

I SOIL WATER POTENTIAL

1.1.Introduction

Soil water content is not sufficient to specify the entire status of water in soil. For example, if soils with a same water content but with different particle size distribution are placed in contact with each other, water will flow from a coarse textured soil to a fine textured soil.

One needs to define a property that will help to explain this observation.

Perhaps the following analogy will help. Heat content (analogous to soil water content) is a property of a material that is useful for many purposes. It will not, however, tell us directly whether heat will flow. Therefore a heat intensity term, temperature, has been defined which permits to determine the direction of heat flow. The soil water term that is analogous to temperature (i.e. the intensity with which the water is in the soil) is called the soil water potential. Water potential is a much more complicated property than temperature.

1.2.Energy state of soil water

Soil water, like other bodies in nature, can contain energy in different quantities and forms. Classical physics recognizes two principal forms of energy, kinetic and potential. Since the movement of water in the soil is quite slow, its kinetic energy, which is proportional to the velocity squared, is generally considered to be negligible. On the other hand, the potential energy, which is due to position or internal condition, is of primary importance in determining the state and movement of water in the soil.

The potential energy of soil water varies over a very wide range. Differences in potential energy of water between one point and another give rise to the tendency of water to flow within the soil. The spontaneous and universal tendency of all matter in nature is to move from where the potential energy is higher to where it is lower and to equilibrate with its surroundings. In the soil, water moves constantly in the direction of decreasing potential energy until equilibrium, definable as a condition of uniform potential energy throughout, is reached.

The rate of decrease of potential energy with distance is in fact the moving force causing flow. A knowledge of the relative potential energy state of soil water at each point within the soil can allow us to evaluate the forces acting on soil water in all directions, and to determine how far the water in a soil system is from equilibrium. This is analogous to the well-known fact that an object will tend to fall spontaneously from a

higher to a lower elevation, but that lifting it requires work. Since potential energy is a measure to the amount of work a body can perform by virtue of the energy stored in it, knowing the potential energy state of water in the soil and in the plant growing in that soil can help us to estimate how much work the plant must expend to extract a unit amount of water.

Clearly, it is not the absolute amount of potential energy “contained” in the water which is important in itself, but rather the relative level of that energy in different regions within the soil. The concept of soil water potential is a criterion, for this energy. It expresses the specific potential energy (= per unit mass) of soil water relative to that of water in a standard reference state. The standard state generally used is that of a hypothetical reservoir of pure free water (i.e. water not influenced by the solid phase), at atmospheric pressure, at the same temperature as that of soil water (or at any other specified temperature) and at a given and constant elevation.

It is the convention to assign to free and pure liquid water a potential value of zero.

Since the elevation of this hypothetical reservoir can be set at will, it follows that the potential which is determined by comparison with this standard is not absolute, but by employing even so arbitrary a criterion we can determine the relative magnitude of the specific potential energy of water at different locations or times within the soil.

The concept of soil water potential is of great fundamental importance. This concept replaces the arbitrary categorizations which prevailed in the early stages of the development of soil physics and which purported to recognize and classify different forms of soil water : e.g. gravitational water, capillary water, hygroscopic water.

New definition by the soil physics terminology committee of the International Soil Science Society provided more clarity in what used to be a rather complicated theoretical set of criteria. The total potential of soil water was defined as follows : “ the amount of work that must be done per unit quantity (mass, volume or weight) of pure free water in order to transport reversibly and isothermally an infinitesimal quantity of water from a pool of pure water at a specified elevation at atmospheric pressure (standard reference state) to the soil water at the point under consideration in the soil-plant-atmosphere-system” (figure 1).

If work is required the potential is positive, but if water in the reference state can accomplish work in moving into the soil the potential is negative.

Soil water is subjected to a number of force field which cause its potential to differ from that of pure free water. Such forces result from the attraction of the solid matrix for water, as well as from the presence of dissolved salts and the action of the local pressure in the soil gas phase and the action of the gravitational field. Accordingly the

total potential (ψ_t) of soil water relative to a chosen standard rate can be thought of as the sum of the separate contributions of the various components as follows :

$$\psi_t = \psi_g + \psi_o + \psi_m + \psi_{e.p} + \dots$$

- where :
- ψ_t = total soil water potential
 - ψ_g = gravitational potential
 - ψ_o = osmotic potential
 - ψ_m = matric potential
 - $\psi_{e.p}$ = external gas pressure potential
 - ... = additional terms are theoretically possible

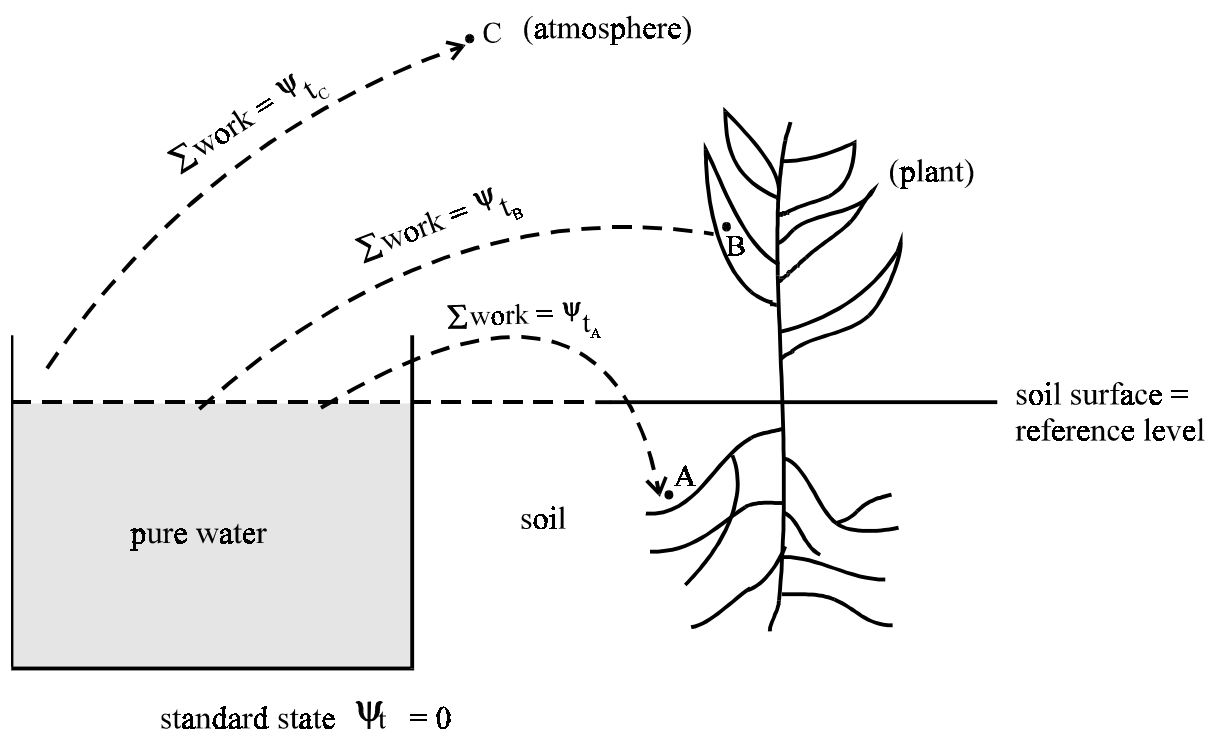


Figure 1. Potential of soil water, water in plant cell and water in the atmosphere.

The main advantage of the total potential concept is that it provides a unified measure by which the state of water can be evaluated at any time and every where within the soil-plant-atmosphere system.

1.3. Quantitative expression of soil water potential

The dimensions of the soil water potential are those of energy per unit quantity of water and the units depend on the way the quantity is specified. Common alternatives used are :

a. Energy per unit mass of water (J/kg)

This method of expression is not widely used.

b. Energy per unit volume of water (pressure) (J/m³ or N/m²)

This is the most common method of expressing potential and can be written with units of either Pascal or bar or atmosphere.

c. Energy per unit weight of water (head) (J/N = Nm/N = m)

This method of expressing potential is also common and has units of length.

For conversion from one unit to another knows that :

- 1 bar corresponds to 100 J/kg
- 1 bar = 10⁵ Pa
- 1 bar corresponds to 10 m water head

1.4. Gravitational potential

Every body on the earth's surface is attracted towards the centre of the earth by a gravitational force equal to the weight of the body, that weight being the product of the body's mass by the gravitational acceleration. To rise a body against this attraction, work must be expended and this work is stored by the rised body in the form of gravitational potential energy. The amount of this energy depends on the body's position in the gravitational force field.

The gravitational potential of soil water at each point is determined by the elevation of the point relative to some arbitrary reference level. If the point in question is above the reference, ψ_g is positive. If the point in question is below the reference, ψ_g is negative. Thus the gravitational potential is independent of soil properties. It depends only on the vertical distance between the reference and the point in question.

At a height z below a reference level (e.g. the soil surface) the gravitational potential of a mass M of water, occupying a volume V is :

$$- M g z = - \rho_w V g z$$

where : ρ_w = density of water
 g = acceleration of gravity

Gravitational potential can be expressed :

- per unit mass : $\psi_g = -gz$ (J/kg)
- per unit volume : $\psi_{gv} = \psi_g \rho_w = -\rho_w gz$ (Pa)
- per unit weight : $\psi_{gw} = \frac{\psi_g}{g} = -z$ (m)

1.5.Osmotic potential

The osmotic potential is attributable to the presence of solutes in the soil water. The solutes lower the potential energy of the soil water. Indeed, the fact that water molecules move through a semi-permeable membrane from the pure free water into a solution (osmosis) indicates that the presence of solutes reduces the potential energy of the water on the solution side (figure 2). At equilibrium sufficient water has passed through the membrane to bring about significant difference in the heights of liquid. The difference (z) in the levels represents the osmotic potential.

Since the osmotic potential of pure free water is zero the osmotic potential of a solution at the same temperature of free water is negative (water flow occurs from point of high potential to one with lower potential).

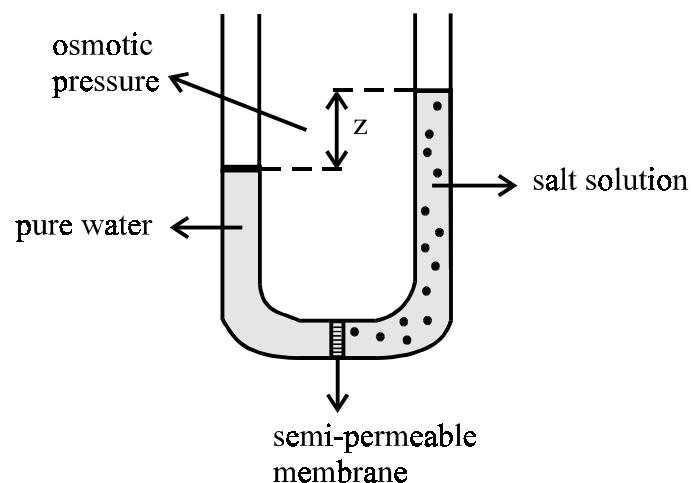


Figure 2. Schematic presentation of osmosis.

Differences in osmotic potential only play a role in causing movement of water when there is an effective barrier for salt movement between the two locations at which the

difference in ψ_o was observed. Otherwise, the concentration of salts will become the same throughout the profiles by the process of diffusion and the difference in ψ_o will no longer exist. Therefore osmotic potential does not act as a driving force in water flux. This potential is of importance in water movement into and through plant roots, in which there are layers of cells which exhibit different permeabilities to solvent and solute.

1.6. Matric potential

Matric potential results from forces associated with the colloidal matric and includes forces associated with adsorption and capillarity. These forces attract and bind water in the soil and lower its potential energy below that of bulk water. The capillarity results from the surface tension of water and its contact angle with the solid particles. In an unsaturated (three-phase) soil system, curved menisci form which obey the equation of capillarity :

$$P_i - P_a = \Delta P = \gamma \left(\frac{1}{R_1} + \frac{1}{R_2} \right)$$

where : P_i = pressure of soil water, can be smaller than atmospheric
 P_a = atmospheric pressure, conventionally taken as zero
 ΔP = pressure deficit
 γ = surface tension of water
 R_1, R_2 = principal radii of curvature of a point on the meniscus, taken as negative when the meniscus is concave

As we assume the soil pores to have a cylindrical shape (figure 3) the meniscus has the same curvature in all directions and equation above becomes :

$$P_i = \Delta P = \frac{-2\gamma}{R}$$

since :

$$R = \frac{r}{\cos\alpha}$$

($\alpha = 0$: angle of contact between water and the soil particle surface)

$$P_i = \Delta P = \frac{-2\gamma}{r} \quad \text{with } \Delta P \text{ equals } -h \rho_w g$$

where : r = radius of the capillary tube
 h = height of capillary rise
 ρ_w = density of water (10^3 kg/m^3)
 g = acceleration of gravity ($9.81 \text{ m/s}^2 \approx 10 \text{ m/s}^2 \approx 10 \text{ N/kg}$)

If the soil were like a simple bundle of capillary tubes, the equations of capillarity might be themselves suffice to describe the relation of the negative pressure potential or matric potential to the radii of the soil pores in which the menisci are contained. However, in addition to the capillarity phenomenon, the soil also exhibits adsorption, which forms hydration envelopes, over the particle surfaces. These two mechanisms of soil water interaction are illustrated in figure 4.

The presence of water in films as well as under concave menisci is most important in clayey soil and at high suctions or low potential, and it is influenced by the electric double layer and the exchangeable cations present. In sandy soils adsorption is relatively unimportant and the capillary effect predominates.

In general, however, the matric potential results from the combined effect of the two mechanisms, which cannot easily be separated since the capillary “wedges” are at a state of internal equilibrium with the adsorption “films” and the ones cannot be changed without affecting the others. Hence matric potential denotes the total effect resulting from the affinity of the water of the whole matric of the soil, including its pores and particle surfaces together.

The matric potential can be expressed :

- per unit mass : $\psi_m = -gh = \frac{-2\gamma}{\rho_w r}$ (J/kg)

- per unit volume $\psi_m \rho_w = -\rho_w gh = \frac{-2\gamma}{r}$ (Pa)

- per unit weight $\psi_m \frac{1}{g} = -h = \frac{-2\gamma}{\rho_w g r}$ (m)

In saturated soil (below the ground water level) the liquid phase is at hydrostatic pressure greater than atmospheric and thus its pressure potential is considered positive (figure 3). Thus water under a free water surface is at a positive pressure potential (hydrostatic pressure potential ψ_h), while water at such a surface is at zero pressure potential (assuming atmospheric pressure in the soil) and water which has risen in a capillary tube above that surface is characterised by a negative pressure or matric potential.

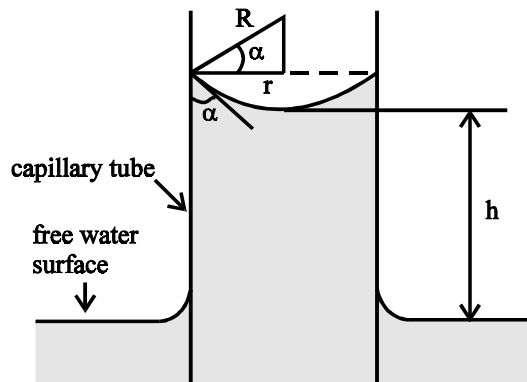
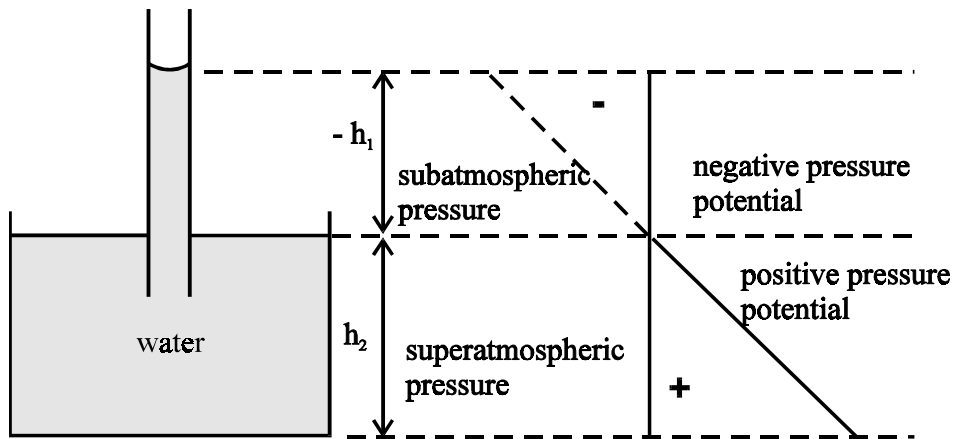


Figure 3. Capillary rise of water into a capillary tube.

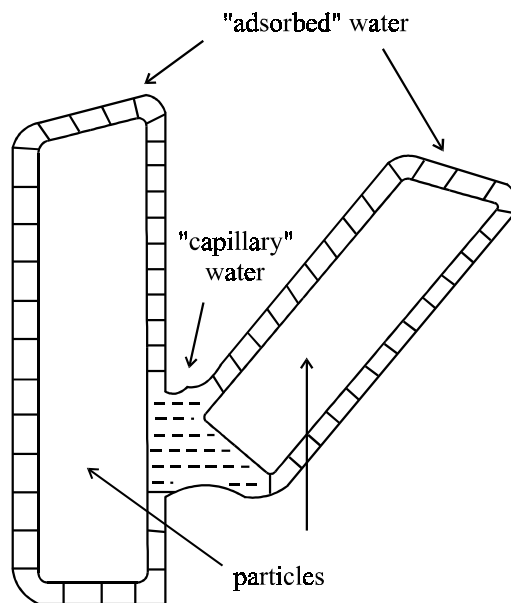


Figure 4. Water in an unsaturated soil is subject to capillarity and adsorption, which combine to produce a matric potential.

Since soil water may exhibit either of the two potentials, but not both simultaneously, the matric and the hydrostatic pressure potential are referred to as the pressure potential (ψ_p).

Nevertheless it is an advantage in unifying the matric potential and hydrostatic pressure potential in that this unified concept allows one to consider the entire profile in the field in terms of a single unsaturated zone, below and above the water table.

1.7. External gas pressure potential

A factor which may affect the pressure of soil water is a possible change in the pressure of the ambient air. In general this effect is negligible in the field as the atmospheric pressure remains nearly constant small barometric pressure fluctuations notwithstanding. However, in the laboratory the application of excess air pressure to change the soil water pressure is a common practice resulting into the so called external gas pressure of pneumatic potential .

FINAL REMARKS

1. Matric potential and the former term matric suction are numerically equal - when expressed in the same units - but except for the sign.
2. The effect of an external gas pressure different from the atmospheric (reference) pressure is generally also included in the pressure potential so that :

$$\psi_p = \psi_m + \psi_h + \psi_{e.p}$$

Accordingly the total potential being :

$$\psi_t = \psi_g + \psi_o + \psi_p$$

characterises fully the state of water in soil under the prevailing conditions ; the gradients of these three parameters are the basis for transport theory.

1.8. Hydraulic head

The total potential is obtained by combining the relevant component potentials :

$$\psi_t = \psi_g + \psi_o + \psi_p$$

Equilibrium, which is defined as the situation where mass transfer of water in the liquid phase is absent, is obtained when the value of the total potential at different points in the system is constant. Usually, sufficient condition is that the sum of the component potentials, ψ_o being ignored, is constant. The equilibrium condition states then that :

$$\psi_g + \psi_p = constant = \psi_H \quad (1)$$

called hydraulic potential.

As already stated, the external gas pressure or pneumatic potential in the field may be assumed to be zero. Also the soil water within a profile may exhibit either matric or hydrostatic pressure potential (figure 3) but not simultaneously. Therefore it is an advantage in unifying both in a single continuous potential extending from the saturated region into the unsaturated region below and above the water table.

As it is often usual to designate the potential in terms of head, equation (1) becomes:

$$H = h + z$$

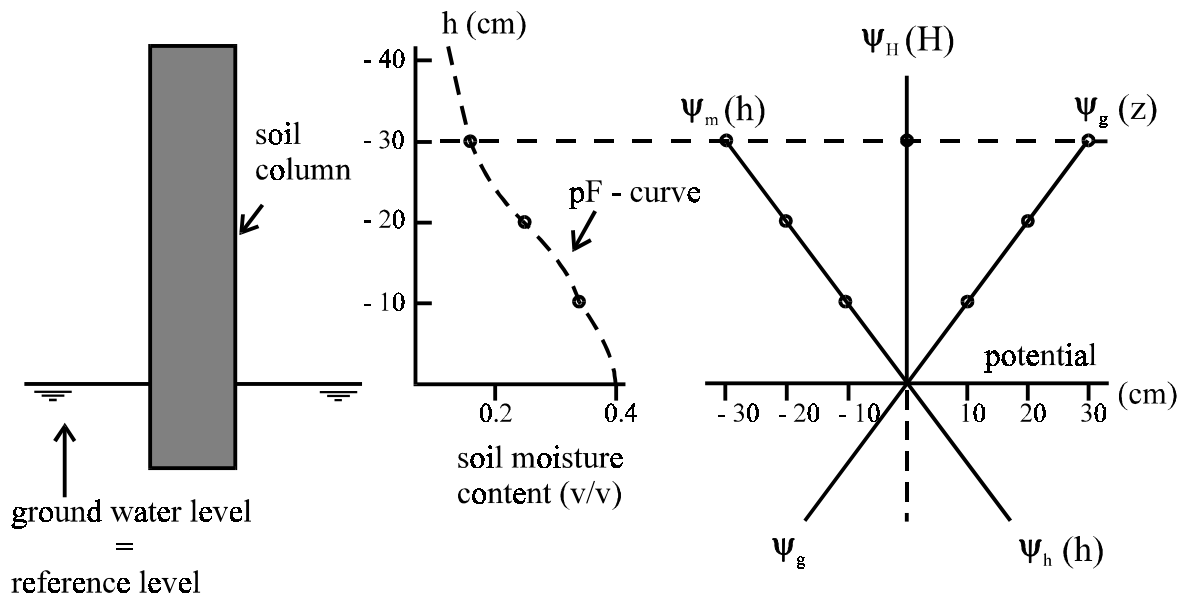
where :

- H = the hydraulic head (m)
- h = the soil water pressure head (m)
 - > 0 under the water table (saturated zone)
 - < 0 above the water table (unsaturated zone)
- z = the gravitational head (m)

The definition is very important because the hydraulic gradient between two points under consideration in a soil is the driving force for water movement.

In figure 5 the condition is applied to a vertical soil column in equilibrium with a water table. No water movement occurs in the column. The water table is taken as the reference level for the gravitational potential.

Under the water table matric potential equals zero, but a pressure potential called hydrostatic pressure potential occurs which can also be presented by a value of h but with always a positive sign.



height (cm)	$\psi_g(z, \text{cm})$	$\psi_m(h, \text{cm})$	$\psi_h(h, \text{cm})$	$\psi_H(H, \text{cm})$
30	30	-30	0	0
20	20	-20	0	0
10	10	-10	0	0
0 reference level	0	0	0	0
-10	-10	0	10	0
-20	-20	0	20	0

Figure 5. Equilibrium condition in a soil column.

Conversion table for units of soil water potential (*)

Specific potential units	Volumetric potential units				Weight potential units
Joule kg ⁻¹	bar	millibar	Pa	atmosphere	m
0.0001	0.000001	0.001	0.1	0.000000987	0.001017 x 10 ⁻²
1	0.01	10	10 ³	0.00987	10.17 x 10 ⁻²
100	1	1000	10 ⁵	0.987	10.17
0.1	0.001	1	10 ²	0.000987	1.017 x 10 ⁻²
101.3	1.013	1013	1.013 x 10 ⁵	1	10.30
0.09833	0.0009833	0.9833	98.33	0.0009703	10 ⁻²

(*) The density of water was taken as 1.000 g cm⁻³. This holds only at 4°C but is approximately correct at other temperatures.