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I.C.T.P., P.O. BOX 586, 34100 TRIESTE, ITALY, CABLE CENTRATOM TRIESTE

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COLLEGE ON SOIL PHYSICS
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"Soil Water Potential" - Part I
"Tensiometer" - Part II

R. HARTMANN
Department of Soil Physics
State University of Ghent
Ghent, Belgium

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I . SOIL WATER POTENTIAL

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.

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 tranport 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:

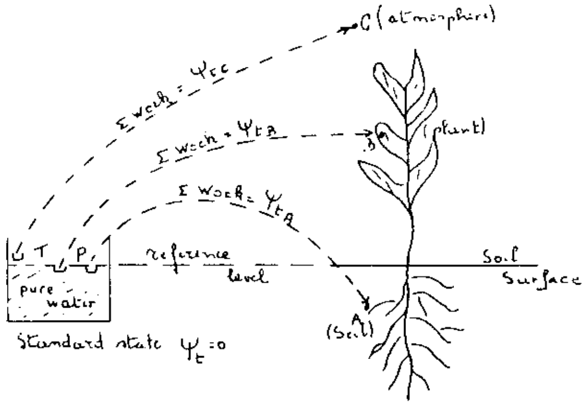

Figure 1. Potential of soil water, water in plant cell and water in the atmosphere.

$$\Psi_t = \Psi_g + \Psi_o + \Psi_m + \Psi_{e.p} + \ldots$$

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

The dots signify that additional terms are theoretically possible.

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.

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.

Joule kg^{-1}

This method of expression is not widely used.

b. Energy per unit volume of water (pressure).

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

Joule m^{-3} or $N\ m^{-2}$ (Pa)

c. Energy per unit weight of water (head).

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

Joule N^{-1} = $Nm\ N^{-1}$ = m

For conversion from one unit to another knows that:

- 1 bar corresponds to 100 J kg^{-1}
- 1 bar = 10^5 Pa
- 1 bar corresponds to 10 m water head

4. Gravitational potential.

Every body on the earth's surface is attracted towards the center 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.

Conversion table for units of soil water potential (*)

Specific potential units	Volumetric potential units				Weight potential units
Joule/kg	bar	millibar	Pa	atmosphere	m
- 0.0001	- 0.000001	- 0.001	- 0.1	- 0.000000987	$- 0.001017 \times 10^{-2}$
- 1	- 0.01	- 10	$- 10^{3}$	- 0.00987	$- 10.17 \times 10^{-2}$
- 100	- 1	- 1000	$- 10^{5}$	- 0.987	- 10.17
- 0.1	- 0.001	- 1	$- 10^{2}$	- 0.000987	$- 1.017 \times 10^{-2}$
- 101.3	- 1.013	- 1013	$- 1.013 \times 10^{5}$	- 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.

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 is the density of water and g the acceleration of gravity.

Gravitational potential can be expressed:

- per unit mass: $\psi_g = - gz$ (J kg^{-1})

- per unit volume: $\psi_{gv} = \psi_g \cdot \rho_w = - \rho_w g z$ (Pa)

- per unit weight: $\psi_{gw} = \psi_g 1/g = - z$ (m)

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).

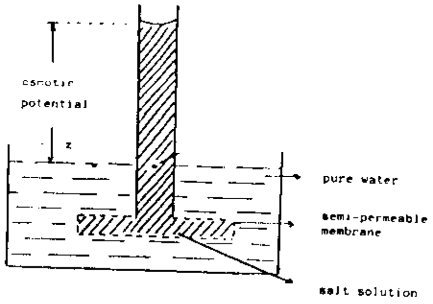

Figure 2. Schematic presentation of osmosis.

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.

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

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

(*) Matric potential and the former term matric suction are numerically equal - when expressed in the same units - but except for the sign.

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

$$R = \frac{-r}{\cos\alpha} \quad (\alpha = 0; \text{ angle of contact between water and the soil particle surface})$$

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

where: h = height of capillary rise
ρ_w = density of water
g = acceleration of gravity
r = radius of the capillary tube

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 capillary 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.

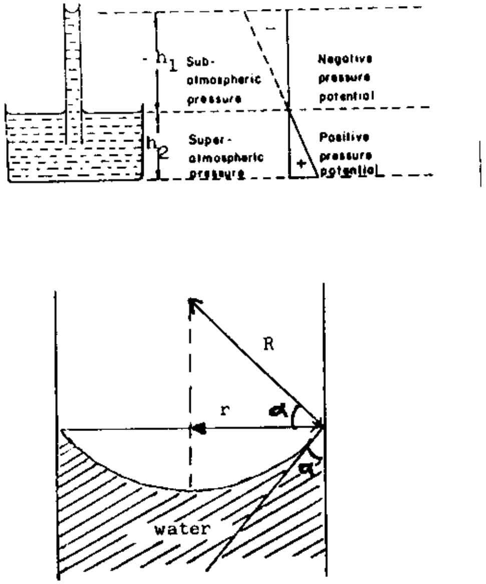

Figure 3 : Capillary rise of water into a capillary tube.

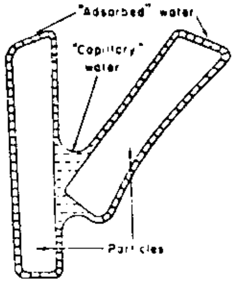

Figure 4 : Water in an unsaturated soil is subject to capillarity and adsorption, which combine to produce a matric potential.

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:

$$\psi_m = -g\ h = -\frac{2\gamma}{\rho_w r} \qquad (\mathrm{J\ kg^{-1}})$$

- per unit volume:

$$\psi_m\ \rho_w = -\rho\ g\ h = -P = \frac{-2\gamma}{r} \qquad (\mathrm{Pa})$$

- per unit weight:

$$\psi_m \frac{1}{g} = -h = \frac{-2\gamma}{\rho_w\ g\ r} \qquad (\mathrm{m})$$

The matric potential is a dynamic property of the soil.

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 characterized by a negative pressure or 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 continuous potential, extending from the saturated zone into the unsaturated zone, below and above the water table.

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 (See determination of the soil water characteristis curve by the pressure plate extraction apparatus).

FINAL REMARK.

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:

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

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

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:

$$\psi_g + \psi_p = \text{constant} = \psi_H \qquad (1)$$

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

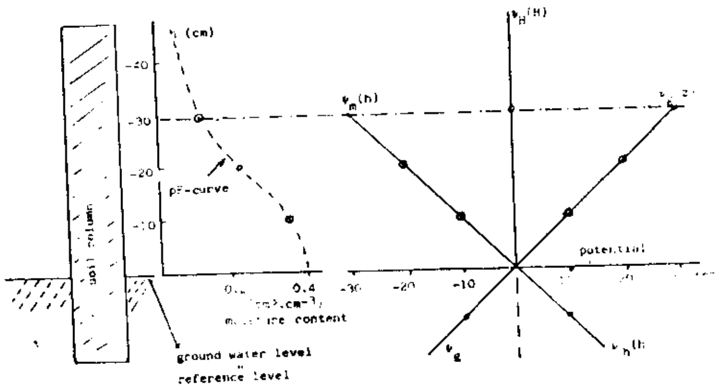

Figure 5. Equilibrium condition in a soil column.

height(cm)	ψ_g (z,cm)	ψ_m (h,cm)	ψ_h (h,cm)	ψ_H (H,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

EXAMPLES

SOIL WATER POTENTIALS

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Source:

"APPLIED SOIL PHYSICS"

by R.J. Hanks and G.L. Ashcroft

Advanced Series in Agricultural Sciences 8

Springer - Verlag Berlin 1980

ADDENDUM: EXAMPLES

A. Calculation of the gravitational potential.

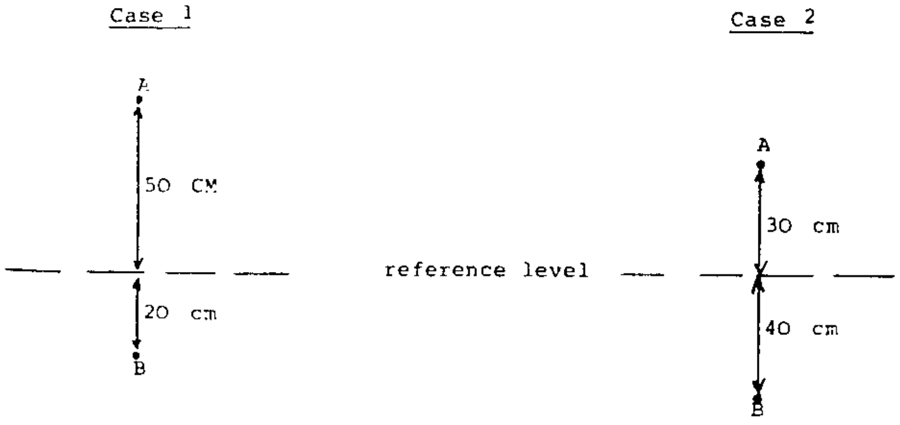
EXAMPLE

Given: 1. Two points in a soil profile:
- Point A is located 50 cm vertically above the reference level
- Point B is located 20 cm vertically under the reference level

2. Two points in a soil profile:
- Point A is located 30 cm above the reference level
- Point B is located 40 cm under the reference level

Questions: 1. Give a schematic design of the locations of the points for the two different situations

2. calculate the difference in gravitational potential (per unit weight of water) between A and B for the two cases



Case 1

$z_A = 50$ cm

$z_B = -20$ cm

$\Delta z = 50 \text{ cm} - (-20 \text{ cm}) = 70$ cm

Case 2

$z_A = 30$ cm

$z_B = -40$ cm

$\Delta z = 30 \text{ cm} - (-40 \text{ cm}) = 70$ cm

B. Water potentials for equilibrium conditions.

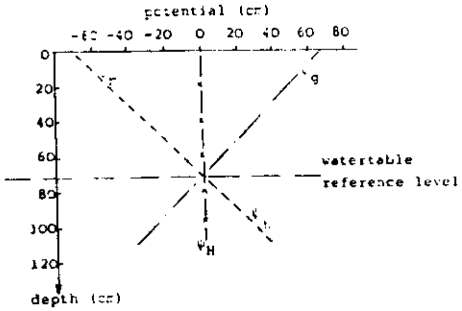
EXAMPLE 1.

Soil profile in which the liquid phase (water) is in equilibrium with a water table at a depth of 70 cm. The reference level is chosen at the water table.

Find: Values of ψ_g, ψ_m, ψ_h and ψ_H until depth z = 110 cm.

Solution:

Depth (cm)	ψ_g (z,cm)	ψ_m (h,cm)	ψ_h (h,cm)	ψ_H (H,cm)	
0	70	- 70	0	0	
10	60	- 60	0	0	
20	50	- 50	0	0	C
30	40	- 40	0	0	O
40	30	- 30	0	0	N
50	20	- 20	0	0	S
60	10	- 10	0	0	T
70	0	0	0	0	A
80	- 10	0	10	0	N
90	- 20	0	20	0	T
100	- 30	0	30	0	
110	- 40	0	40	0	



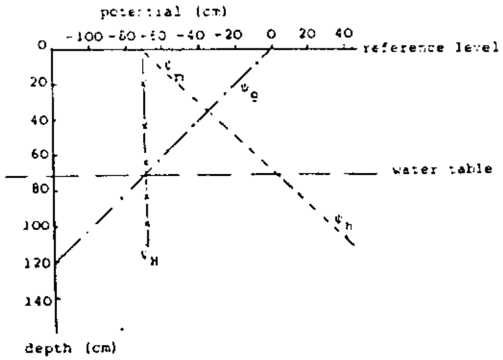
EXAMPLE 2.

Soil profile in which the liquid phase (water) is in equilibrium with a water table at a depth of 70 cm. The reference level is chosen at the soil surface.

Find: Values of ψ_g, ψ_m, ψ_h and ψ_H until depth z = 110 cm.

Solution:

Depth (cm)	ψ_g (z,cm)	ψ_m (h,cm)	ψ_h (h,cm)	ψ_H (H,cm)	
0	0	- 70	0	- 70	
10	- 10	- 60	0	- 70	
20	- 20	- 50	0	- 70	C
30	- 30	- 40	0	- 70	O
40	- 40	- 30	0	- 70	N
50	- 50	- 20	0	- 70	S
60	- 60	- 10	0	- 70	T
70	- 70	0	0	- 70	A
80	- 80	0	10	- 70	N
90	- 90	0	20	- 70	T
100	- 100	0	30	- 70	
110	- 110	0	40	- 70	



C. Water potentials for non-equilibrium conditions.

We will now look at water potentials throughout the profile of a soil in which water is flowing. Liquid water flows as a result of a hydraulic potential gradient; thus ψ will vary throughout the parts of the soil in which flow is occuring. Measurements with tensiometers must be taken to obtain exact values of ψ_m.

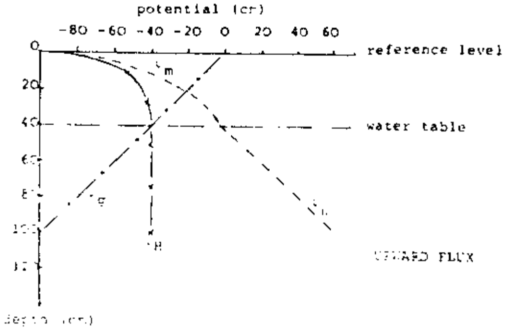
EXAMPLE 1.

Water evaporates at the soil surface. Water table is located 40 cm below soil surface. The reference level is at the soil surface.

Find: Values of ψ_g, ψ_m, ψ_h and ψ_H from the soil surface to a depth of 100 cm. In order to find , measured values of ψ_m must be available. Draw the potential diagram.

Solution.

Depth (cm)	ψ_g (z,cm)	ψ_m (h,cm) "measured"	ψ_h (h,cm)	ψ_H (H,cm)
0	0	- 100	0	- 100
10	- 10	- 45	0	- 55
20	- 20	- 26	0	- 46
30	- 30	- 12	0	- 42
40	- 40	0	0	- 40
50	- 50	0	10	- 40
60	- 60	0	20	- 40
70	- 70	0	30	- 40
80	- 80	0	40	- 40
90	- 90	0	50	- 40
100	- 100	0	60	- 40



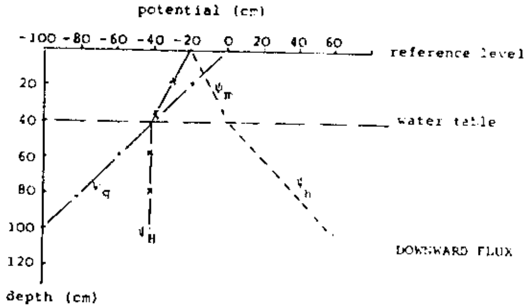
EXAMPLE 2

In that case water is flowing into a drain located at a depth of 40 cm below the soil surface. The latter being the reference level.

Find: Values of ψ_g, ψ_m, ψ_h and ψ_H up to a depth of 100 cm. ψ_m values are measured.

Solution:

Depth (cm)	ψ_g (g,cm)	ψ_m (h,cm)	ψ_h (h,cm)		ψ_H (H,cm)		
0	0	- 20	0	↓	- 20	W	
10	- 10	- 15	0		- 25	A	F
20	- 20	- 10	0		- 30	T	L
30	- 30	- 5	0		- 35	E	O
40	- 40	0	0	—	- 40	R	W
50	- 50	0	10		- 40		
60	- 60	0	20		- 40		S
70	- 70	0	30		- 40	C	T
80	- 80	0	40		- 40	O	T
90	- 90	0	50		- 40	N	N
100	- 100	0	60		- 40		T

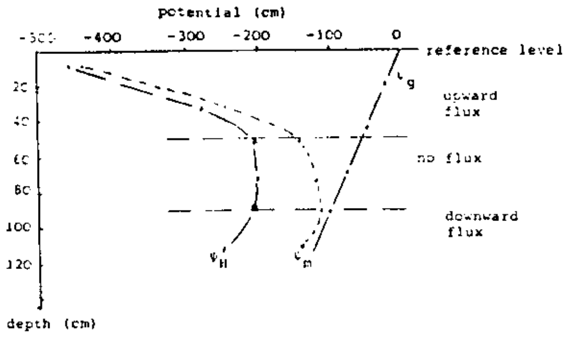


EXAMPLE 3.

A soil was initially very dry. It received rain that wet the soil from the surface downwards. After a few days, the surface dries out and water moved upwards in response to the evaporation. At lowerd depths, however, the soil water moved downwards into the soil that had not been wetted by the rain. Soil surface is the reference level.

Find: Values of ψ_g, ψ_m, ψ_h and ψ_H throughout the profile to a depth of 100 cm using measured values of ψ_m.

Depth	ψ_g	ψ_m	ψ_h	ψ_H
(cm)	(z,cm)	(h,cm)	(h,cm)	(H,cm)
10	- 10	- 448	0	- 458
30	- 30	- 245	0	- 275
50	- 50	- 155	0	- 205
70	- 70	- 132	0	- 202
90	- 90	- 116	0	- 206
110	- 110	- 132	0	- 242



II. TENSIOMETER

1. Hydrostatic pressure potential - Piezometer.

As discussed earlier the hydrostatic (positive) pressure potential ψ_h under field conditions applies to saturated soils and is measured with a piezometer (figure 6).

A piezometer is a tube of a few cm inner diameter, open at both ends, which is installed in a soil profile. If the lower end is below the groundwater table, a piezometer is partially filled with water. By determining the height of the water level in a piezometer it is possible to calculate the (positive) hydrostatic pressure potential of the soil water at the lower end of the tube. The diameter of piezometers is chosen large enough that capillary rise and resistance to water flow are negligible. As a result, any variation in hydraulic potential that may arise inside the piezometer, is instantaneously equalized. Thus, even if the hydrostatic pressure potential at the lower end is changing rapidly, the water inside a piezometer goes through a series of static equilibria and at any moment it can be assumed that the hydraulic head is uniform and equal to the hydraulic head of the soil water at the open lower end. There exchange of water takes place such that the pressure is always locally uniform. The static hydraulic head in piezometers can be determined by measuring the depth of the water level, since at the flat air-water interface the pressure potential is zero.

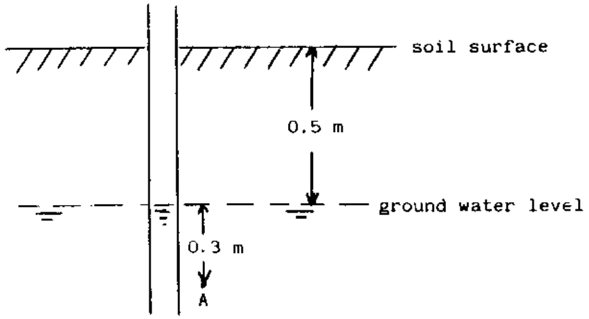


Figure 6. A piezometer in a soil profile.

Figure 6 shows a piezometer in a soil profile in which the water is at static equilibrium. The reference point $z = 0$ is taken at the soil surface. In the piezometer at the water level $H = h + z = 0 - 0{,}5$ m $= - 0{,}5$ m. Thus at point A, H must also be $- 0{,}5$ m ($H = h + z = 0{,}30$ m $- 0{,}80$ m $= - 0{,}50$ m).

The hydrostatic pressure potential expressed per unit weight of water at any point in the soil under the water table is the distance between the point and the water level in the piezometer tube.

The water level in a piezometer tube is at the level of the groundwater table in a situation of static equilibrium, independent of the depth of the lower end.

2. Matric potential - Tensiometer.

Piezometers cannot be used to measure negative pressure potentials because in unsaturated conditions, water flows out of the tube into the soil leaving the tube dry. The negative pressure or matric potential can be measured with the so-called tensiometer.

The tensiometer consists of a liquid filled porous cup, mostly of ceramic material and connected to a pressure measuring device such as a mercury manometer or vacuum gauge via a liquid-filled tube (Figure 7).

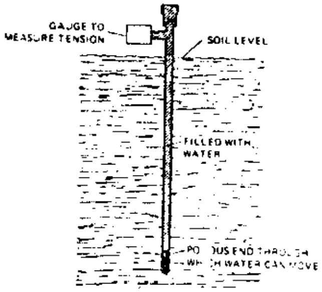


Figure 7. Tensiometers with a vacuum gauge.

If the ceramic cup is embedded in soil, the soil solution can flow into or out of the tensiometer through the very small pores in the ceramic cup. Analogously to the situation discussed for piezometer, this flow continues until the (negative) pressure potential of the liquid in the cup has become equal to the (negative) pressure potential of the soil water around the cup. Thus the (negative) pressure potential called matric potential ψ_m of soil water can be measured with a tensiometer, and is therefore also often called tensiometer pressure potential.

3. Principle of the tensiometer.

When the cup is placed in a water reservoir (figure 8), the water inside the cup comes into hydraulic contact with the water in the reservoir through the water-filled small pores in the ceramic walls. The water level in the tube will indicate the level of the water in the reservoir.

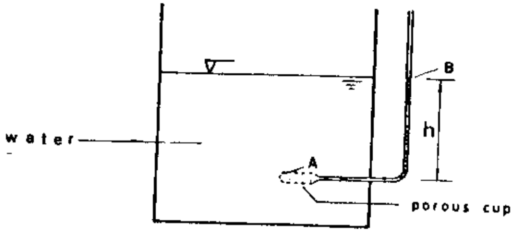


Figure 8. Porous cup connected with a piezometer tube for measuring pressure potentials under the water table.

The pressure is given by the height h of the water level above the middle of the porous cup and the pressure P_A equals:

$$P_A = \rho_w g h$$

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

If we place now the porous cup, connected with a U-shape water filled tube in a soil than the bulk water inside the cup will come in hydraulic contact with the liquid phase in the soil. When initially placed in the soil, the water in the tensiometer is at atmospheric pressure. Soil water in unsaturated soil has a negative pressure and therefore exercices a suction which drawn out a certain amount of water from the rigid and air-tight tensiometer, causing a drop in the water level at the open end of the U-tube (figure 9).

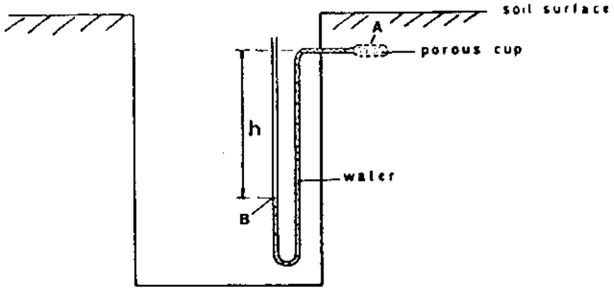


Figure 9. Tensiometer for measuring pressure potentials in soils.

The drier the soil, the higher the suction and the lower the water level at equilibrium in the U-tube. The height h of the liquid column that has moved into ("sucked into") the soil in figure 9 is therefore an index of the magnitude of the potential, or:

$$P_A = - \rho_w g h$$

As h is measured downwards the minus sign is introduced so that P_A gives a negative pressure.

This type of tensiometer is very simple and useful to illustrate the basic principles involved. Practical applications often do not allow the use of the water manometer because the U-tube extends below the level of the tensiometer cup and measurements thus requires inconvenient, deep pits. Therefore open manometers, filled with immiscible liquids of different densities such as mercury are used so that these problems do not arise (figure 10).

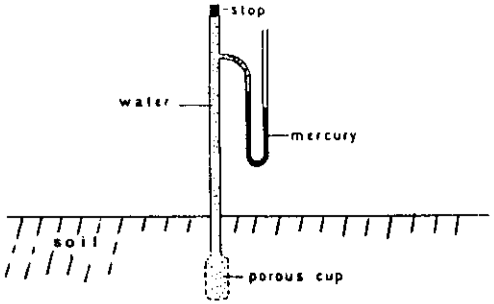


Figure 10. Tensiometer with mercury manometer.

Using mercury implies that a relatively short height indicated a relatively large pressure difference in the manometer (1 cm of mercury corresponds to 13.55 cm of water). Besides the simple water or mercury manometer a vacuum gauge or an electrical transducer is also used.

4. How to calculate the soil water pressure head h and the hydralic head H.

Let x be the height of the mercury in the manometer (in cm) and z the vertical axis. At the interface water-mercury in the manometer, the pressure is the same in water and in mercury (being P_B). The repartition of the pressure is hydrostatic in the water column between point B and the tensiometer cup (point A), but also between point B and the free surface of the mercury in the reservoir (point C).

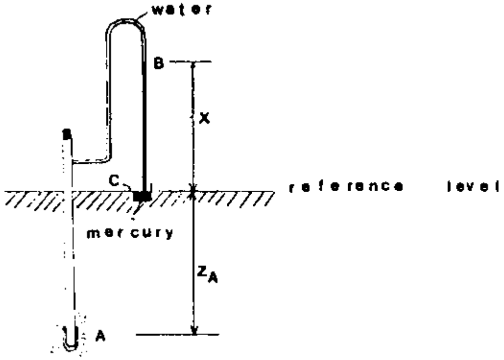


Figure 11. Tensiometer installation with the mercury level in the reservoir at the soil surface being the reference level.

Using the hydrostatic law for liquids in equilibrium one obtains per unit weight of liquid the following hydraulic head equation:

$$z + P/\rho g = \text{constant}$$

where: z = gravitational head,
$P/\rho g$ pressure head.

From figure 11 one obtains:

- in water:

$$z_A + \frac{P_A}{\rho_w\ g} = z_B + \frac{P_B}{\rho_w\ g}$$

Because soil surface is taken as reference level for the gravitational potential, and point A is located below that level, the gravitational head is negative ($- z_A$).

$$P_A - z_A \rho_w g = P_B + z_B \rho_w g$$

$$P_A = P_B + z_B \rho_w g + z_A \rho_w g = P_B + \rho_w g(z_A + z_B) \qquad (1)$$

- in mercury:

$$z_B + \frac{P_B}{\rho_{Hg}\ g} = z_C + \frac{P_C}{\rho_{Hg}\ g}$$

because: $z_C = 0$ reference level
P_C = atmospheric pressure = 0

the equation becomes:

$$Z_B + \frac{P_B}{\rho_{Hg}\ g} = 0$$

or:

$$P_B = - \rho_{Hg} g\ z_B \qquad (2)$$

(2) in (1) gives:

$$\frac{P_A}{\rho_w\ g} = \frac{- \rho_{Hg}\ g\ z_B}{\rho_w\ g} + z_A + z_B \qquad (3)$$

Since: $\rho_{Hg} = 13600\ \text{kgm}^{-3}$
$\rho_w = 1000\ \text{kg m}^{-3}$

(3) becomes:

$$h_A = - 13.6\ z_B + z_A + z_B$$

or:

$$h_A = - 12.6\ z_B + z_A$$

$$h_A = - 12.6\ x + z_A \qquad (4)$$

Normally the free surface of the mercury in the reservoir (point C) is located y cm above the soil surface (reference level) (figure 12).

Equation (4) becomes:

$$h_A = - 12.6\ x + y + z_A \qquad (5)$$

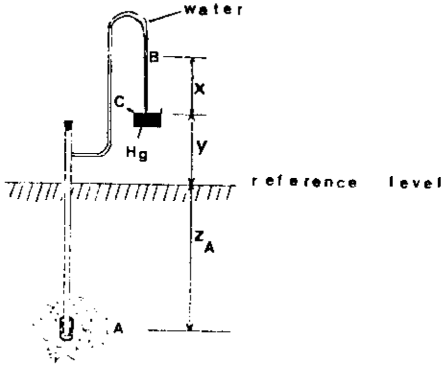


Figure 12. Tensiometer installation with the mercury reservoir y cm above soil surface.

The hydraulic head H, being the sum of the pressure head h and the gravitational head z, ($H = h + z$), becomes:

$$H = -\ 12.6\ x + y + z_A + (-z_A)$$

$$H = -\ 12.6\ x + y \qquad (6)$$

Example

Given: The porous cup of a tensiometer with mercury manometer is installed 0.3 m under the soil surface. The height of the mercury in the manometer is 0.31 m. The level of the mercury reservoir is located 0.4 m above the soil surface. Reference level is the soil surface.

Calculate: - soil water pressure head h
- hydraulic head H

Solution:

$$h = (-\ 12.6 \times 0.31 + 0.4 + 0.3)\ \text{m} = -\ 3.20\ \text{m}$$

$$H = (-12.6 \times 0.31 + 0.4)\ \text{m} = -\ 3.50\ \text{m}$$

5. Some characteristics of the tensiometer.

- cup conductance:

$$K' = \frac{\Delta V}{\Delta t\ \Delta h}$$

being the volume of water passing through the cupwall under a unit pressure difference per unit time ($m^3\ s^{-1}\ Pa^{-1}$)

- sensitivity of the manometer:

$$S = \frac{\Delta h}{\Delta V}$$

being the change in manometer reading per unit volume change of water ($Pa\ m^{-3}$)

- response time of the system:

$$T_R = \frac{1}{K'S}$$

is a measure of the over-all responsiveness of the instrument to a change of soil-water potential at the cup surface (s)

6. Practices and limitations of tensiometers.

The purpose of the measurements with tensiometers is to characterize the existing pressure potential of the soil water.

Water within the tensiometer should be continuous throughout the system to allow a correct transfer of pressure from the soil to the mercury. Occurence of gas bubbles disrupts this continuity and makes the system inoperative. The fine porous cup has the function of not allowing penetration of air from the unsaturated soil into the water-filled tensiometer tube, even though water can and should move through it. The fine pores inside the wall of the ceramic cup have a high air-entry value which is the pressure needed to remove the water from the pores in the cup replacing it by air. Even with a high air entry value breakdown of the system occurs due to entrapped air within the tensiometer tube or to air coming out of solution at reduced pressure.

Due to the fact that the manometer measures a partial vacuum relative to the external atmospheric pressure, measurements by tensiometry are generally limited to about - 850 cm of water. Use of tensiometers in the field is therefore only possible when pressures do not fall below this value. However, the limited range of pressure measurable by the tensiometers is not as serious as it may seen at first sight. In many agricultural soils the tensiometer range accounts for more than 50 % of the amount of soil water taken up by the plants. To what extend the available water range expressed e.g. as a percentage of the water between pF 2 and pF 4.2, is covered by the tensiometer depends on the shape of the moisture characteristic curve (pF-curve) as shown for three soil types in figure 13.

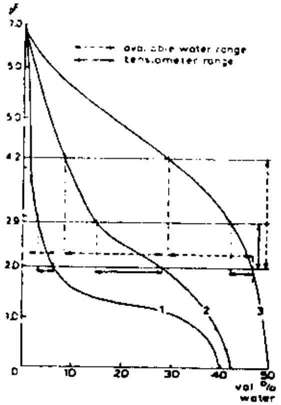


Figure 13. Part of the available moisture range covered by tensiometers, depending on soil type

1. Sand 50 % of available moisture
2. Loam 75 % of available moisture
3. Clay 25 % of available moisture

Thus where soil management (particularly in irrigation) is aimed at maintaining high pressure potential conditions which are mostly favorable for plant growth, tensiometers are definitely useful.

Air diffusion through the porous cup into the system requires frequent purging with deaired water. Tensiometers are also sensitive to temperature gradients between their various parts. Hence the above-ground parts should preferably be shielded from direct exposure to the sun. Therefore it is also suggested to make readings always at the same time of the day (e.g. at 08.00 a.m.).

When installing a tensiometer it is important for proper functioning that good contact be made between the porous cup and the surrounding soil. Generally the porous cup is pushed into a hole with a slightly smaller diameter to ensure good contact. If the soil is initially rather dry and hard, prewetting of the hole may be necessary. In a stony soil a small excavation should be made and filled with very fine sand into which the tensiometer can be placed.

With mercury manometers, even when small diameter nylon tubing (+/- 2 mm) is used, often a considerable volume of water must be adsorbed by the soil (during water uptake or drying process) or by the porous cup (replenishing by rainfall or irrigation) before the potential that really exists can be read off correctly. A very convenient modern device, the electronic transducer can be used which reacts to very small changes in pressure and converts these changes in a small electrical current which can be registered and amplified by a voltmeter. This system is very accurate but also very sensitive to the occurence of small air bubbles in the tensiometer system. Moreover is it rather expensive.

Since the porous cup walls of the tensiometer are permeable to both water and solutes, the water inside the tensiometer tends to assume the same solute composition and concentration as soil water, and the instrument does not indicate the osmotic potential of soil water.

7. Applications of measurements.

By the use of several tensiometers at different depths the direction and magnitude of water movement can easily be as certained.

EXAMPLES

1. Determination of the direction of water flow at different levels in the soil profile (Figure 14).

The concept of the water potential is well suited for the analysis of water flow in soils, since all flow is a consequence of potential gradients. Darcy's law, though originally conceived for saturated flow only, was extended to unsaturated flow, with the provision that the conductivity is a function of soil water content θ.

For a vertical one dimensional water flow Darcy's equation can be written as follows:

$$q = - K(\theta)\,\frac{dH}{dz} \tag{7}$$

where: q = flux

$K(\theta)$ = hydraulic conductivity

H = hydraulic head

$= h + z$ with h = soil water pressure head

z = gravitational head

The minus sign in the equation indicates that the flow is in the direction of decreasing potential. This means also that if we have two tensiometers located at depths z_1 and z_2 ($z_1 < z_2$):

- q will be negative (upward flow - evaporation) if $H_2 > H_1$; the rise of mercury in manometer n° 2 is lower than in manometer n° 1
- q will be positive (downward flow - percolation) if $H_2 < H_1$; the opposite situation is observed
- q will be zero (plane of zero flux) at a certain depth z when the curve H(z) will show a maximum or the rise of the mercury a minimum because $dH/dz = 0$. A graphical example is presented in figure 14.

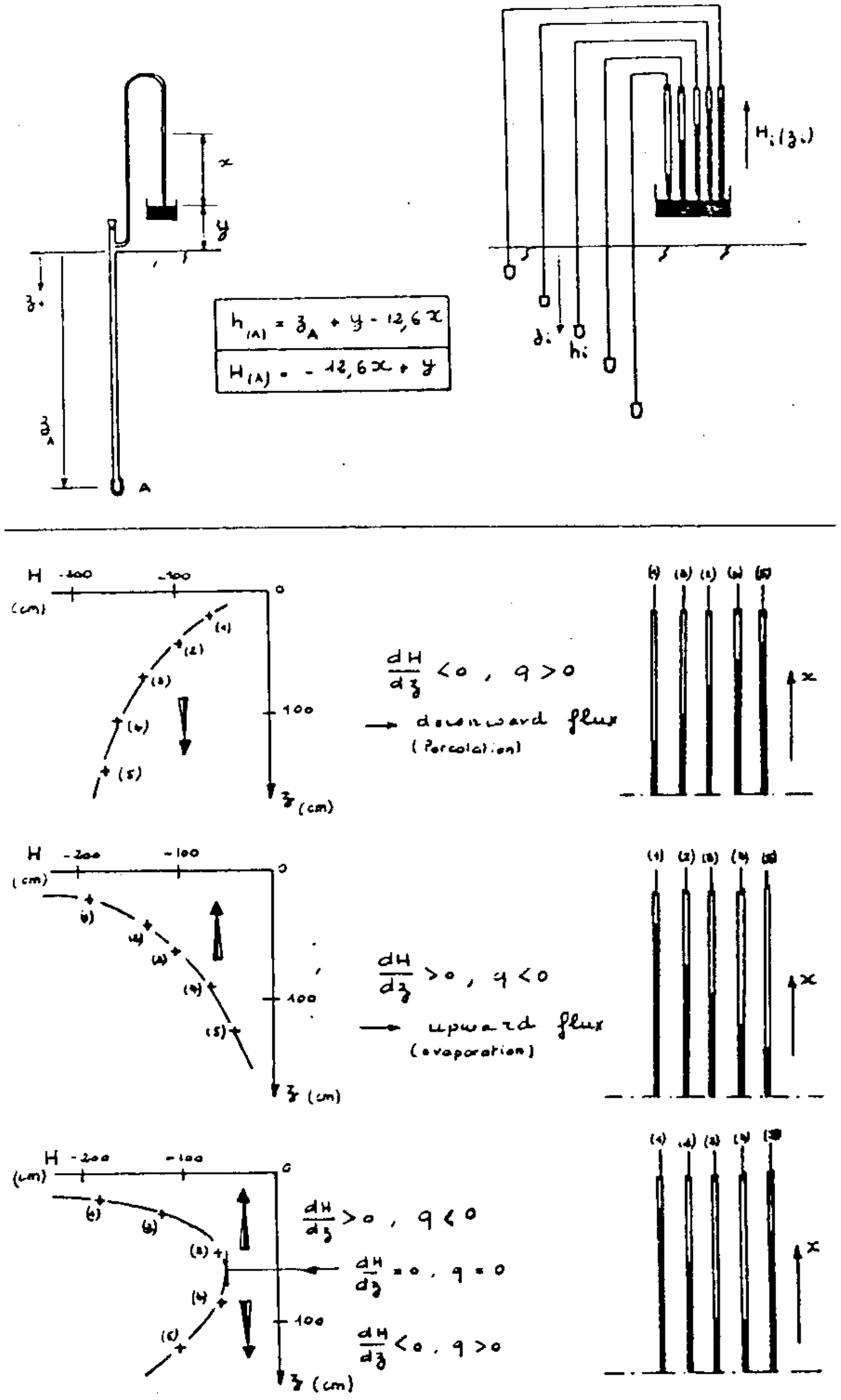


Figure 14. Hydraulic head profiles. The manometers from left to right increase with depth

- Numerical example.

Reference level being the soil surface.

tensiometer $z_1 = 50$ cm $x = 10.7$ cm $y = 20$ cm
tensiometer $z_2 = 75$ cm $x = 13.8$ cm $y = 20$ cm

$H_1 = - 12.6\ x + y = - 1.05$ m
$H_2 = - 12.6\ x + y = - 1.54$ m

In this situation downward flow occurs since flow is towards the position with the lowest water potential.

2. Flux control at a certain depth.

From agricultural point of view it could be of interest to know if there is a recharge of the water table or capillary rise. Therefore only 2 tensiometers are needed with a depth distance of say 25 cm in the control zone. A simple reading of the rise of mercury in the manometer will indicate the flow direction.

Knowing the moisture content θ at the depth between z_1 and z_2, the $K(\theta)$ relation of that soil and the hydraulic head gradient dH/dz, one can calculate the instantaneous water flow q (see equation 7).

3. Determination of the soil water characteristic curve (or retentivity curve).

The $h-\theta$ relation (retentivity curve) of a soil layer in situ can be established:

- knowing the soil water pressure head (h) using tensiometers (see equation 5)
- knowing the soil water content (θ) using the neutron moisture meter.

4. Scheduling irrigation.

The root zone for most agricultural plants is limited to the unsaturated part of the profile because the plant roots do not proliferate in a saturated soil where aeration is limiting. Consequently in a non-saline soil the plant behaviour is largely determined by the matric potential of the soil water. Moreover the plant does not depend as much on the quantity of water present as it does on the water potential.

Water should be applied to the soil when the matric potential is still high enough that the soil can and does supply water fast enough to meet the atmopsheric demands without placing the plant under a stress that will reduce yield or quality of the harvested crop.

Although the tensiometers function over only a limited part of the available water range (0 to - 800 cm water) it is usually in this range that plants should be irrigated.

From practical point of view tensiometers are installed at minimum 2 locations. One unit should be placed in the zone of maximum root activity and another near the bottom of the active rootzone.

The time to irrigate is determined by following the matric potential readings in the zone of the greatest root activity. The exact value of the matric potential at which water should be applied is not the same for every crop. A good approximation of that matric potential is available for many common crops (table 1). For most crops it is time to irrigate when the top tensiometer reads - 300 to - 500 cm water and the bottom tensiometer begins to indicate drying.

Table 1. Matric potential at which water should be applied for maximum yields of various crops grown in deep, well-drained soil that is fertilized and otherwise managed for maximum production. Where two values are given, the higher value is used when evaporative demand is high and the lower value when it is low; intermediate values are used when the atmospheric demand for evapotranspiration is intermediate. (The values are subject to revision as additional experimental data become available). (TAYLOR and ASHCRIFT, 1972).

Crop	*Matric potential (joules/kg)*	*Equivalent matric suction (centibars)*	*Reference*
Vegetative crops			
Alfalfa	−150	150	S. A. Taylor[a]
Beans (snap and lima)	−75 to −200	75 to 200	Vittam et al. (1963)
Cabbage	−60 to −70	60 to 70	Vittam et al. (1963), and Pew (1958)[b]
Canning peas	−30 to −50	30 to 50	S. A. Taylor[a]
Celery	−20 to −30	20 to 30	A. W. Marsh,[c] and Marsh (1961)
Grass	−30 to −100	30 to 100	Vissar (1959)
Lettuce	−40 to −60	40 to 60	A. W. Marsh,[c] Vissar (1959), and Pew (1958)[b]
Tobacco	−30 to −80	30 to 80	Jones et al. (1960)[d]
Sugar cane			
Tensiometer	−15 to −50	15 to 50	Waterhouse et al. (1954)[e]
Blocks	−100 to −200	100 to 200	Robinson (1963)
Sweet corn	−50 to −100	50 to 100	S. A. Taylor,[a] and Vittam et al. (1963)
Turfgrass	−24 to −36	24 to 36	Morgan (1964)
Root crops			
Onions			
Early growth	−45 to −55	45 to 55	Pew (1958)[b]
Bulbing time	−55 to −65	55 to 65	Pew (1958)[b]
Sugar beets	−40 to −60	40 to 60	S. A. Taylor[a]
Potatoes	−30 to −50	30 to 50	S. A. Taylor,[a] Vittam et al. (1963), and Pew (1958)[b]
Carrots	−55 to −65	55 to 65	Pew (1958)[b]
Broccoli			
Early	−45 to −55	45 to 55	Pew (1958)[b]
After budding	−60 to −70	60 to 70	Pew (1958)[b]
Cauliflower	−60 to −70	60 to 70	Pew (1958)[b]
Fruit crops			
Lemons	−40	40	A. W. Marsh[c]
Oranges	−20 to −100	20 to 100	Stolzy et al. (1963)
Deciduous fruit	−50 to −80	50 to 80	A. W. Marsh,[c] and Vissar (1959)
Avocadoes	−50	50	Richards et al. (1962)
Grapes			
Early season	−40 to −50	40 to 50	A. W. Marsh[c]
During maturity	< −100	> 100	A. W. Marsh[c]
Strawberries	−20 to −30	20 to 30	A. W. Marsh,[c] and Marsh (1961)
Cantaloupe	−35 to −40	35 to 40	Marsh (1961), and Pew (1958)[b]

Table 1 (contd.)

Crop	*Matric potential (joules/kg)*	*Equivalent matric suction (centibars)*	*Reference*
Tomatoes	−80 to −150	80 to 150	Vittam et al. (1958),[c] and Vittam et al. (1963)
Bananas	−30 to −150	30 to 150	Schmeuli (1953)[f]
Grain crops			
Corn			
Vegetative period	−50	50	S. A. Taylor[a]
During ripening	−800 to −1200	800 to 1200	S. A. Taylor[a]
Small grains			
Vegetative period	−40 to −50	40 to 50	S. A. Taylor[a]
During ripening	−800 to −1200	800 to 1200	S. A. Taylor[a]
Seed crops			
Alfalfa			
Prior to bloom	−200	200	Taylor et al. (1959)
During bloom	−400 to −800	400 to 800	Taylor et al. (1959)
During ripening	−800 to −1500	800 to 1500	Taylor et al. (1959)
Carrots			
During seed year at 60 cm depth	−400 to −600	400 to 600	Hawthorn (1951)[g]
Onions			
During seed year at 7 cm depth	−400 to −600	400 to 600	Hawthorn (1951)[g]
at 15 cm depth	−150	150	Hawthorn (1951)[g]
Lettuce			
During productive phase	−300	300	Hawthorn et al. (1956)[g]
Coffee	Requires short periods of low potential to break bud dormancy, followed by high water potential		Alvin (1960)