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SOIL WATER POTENTIAL: 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).

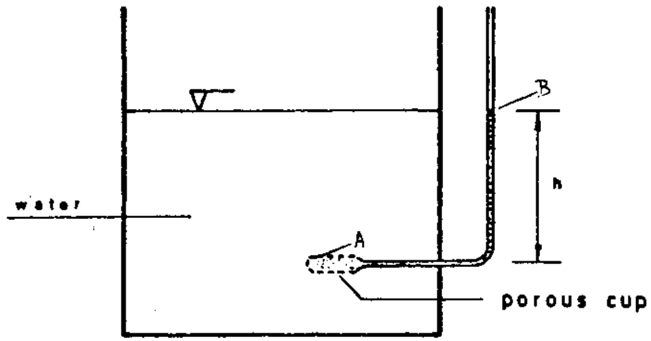


Figure 1 A : Measuring pressure potential with porous cup.

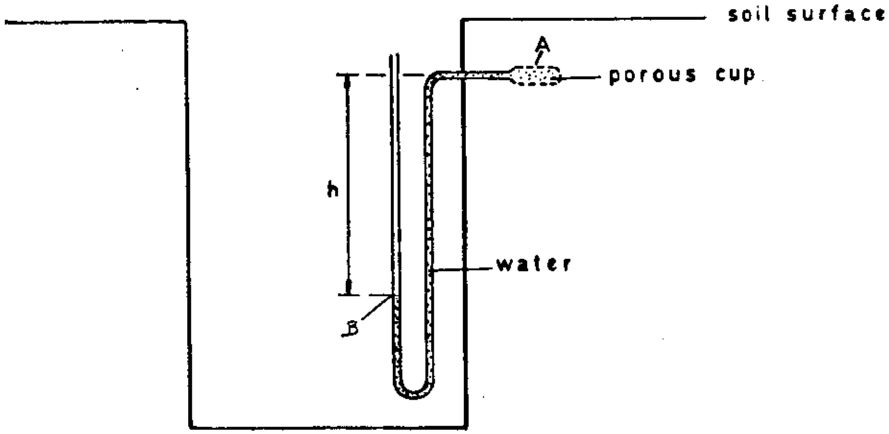


Figure 1 B : Tensiometer for measuring pressure potentials in soils.

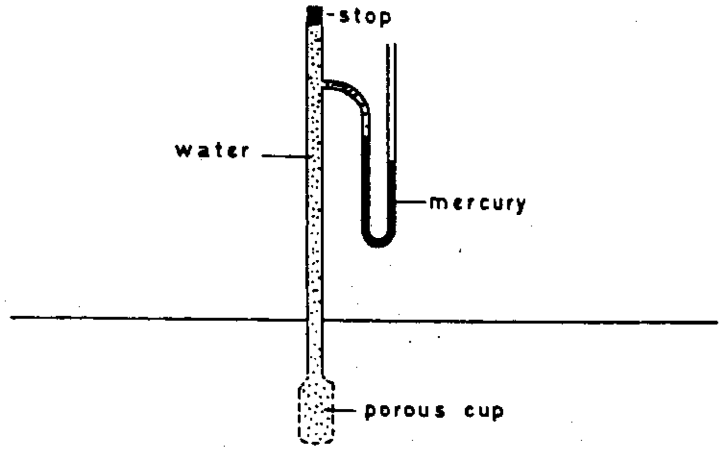


Figure 2 : Tensiometer with mercury manometer.

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_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).

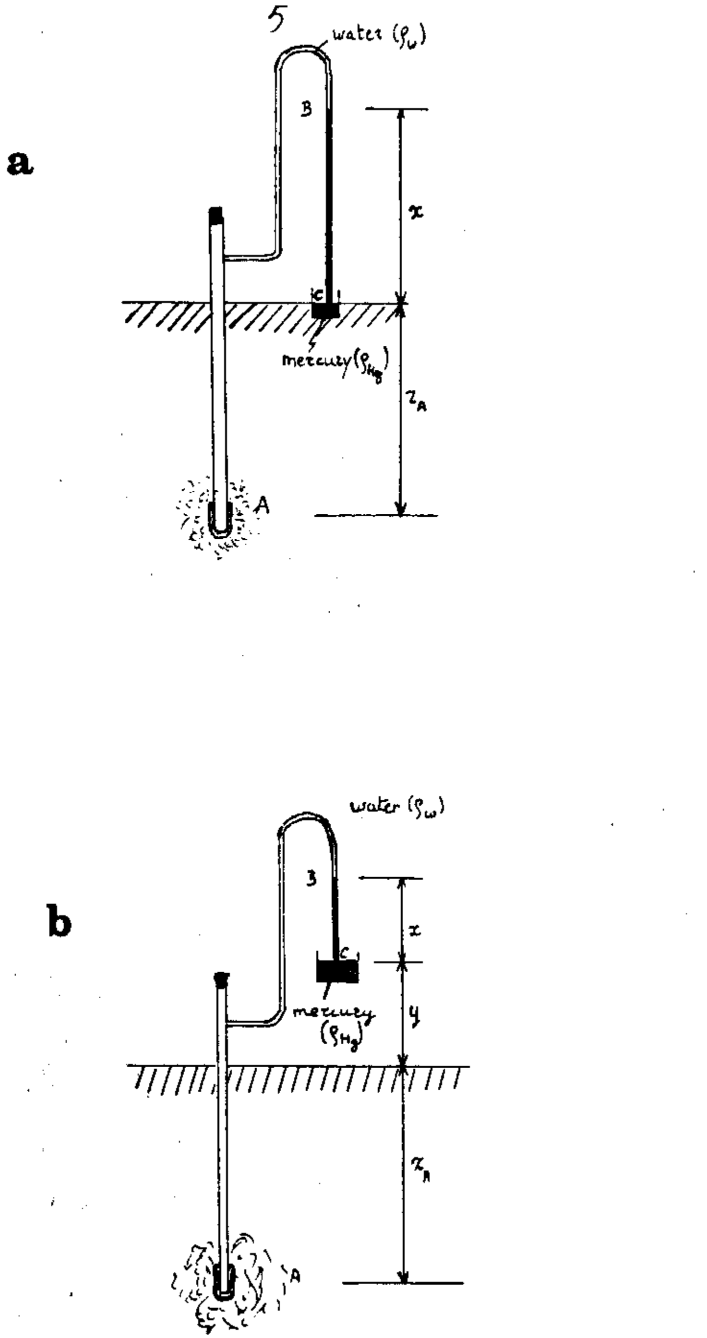


Figure 3 : Tensiometer installation with the mercury level in reservoir as a fixed reference.

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 :

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

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

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

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

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

(2) in (1)

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

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

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

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

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

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 :

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

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

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

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

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 ≈ -0,32 atm.

$H = (-12,6 \times 31 + 40)$ cm = - 350,6 cm of H_2O ≈ -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 througout 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 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.).

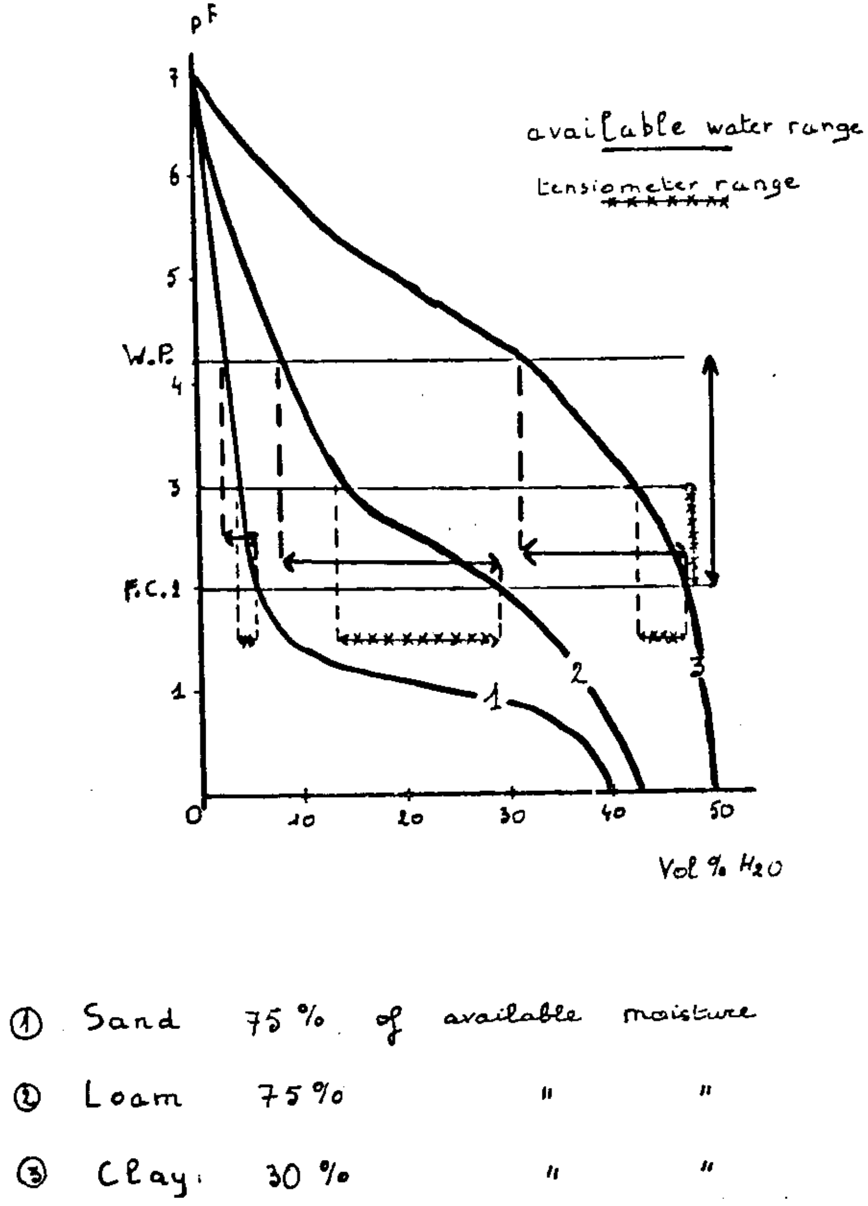


Figure 4 : Part of the available moisture range covered by tensiometer depending on soil type.

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 :

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

where :

q = flux,

$K(\theta)$ = hydraulic conductivity,

H = hydraulic head,

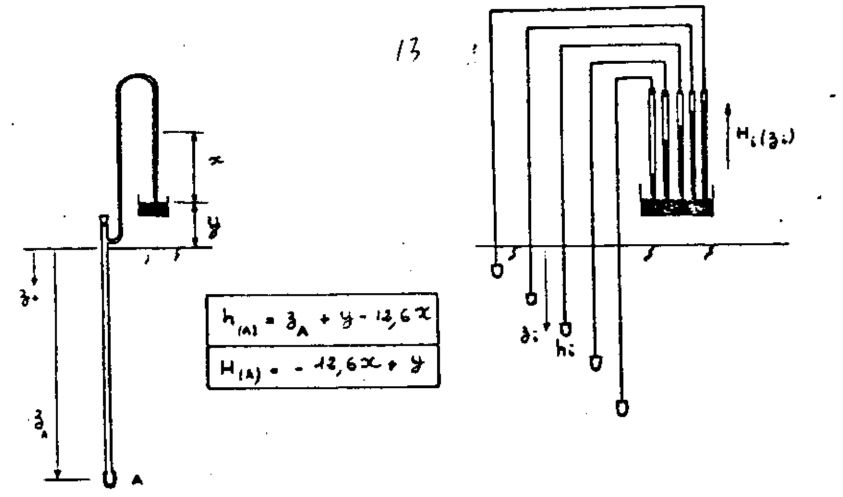
↳ = $h - z$ with h : soil water pressure head,

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.



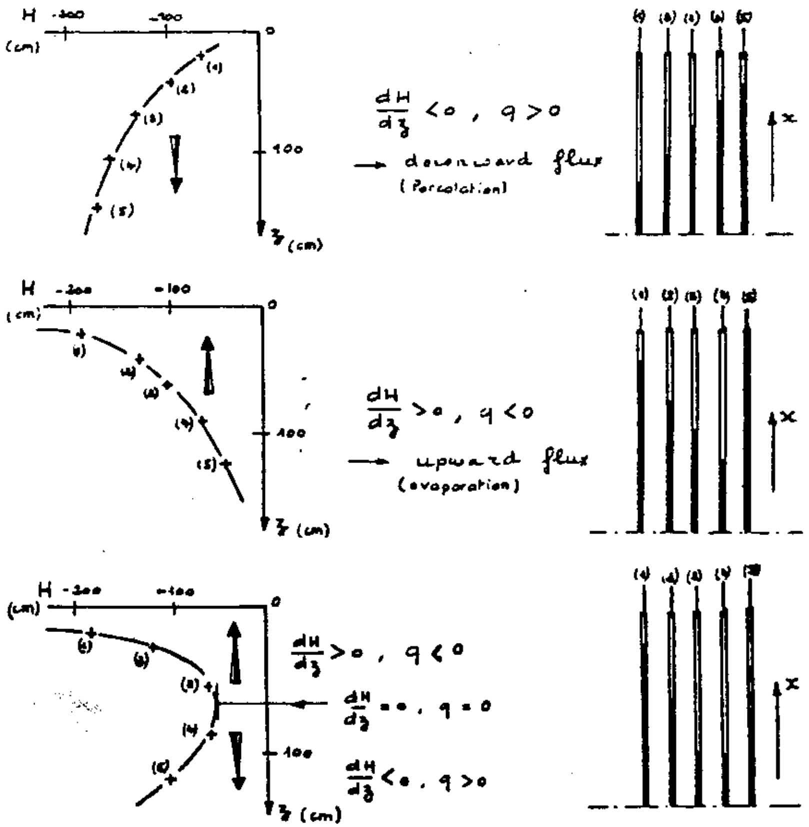


Figure 5 : Hydraulic head profiles. The manometers from left to right increase with depth.

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.

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