find: The values of ψ_p, ψ_m, ψ_z, and ψ_h throughout the soil profile to -1100 mm.
Solution:

ψ_p	ψ_m	ψ_z	ψ_h
0	-700	0	-700
0	-600	-100	-700
0	-500	-200	-700
0	-400	-300	-700
0	-300	-400	-700
0	-200	-500	-700
0	-100	-600	-700
0	0	-700	-700
100	0	-800	-700
200	0	-900	-700
300	0	-1000	-700



Self-Study

Optional readings

- **Student report on soil property measurement methods**
  - Available in Moodle (optional reading)
- Water Field study of different devices to measure soil moisture
  - journal article on measuring soil water by ETHZ researchers (optional reading).
- Time domain reflectometry measurement principles and applications
  - Additional information on TDR (optional reading)

Note: to read the articles, click on the links above from within the EPFL network, or connected to the EPFL network via VPN

Useful Youtube channels

- Selker and Or: Soil Hydrology and Biophysics
  - Various concepts of water flow in soil and how it is modeled are given in this Youtube channel. If you are finding difficulties with some concepts given in class, then you might find videos in this site useful. For example:
    - Total hydraulic head
    - Soil moisture characteristic curve

- L’eau et les sols
  - This channel presents a MOOC on "L'eau et les sols - hydrodynamique des milieux poreux". It covers many topics that we study in this course.

This week exercises & assignments

- **Exercises** for **Weeks 1 and 2** are available in Moodle.
  - Continue the exercises from last week. You should be able to complete all the exercises based on what we have done so far.
- **Computer Lab:** Pedotransfer functions (Assignment 1)
- **For next week:** Read pages 13-24 of Notes 2.pdf