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SOIL WATER POTENTIAL
TENSIOMETER

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SOIL WATER POTENTIAL

TENSIOMETER

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SOIL WATER POTENTIAL

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SOIL WATER POTENTIAL

1. 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 for each parcel of matter 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 of 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-plant-atmosphere-system" (Figure 1).

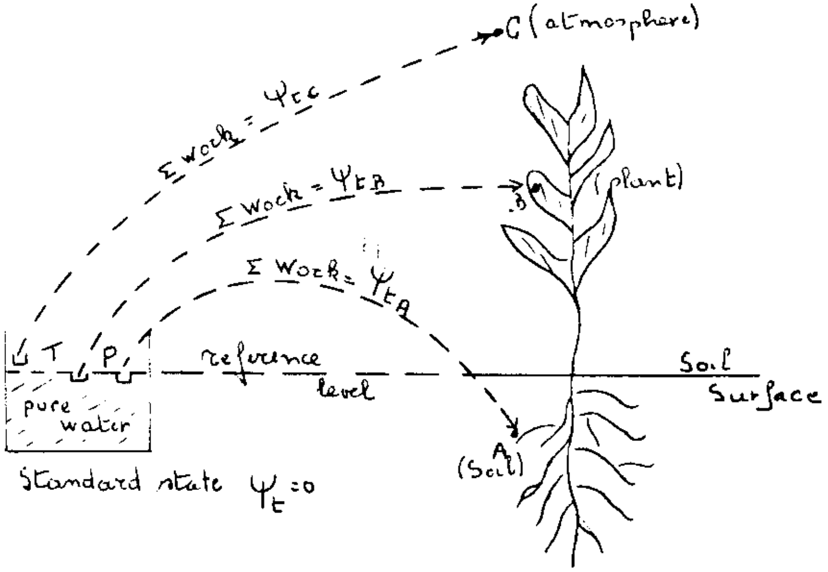

Figure 1 : Potential of soil water, water in plant cell and water in the atmosphere.

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 fields 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 :

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

where:

ψ_t = total potential,
ψ_m = matric potential,
ψ_g = gravitational potential,
ψ_o = osmotic potential,
ψ_p = pressure potential.

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.

2. Quantitative expression of soil water potential

The soil water potential can be expressed in at least three ways :

a) as an energy per unit mass of water :

erg.g^{-1}

b) as an energy per unit volume of water (unit of pressure) :

erg.cm^{-3} or dyne cm^{-2} (bars, atmosphere, etc...)

c) as an energy per unit weight of water (unit of head) :

erg.dyne^{-1} or cm (head)

Whatever can be expressed in units of hydrostatic pressure can also be expressed in terms of an equivalent head of water, which is the height of a liquid column corresponding to the given pressure. For example, a pressure of 1 atm. is equivalent to a vertical water column or hydraulic head of 1033 cm and to a mercury head of 76 cm. This method of expression is certainly simpler, and often more convenient then the previous methods. Expression in terms of unit weight is simple and attractive for applied work. Hence it is common to characterize the state of soil water potential in terms of the total potential head, which are usually expressible in centimeters or meters of water.

3. 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.

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.

Conversion table for units of soil water potential (1).

Specific potential units			Volumetric potential units			Weight potential units
ergs/g	joules/kg	bar	millibar	centibar	atmosphere	cm
-1	-0.000 1	-0.000 001	-0.001	-0.000 1	-0.000 000 987	-0.001 017
-10 000	-1	-0.01	-10	-1	-0.009 87	-10.17
-1 000.000	-100	-1	-1 000	-100	-0.987	-1 017
-1 000	-0.1	-0.001	-1	-0.1	-0.000 987	-1.017
-1 013 000	-101.3	-1.013	-1 013	-101.3	-1	-1 030
-983.3	-0.098 33	-0.000 983 3	-0.983 3	-0.098 33	-0.000 970 3	-1

(1) 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.

At a height z above a reference the gravitational potential energy 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 : $\psi_g = g z$ $(erg.g^{-1})$

per unit volume : $P_g = \rho_w g z$ $(dyne.cm^{-2})$

per unit weight : $z = z$ (cm)

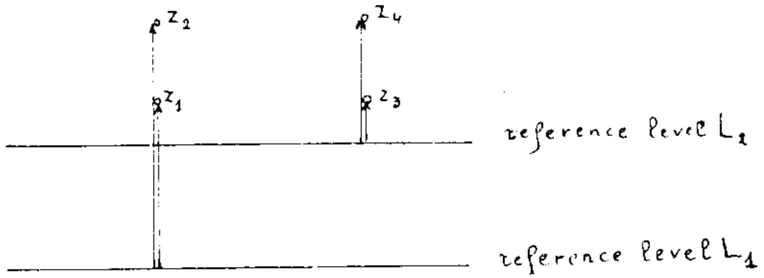

Figure 2 : The difference in gravitational potential between two points is identical for different reference levels.

Assume a reference level L_1 (Figure 2) and the presence of 1 gram of water at different heights z_1 cm and z_2 cm above that level. The gravitational potential (z) is now z_1 cm and z_2 cm respectively. The reference level, which is arbitrary, can be shifted to level L_2. Then the z potentials are z_3 cm and z_4 cm respectively.

Still the difference between the two ($z_4 - z_3$) is equal to the earlier difference when the reference level was at L_1 ($z_2 - z_1$). Differences in potential are generally more important than their absolute values when studying water movement in soils. The reference elevation can usually be arbitrarily chosen. For the sake of convenience it is costumary to set the reference level at the elevation of a pertinent point within the soil. In practice it means normally the soil surface.

4. Osmotic potential

The presence of solutes in soil water lowers its potential energy. Indeed the fact that water molecules move through a semi-permeable membrane from the pure free water into the solution indicated that the presence of solutes reduces the ability of water to perform work (Figure 3)

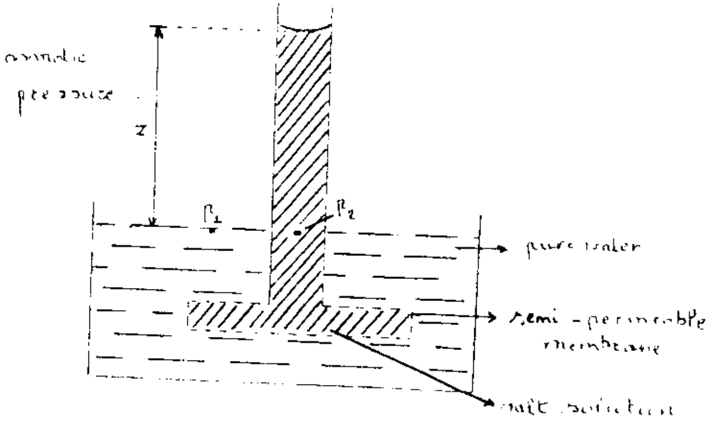

Figure 3 : Schematic presentation of osmosis.

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).

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 flow. (Barriers for the movement of salts are formed by the surface of roots). Nevertheless the osmotic potential is important as it has to be add to the matric potential in order to estimate how much work the plant must expend to extract a unit amount of water from the soil.

The magnitude of the osmotic potential can be calculated by means of following equation (law of Van 't Hoff)

$$\pi = - \frac{n}{v} RT$$

where :

π = osmotic pressure (atmosphere),
R = universal gas constant (0.082 l atm mol^{-1} K^{-1}),
$\frac{n}{v}$ = molarity of salt solution (mol l^{-1}),
T = absolute temperature (273 + t°C).

Example : Solution containing 0,01 N NaCl at 25°C

$$\pi_{Na} = \frac{0.082 \times 298 \times 0.01}{1} = - 0.25 \text{ atm.}$$

$$\pi_{Cl} = \frac{0.082 \times 298 \times 0.01}{1} = - 0.25 \text{ atm.}$$

Total osmotic potential equals - 0.50 atm.

5. Matric potential.[1]

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 (law of Laplace):

$$p_a - p_1 = \Delta P = \gamma \left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

where p_a is the atmospheric pressure, conventionally taken as zero; p_1 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 meniscus is concave.

As we assume the soil pores to have a cylindrical shape (Figure 4) the meniscus has the same curvature in all directions and equation above becomes:

$$-p_1 = \Delta P = \frac{2\gamma}{R}$$

since:

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

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

where: h = height of capillary rise,
ρ_w = density of water,
g = acceleration of gravity

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

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 5.

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:

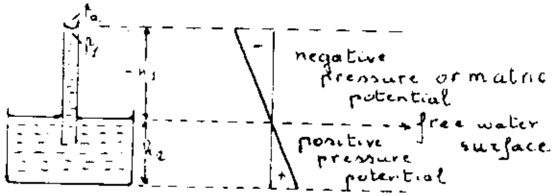
$$-gh = -\frac{2\gamma}{r\rho} \quad (\text{erg.g}^{-1})$$

- per unit volume:

$$-P = -\frac{2\gamma}{r} \quad (\text{dyne.cm}^{-2})$$

- per unit weight:

$$-h = -\frac{2\gamma}{\rho g r} \quad (\text{cm})$$



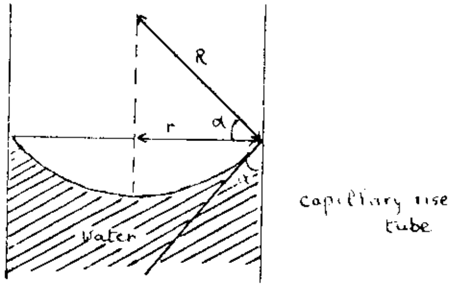


Figure 4 : Capillary rise of water into a capillary tube.

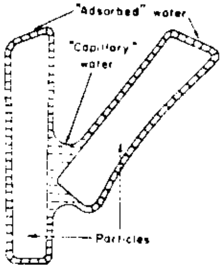


Figure 5 : Water in an unsaturated soil is subject to capillarity and adsorption, which combine to produce a matric suction (matric potential).

The matric potential is a dynamic property of the soil. In a saturated soil ψ_m is zero, in unsaturated soil ψ_m is negative.

6. 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 air pressure results in a pressure different from that at the standard reference state which gives origin to the so called pneumatic potential, ψ_p^n (See laboratory for the determination of the soil water characteristic curve).

Situation with water table.

In saturated soil the liquid phase is at hydrostatic pressure greater than atmospheric and thus its pressure potential is considered positive (Figure 4). Thus water under a free water surface is at positive pressure potential, 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.

Some soil physicists prefer to separate the positive pressure potential from the matric potential assuming the two to be mutually exclusive and has been termed the submergence potential, ψ_p^u. Accordingly soil water may exhibit either of the two potentials, but not both simultaneously.

Nevertheless it is an advantage in unifying the matric potential and the positive pressure or submergence potential ψ_p^u, 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 region into the unsaturated region, below and above the water table.

In the field ψ_p^u is measured with a piezometer and it is the vertical distance from the point under consideration in the profile to the water surface of a piezometer connected to the point in question if expressed per unit weight.

7. Hydraulic head.

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

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

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:

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

called hydraulic potential.

It is often usual to designate the potential in terms of head (potential energy per unit weight).

In nonequilibrium conditions under isothermal conditions, water flow occurs from locations where the total water potential is high to locations where the total water potential is low. For example, if the total water potential at point A in a soil is - 200 cm and the total water potential at point B is - 350 cm, the water will flow from point A to point B.

As already stated, the pneumatic potential ψ_p^n for field studies may be assumed to be zero. Also the soil water within a profile may exhibit either matric or submergence potential (Figure 4) but not both 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.

In the unsaturated zone (above the water level), equations (1) becomes:

$$\psi_m + \psi_g = \psi_H$$

or in terms of head:

$$h + z = H$$

where: h = soil water pressure head (cm)
z = gravitational head (cm)
H = hydraulic head (cm)

This 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 6 the condition is applied to a vertical soil column in equilibrium with a water table. No water movement occurs in the column. The groundwater table is taken as the reference level for the gravitational potential.

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

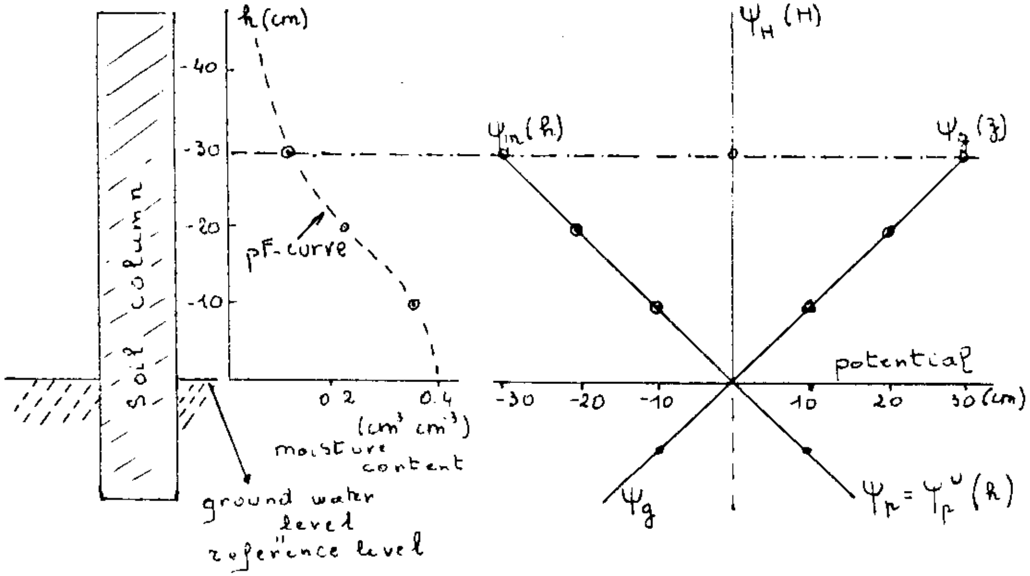


Figure 6. Equilibrium condition in a soil column.

height(cm)	ψ_g (z,cm)	ψ_m (h,cm)	ψ_p (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

Source:

"APPLIED SOIL PHYSICS"

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

Advanced Series in Agricultural Sciences 8

Springer - Verlag Berlin 1980

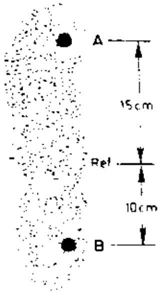
Example 2.1

Given Two points in a soil. Each point is located a specified vertical distance from a reference elevation. (See the figure at the right.)
Find The difference in gravitational potential, $\Delta\psi_z$, between the two points.
Solution:

ψ_{zA} = 15 cm.

ψ_{zB} = -10 cm.

$\Delta\psi_z = \psi_{zA} - \psi_{zB}$ = 15 cm - (-10 cm) = 25 cm



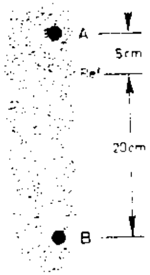
Example 2.2

Given The same two soil points specified in Example 2.1 but with the reference elevation relocated as shown in the figure at the right.
Find The difference in gravitational potential, ψ_z, between the two points.
Solution

ψ_{zA} = 5 cm.

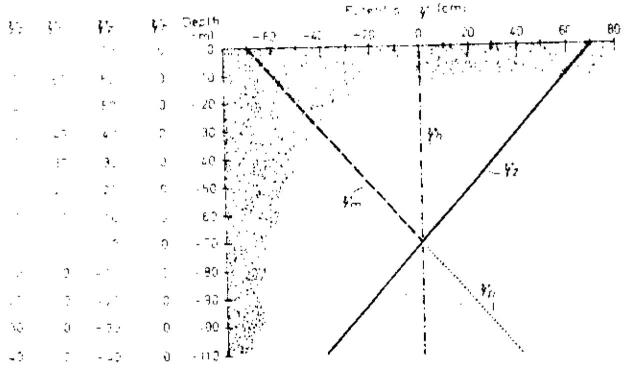
ψ_{zB} = -20 cm.

$\Delta\psi_z = \psi_{zA} - \psi_{zB}$ = 5 cm - (-20 cm) = 25 cm.



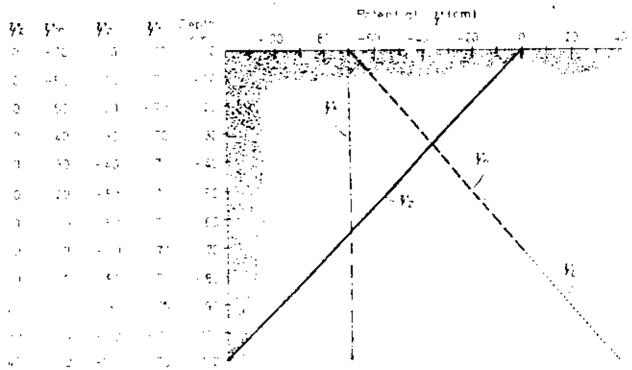
Example 2.3.

Given A soil in which the liquid water is in equilibrium with a water table at -70 cm and the reference level is chosen as -70 cm.
Find The values of ψ_p, ψ_m, ψ_z, and ψ_h throughout the soil profile to -110 cm.
Solution



Example 2.4.

Given The conditions of Example 2.3 except the reference level is the soil surface.
Find The values of ψ_h, ψ_p, ψ_m and ψ_z throughout the soil profile to -110 cm.
Solution



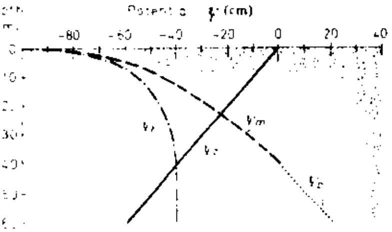
Example 2.5.

Given Water is evaporating at the soil surface and there is a water table at -40 cm. The reference level is at the soil surface

Find Values of ψ_z, ψ_p, and ψ_h throughout the soil profile to -60 cm. In order to find ψ_h, measured or estimated values of ψ_m must be available. Make estimates of ψ_m for the conditions specified.

Solution

ψ_p	ψ_m est	ψ_z	ψ_h	Depth (cm)
0	-105	0	-105	0
0	-45	-10	-55	-10
0	-26	-20	-46	-20
0	-13	-30	-43	-30
0	[illegible]	-40	-40	-40
10	[illegible]	-50	-40	-50
20	0	-60	-40	-60



Note For upward flow the hydraulic potential at -40 cm must be greater than at -30 cm etc. Thus $\psi_{h(-40)} > \psi_{h(-30)} > \psi_{h(-20)} > \psi_{h(-10)} > \psi_{h(0)}$. We may have variations in the gradient $\Delta\psi_h/\Delta z$ with depth, but for upward flow, the sign must always be negative

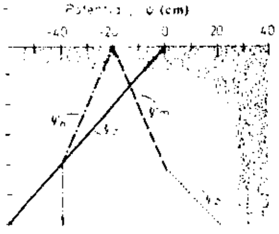
Example 2 6.

Given A soil in which water is flowing into a drain at -40 cm The reference level is the soil surface

Find Values of ψ_p, ψ_z, and ψ_h for the entire soil profile to -60 cm Estimates must first be made of ψ_m

Solution

ψ_z	ψ_p	ψ_m est	ψ_h	Depth (cm)
0		-20	-20	0
-10		-15	-25	-10
-20		-13	-33	-20
-30		-5	-35	-30
-40		0	-40	-40
-50			-40	-50
-60		0	-40	-60



Note Flow is downward, thus $\Delta\psi_h/\Delta z$ must be positive

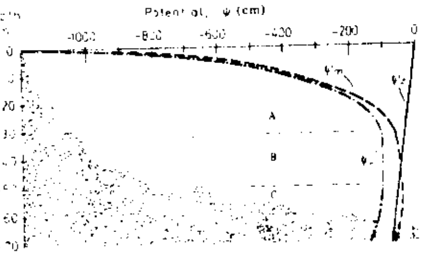
Example 2.7.

Given A soil was initially quite dry It received rain that wet the soil from the surface downward to part way through the profile After a few days, the surface had dried and water moved upward in response to the evaporation At lower depths, however, the soil water moved downward into the soil that had not been wetted by the rain

Find Values of ψ_z, ψ_p, and ψ_h throughout the profile to -60 cm using your estimates for ψ_m

Solution

ψ_z	ψ_p	Estimated ψ_m est.	ψ_h	Depth (cm)
0	0	-1000	-1000	0
-10	0	-390	-400	-10
-20	0	-180	-200	-20
-30	0	-70	-100	-30
-40		-60	-100	-40
-50	0	-50	-100	-50
-60	0	-50	-110	-60
-70	0	-60	-130	-70



Note In zone A, $\Delta\psi_h/\Delta z$ is negative, thus flow is upward In zone B, $\Delta\psi_h/\Delta z$ is zero, thus there is no flow. In zone C, $\Delta\psi_h/\Delta z$ is positive, and as a consequence, flow is downward

TENSIOMETER

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TENSIOMETER

1. Principle

Tensiometer measures the magnitude of the pressure potential h. It consists of a porous cup, mostly of a ceramic material and connected with a piezometer tube filled with water and open at the end (manometer). When the cup is placed in a water reservoir (Figure 1 A) 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.

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 : gravitational constant.

If we place now this 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 exercises a suction which draws 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 1 B).

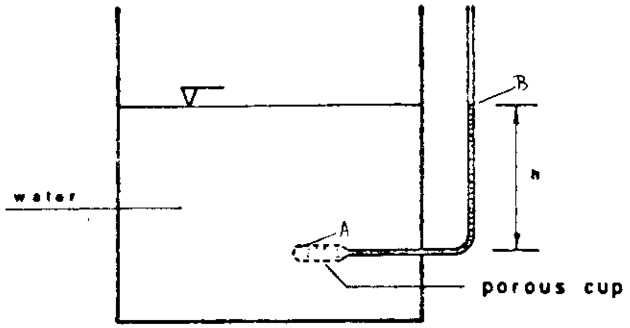


Figure 1 A : Measuring pressure potential with porous cup.

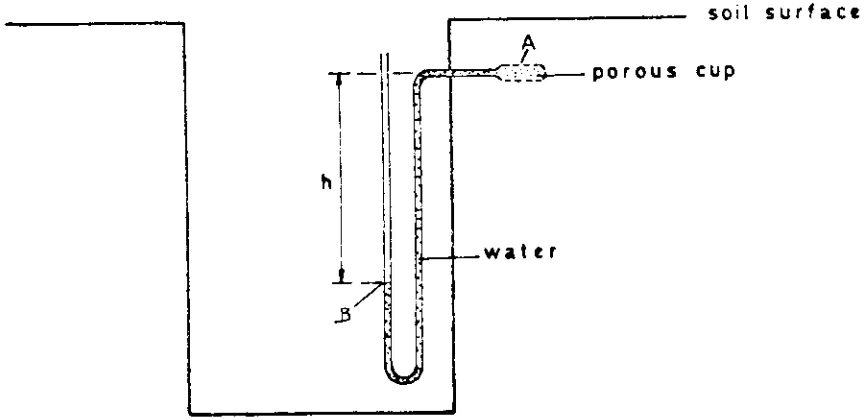


Figure 1 B : Tensiometer for measuring pressure potentials in soils.

The drier the soil, the higher the suction and the lower the water level at equilibrium in the U-tube. The height of the liquid column that has moved into ("sucked into") the soil -h cm in figure 1 B- 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 require 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 2).

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.

2. How to calculate the pressure potential (matric potential and the hydraulic head (Figure 3a en 3b)

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_3). 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).

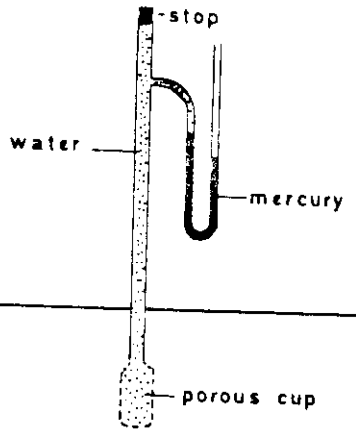


Figure 2 : Tensiometer with mercury manometer.

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

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

where :

z = gravitational head,

$P/_{\rho g}$ = pressure head.

From figure 3 A one obtains :

in water :

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

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

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

in mercury :

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

because :

z_C = 0 reference level,

P_C = atmospheric pressure = 0,

the equation becomes :

$$z_B + P_B/_{\rho_{Hg} g} = 0$$

or

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

(2) in (1)

$$P_A = - \rho_{Hg} g\, z_B + \rho_w g\, (z_A + z_B) \quad \rightarrow \quad \text{per unit mass}$$

$$\frac{P_A}{\rho_w g} = \frac{- \rho_{Hg}\, g\, z_B}{\rho_w g} + z_A + z_B \quad (3) \quad \rightarrow \quad \text{per unit weight}$$

Since :

$\rho_{Hg} = 13.6\ g.cm^{-3}$,

$\rho_w = 1\ g.cm^{-3}$

(3) becomes :

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

or

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

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

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

Equation (4) becomes :

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

The hydraulic head H, being the sum of the pressure head and gravitational head, becomes :

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

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

Example :

$x = 31$ cm of Hg,

$y = 40$ cm,

$z = 30$ cm

$h = (-12.6 \times 31 + 40 + 30)$ cm $= -320,6$ cm of $H_2O \simeq -0,32$ atm.

$H = (-12,6 \times 31 + 40)$ cm $= -350,6$ cm of $H_2O \simeq -0,34$ atm.

3. 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 ($cm^3.min^{-1}.atm^{-1}$),

- sensitivity of the manometer "S" $= \frac{\Delta h}{\Delta V}$

  being the change in manometer reading per unit volume change ($atm.cm^{-3}$),

- 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 (min.).

4. Practices and limitations of tensiometers

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

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

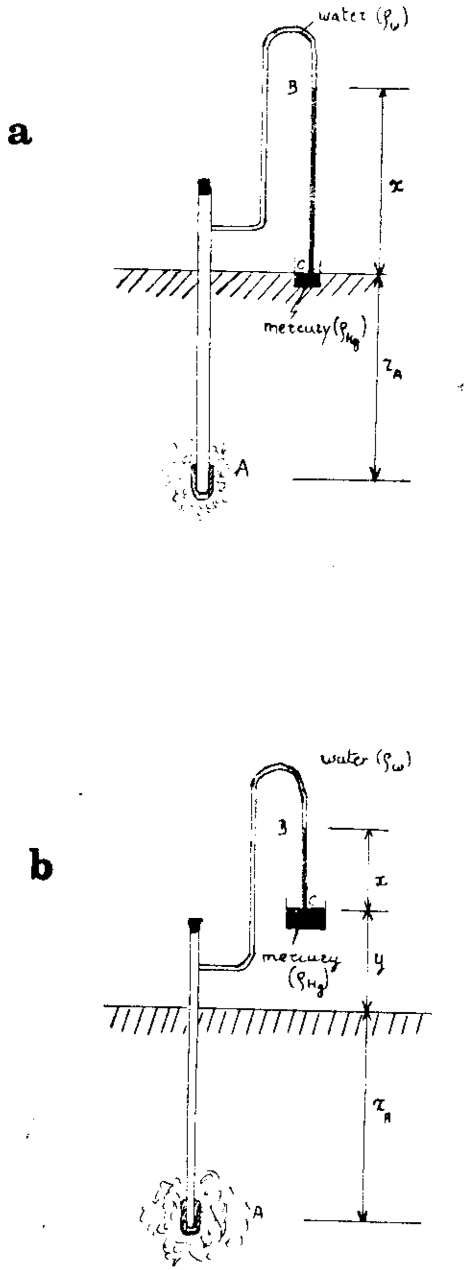


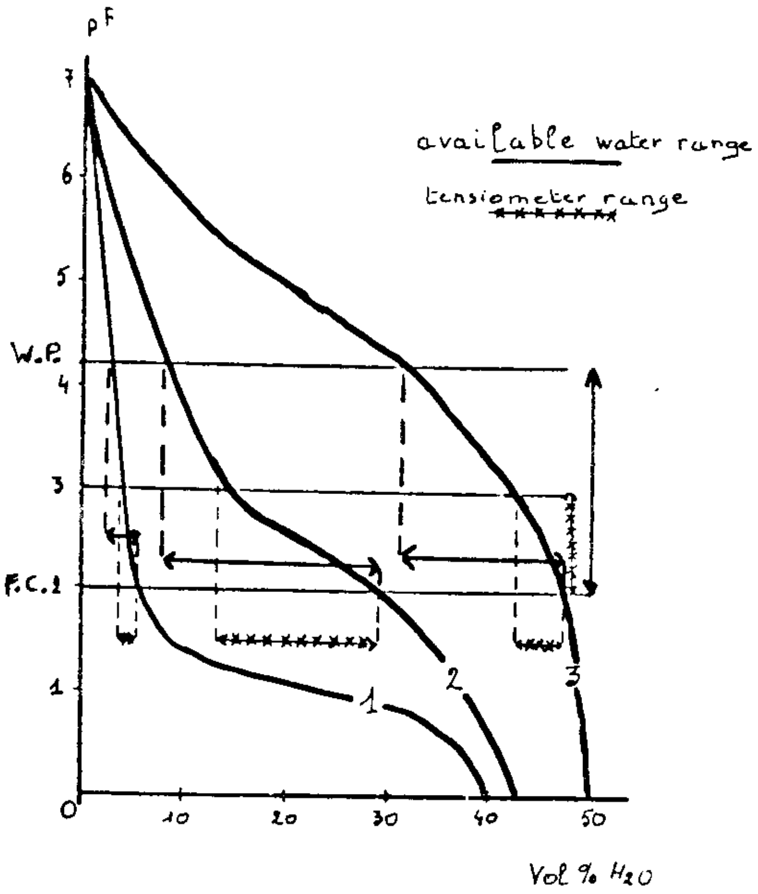
Figure 3 : Tensiometer installation with the mercury level in reservoir as a fixed reference.

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 negative pressure of about 850 cm of water. Use of tensiometers in the field is therefore only possible when pressures do not exceed this value. However, the limited range of pressure measurable by the tensiometers is not as serious a problem as it may seen at first sight. Though the range of 0 to – 0.8 bar is but a small part of the total range. In many agricultural soils the tensiometer range accounts for more than 50 % of the amount of soil water taken up by 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 pF-curve as shown for three soil types in figure 4.

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 prefereably be shielded from direct exposure to the sun. Therefore it is also suggested to make readings always at the same point of day time (e.g. at 08.00 a.m.).



① Sand 75 % of available moisture

② Loam 75 % " "

③ Clay. 30 % " "

Figure 4 : Part of the available moisture range covered by tensiometer depending on soil type.

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 absorbed 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 registred 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 rater 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.

5. 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 5)

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 :

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

where :

q = flux,

$K(\theta)$ = hydraulic conductivity,

H = hydraulic head,

↳ = $h - z$ with h : soil water pressure head,

z : gravitational head with z positive downwards.

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 where the curve $H(z)$ will show a maximum or the rise of the mercury a minimum because $\frac{dH}{dz} = 0$

A graphical example is presented in figure 5.

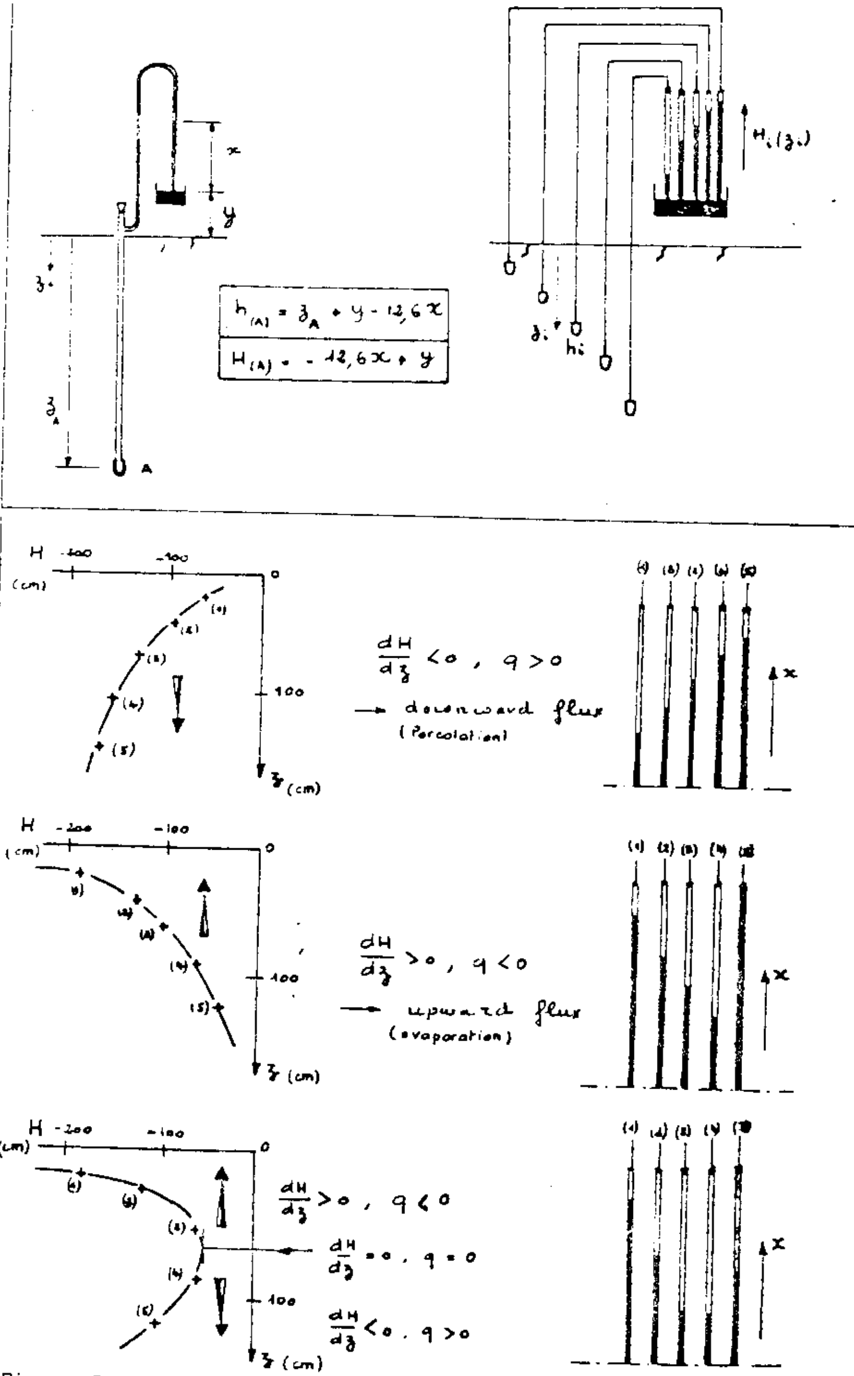


Figure 5 : Hydraulic head profiles. The manometers from left to right increase with depth.

Numerical example

tensiometer z_1 = 50 cm x = 10.7 cm y = 20 cm

tensiometer z_2 : 75 cm x = 13.8 cm y = 20 cm

$H_1 = -12.6\ x + y = -104.8$ cm

$H_2 = -12.6\ x + y = -153.9$ cm

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 (Θ) 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 retentivity curve

The h-Θ 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 atmospheric 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.

[redacted]

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. (These values are subject to revision as additional experimental data become available). (TAYLOR and ASHCROFT, 1972).

Crop	Matric potential (cm)
Vegetative crops	
Alfalfa	- 1500
Beans	- 750 to - 2000
Cabbage	- 600 to - 700
Canning peas	- 300 to - 500
Celery	- 200 to - 300
Grass	- 300 to - 1000
Lettuce	- 400 to - 600
Rootcrops	
Sugar beets	- 400 to - 600
Potatoes	- 300 to - 500
Carrots	- 550 to - 650
Cauliflower	- 600 to - 700
Fruitcrops	
Lemons	- 400
Oranges	- 200 to - 1000
Avocades	- 500
Strawberries	- 200 to - 300
Tomatoes	- 800 to - 1500
Bananas	- 300 to - 1500