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Critical Evaluation of Different Techniques for Determining Soil Water Content

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1. Introduction

To efficiently operate any type of irrigation system, it is necessary to know when to irrigate and the quantity of water to apply during irrigation. To achieve this, it is very important to know the previously available soil water content. A good on-farm irrigation water management requires a routine monitoring of soil water moisture. Soil water must be maintained between a lower and upper limit of availability for an optimum plant growth. Soil moisture is a very dynamic variable that depends on plants evapotranspiration, irrigation frequency, drainage and rainfall. Measuring soil water content for determining the water depth allows avoiding the economic losses due to the effect of underirrigation on crop yield and crop quality, and the environmentally costly effects of overirrigation on wasted water and energy, leaching of nutrients or agricultural chemicals into groundwater supplies.

This chapter describes the applications and limitations of different techniques for determining soil water moisture. A description of how to calculate the irrigation depth as a function of water soil holding capacity, soil depth and bulk density is also included. Six techniques for measurement of soil moisture are described: gravimetric sampling, neutron scattering, tensiometers, porous blocks, time domain reflectometry, impedance and capacitance methods.

2. State of water in the soil

The state of water in the soil can be described in two ways: quantity present and energy status. The quantity present is expressed as gravimetric (mass) or volumetric. The gravimetric water content is the mass of water in a unit mass of dry soil (g of water/g of dry soil). The wet weight of soil sample is determined; the sample is dried at 105 °C to constant weight and reweighed (Gardner, 1986). The volumetric water content is expressed in terms of the volume of water per volume of soil (cm³ of water/cm³ of soil). Volumetric water content can be calculated from gravimetric water using the equation:

$$\theta_v = \theta_w \cdot \rho_b \quad (1)$$

Where θ_v is the volumetric water content, θ_w is the gravimetric water content and ρ_b is the soil bulk density, which must be determined for the same soil under field conditions.

The energy status of water in soil can be expressed as follows (Hanks and Ashcroft, 1980):

$$\Psi_{\text{total}} = \Psi_{\text{matric}} + \Psi_{\text{solute}} + \Psi_{\text{grav.}} \quad (2)$$

Where Ψ_{total} is the total soil water potential (MPa), Ψ_{matric} soil matric potential (MPa), Ψ_{solute} soil solute potential (MPa) and $\Psi_{\text{grav.}}$ pressure potential or gravimetric water potential (MPa). The energy of water in the soil is attenuated by the hydrophilic surfaces of soil particles. As a result of the attraction of water to these surfaces, the energy of the water is decreased. Water forms films around the particles and fills pores. This fraction of the soil water energy is known as capillarity suction or matric water potential. The value of the matric term can be calculated from the capillarity rise equation:

$$\Psi_{\text{matric}} = -\rho_w g h = \frac{-2\gamma \cos(\alpha)}{r} \quad (3)$$

where, ρ_w is the density of water (kg m^{-3}), h = height of rise above a free water surface (m), g = acceleration due to gravity (m s^{-2}), γ = surface tension (N m^{-1}), α = wetting angle (degrees) and r = capillarity radius (m) (Hanks & Ashcroft, 1980; Hillel, 1980). The pressure potential is present in saturated soil due to the pressure of water above a given point and is calculated with the equation:

$$\Psi_{\text{grav.}} = \rho_w g h \quad (4)$$

where, ρ_w , g , and h were previously defined. The presence of solutes in the soil water further decreases its energy potential. The solute or osmotic potential of soil water is less than or equal to zero, and is directly related to the total solute concentration in the water, according to the following equation:

$$\Psi_{\text{solute}} = cRT \quad (5)$$

where, R is the universal gas constant ($8.3143 \text{ J K}^{-1} \text{ mol}^{-1}$), T is the absolute temperature and c is the osmolality of the solution. At low concentrations, where the activity coefficient is near 1, c is approximately equal to the total molar concentration of osmotically active species in the water.

For a given soil, there is a unique relationship between the soil water content and the soil water potential. This relationship is known as the soil water characteristic curve or soil water release curve (Klute, 1986). The curve derived by determining the energy status of water in the soil at several water contents may vary considerably with changes in soil texture (Figure 1)

Two approaches are used to obtain the relationship between soil water content and soil water potential. Either a given water content is first established, and the water potential then determined, or conditions are imposed on a soil sample to bring it to a given water potential, and the water content of the sample is determined after equilibrium is reached.

In the latter case, vacuum and pressure plate apparatus have been used extensively down to -1.5 MPa matric water potential (Klute, 1986). These are best applied where the soil solution

is diluted and therefore the contribution of solutes to total water potential is minimal. In typical applications, moist soil samples are placed on a ceramic plate (down to -0.08 MPa) or a membrane (to -1.5 MPa), and a fixed suction or pressure is applied to a given potential until no more water is forced out of the sample. In practical terms, a vacuum can be applied to the ceramic plates down to potential of approximately -0.8 MPa. Below this potential, the soil samples must be housed in a pressure chamber to which constant air pressure can be applied; water is then force out of the soil sample and through the ceramic plate or membrane until no ore water is drained. At this point, it is assumed that the water potential of the remaining soil water is exactly equal to the negative of the pressure applied. This technique is used down to water potential of -1.5 MPa.

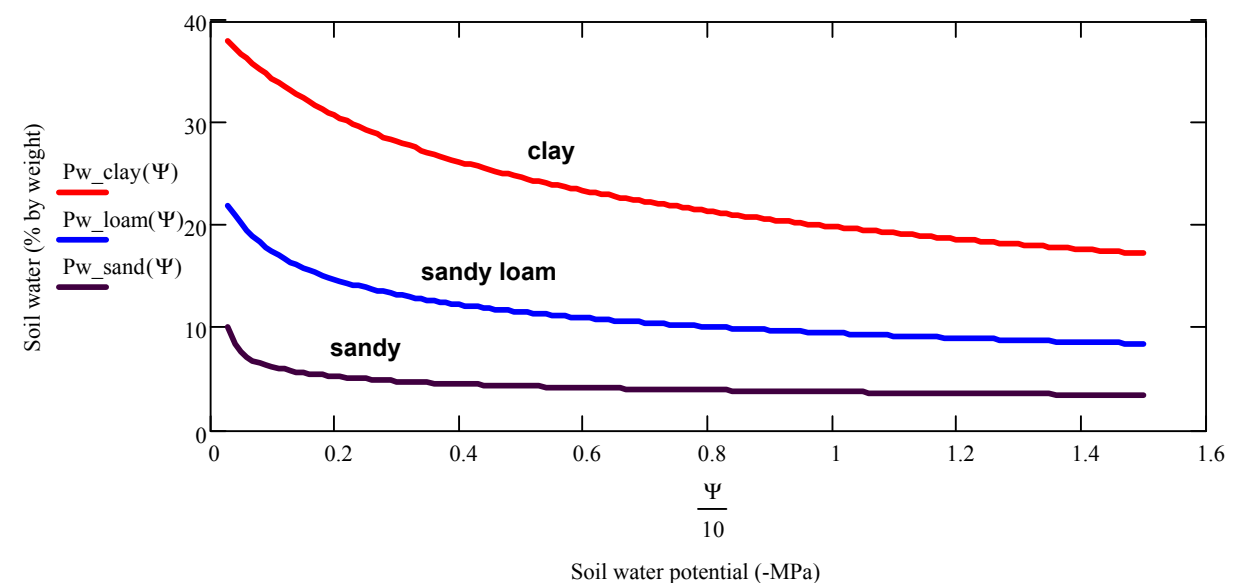


Fig. 1. Typical relationships between soil water content and soil water potential in clay, sandy loam and clay soils.

Psychrometric systems have been used to determine the total soil water potential of samples at different soil water contents. The relative humidity of air in equilibrium with the moist soil sample is determined, and expressed in terms of the corresponding water potential. If the soil is low in salts, only the matric potential is represented; otherwise, the sum of matric and osmotic potential results. Because relative humidity near 100% may be difficult to measure accurately, the psychrometric technique may be difficult to measure accurately, the psychrometric technique is best applied to systems where the soil water potential is less than -0.20 MPa. (Rundel & Jarrel, 1991)

2.1 Depth of available soil water

The Depth of total, depleted and residual available soil water can be calculated from the following equations:

TAW = [θ_{w_FC} - θ_{w_PWP}]*(ρ_b/ρ_w)*Z (6)

DAW = [θ_{w_FC} - θ_{w_actual}]*(ρ_b/ρ_w)*Z (7)

$$RAW = [\theta_{w_actual} - \theta_{w_PWP}] * (\rho_b / \rho_w) * Z \quad (8)$$

where, TAW=depth of total available soil water (cm), DAW= depth of depleted available soil water (cm), RAW= depth of residual available soil water (cm), θ_{w_FC} = gravimetric soil water content at field capacity (g/g), θ_{w_PWP} = gravimetric soil water content at permanent wilting point (g/g), θ_{w_actual} = gravimetric soil water content at the time of measurement (g/g), ρ_b = soil bulk density (g/cm³), ρ_w = density of water (g/cm³), Z = soil depth to irrigate (cm).

3. Gravimetric water content

Gravimetry refers to the measurement of soil water content by weighing. It is the oldest and most direct method, and when done carefully with enough samples is the standard against which other methods are calibrated and compared. This technique requires careful sample collection and handling to minimize water loss between the time it is collected and weighed. Replicated samples at the same soil depth should be taken to reduce the inherent sampling variability that results from small volumes of soil. The equipment required includes a soil auger, sample collection cans, a balance accurate to at least 1 gram and a drying oven (Figure 2).



Fig. 2. Equipment used by the gravimetric technique for measuring soil water content.

The technique involves taking soil samples from each of several desired depths in the crop root zone and temporarily storing them in containers (water vapor-proof). The samples are then weighed and the opened containers oven-dried under specific time and temperature conditions (105 °C for 24 h). The dry samples are re-weighed. Percent soil water content on a dry mass or gravimetric basis, P_w is determined as:

$$P_w = \frac{WSW - DSW}{DSW} * 100 \quad (9)$$

where, WSW = wet sample weight (g), DSW = dry sample weight (g). The difference between wet and dry weight is the mass of water removed by drying. To convert from gravimetric basis to water content on a volumetric basis (P_v), multiply the gravimetric soil water content by the soil bulk density (ρ_b).

$$P_v = P_w * \rho b \quad (10)$$

Although the gravimetric method is relatively simple and inexpensive, it has several limitations. It is time-consuming and labor-intensive compared with other methods of soil moisture measurements, results are known after a minimum of 24 h after sampling, a large number of samples must be taken to remove the inherent variability of this approach. As it is a destructive technique, repeated measurements at the same point in the soil are not possible.

The use of microlysimeters is also a gravimetric method (Boast & Robertson, 1982) that allows repeated measurements at the same time, for a direct estimate of soil evaporation rate in additions to soil water content. The procedure consists in inserting into the soil a small piece of aluminum or PVC pipe (10 to 20 cm in diameter and length). Then the pipe and the enclosed soil are removed by carefully excavating around the perimeter. The pipe is sealed on the bottom, weighed, then placed in a plastic bag and replaced in the same position in the soil, with the plastic bag pulled back to exposure the soil surface to the atmosphere. The soil surrounding the microlysimeter is repacked to resemble the original surface as closely as possible. At a later time the microlysimeter can be removed and reweighed to determine the water loss (soil surface evaporation) during the intervening time period. This may be done several times, after which the soil can be oven-dried and reweighed to back-calculate water content at each weighing. This is an inexpensive, direct and reasonably accurate measurement of soil evaporation (Lascano & van Bavel, 1986), but it is time-consuming and labor intensive. Since the soil in the core is not in hydraulic contact with the soil below, the evaporation rate from the core will eventually diverge from that of the surrounding soil, so a given core should not be used for more than a few days.

4. Neutron scattering

Neutron scattering is a time-tested indirect determination of soil water content. This method estimates the amount of water in a volume of soil by measuring the amount of hydrogen atoms present. A neutron probe consists of a source of fast or high energy neutrons and a detector, both housed in a unit which is lowered into an access tube installed in the soil. The probe is connected by a cable to a control unit located in the soil surface. Clips on the cable allow the cable to be set at pre-selected depths into the soil profile. Access tubes should be installed to the depth of the expected growth of the root crop. The control unit includes electronics for time control, a counter, memory and other electronics for processing readings (Figure 3).

This technique works based on the following principle. Fast neutrons emitted from the interaction of a radioactive alpha-emitter with Beryllium, pass through the access tube into the surrounding soil, where they gradually lose energy by collision with other atomic nuclei. Hydrogen atoms in the soil (mostly in water molecules) are effective in slowing the fast neutrons because they are of approximately the same mass. The result is a cloud of slow or thermalized neutrons; some of them diffuse back to the detector. The size and density of the cloud depends mainly on soil type and soil water content, and is spherical in shape (Figure 4) with a diameter of 15 to 40 cm. Thermalized neutrons that impact the detector create a small electrical impulse, which is amplified and counted. The number of slow neutrons counted in a specified interval of time is linearly related to the total volumetric soil water content. A higher count indicates higher soil water content.



Fig. 3. Neutron probe for measuring soil water content.

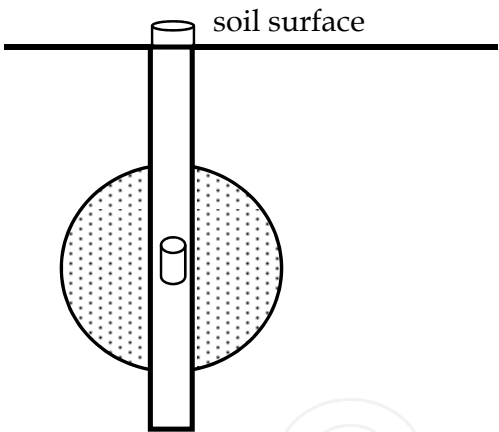


Fig. 4. Spatial sensitivity of neutron scattering in the soil.

Commercial neutron probes combine the source and detector in a single unit which fits in the access tube. They also include a standard material within the housing, so that a standard count may be taken prior to each measurement. This allows expressing the reading as count ratio (count in the soil/count in the standard), to account for changes in source strength associated with radioactive decay and for instrument drift.

Neutron probe must be calibrated for the soil type in which they will be used (Baker, 1990). Manufacturers provide a calibration curve with each neutron prove, but it is probably useful only for moisture measurements in homogeneous sands and gravels. Several studies have shown that factory-supplied curves give large errors when used in agricultural soils (Chanasky & McKenzie, 1986). Soil-specific calibration is necessary because detector readings are affected by the presence of non-water hydrogen (principally in organic matter),

other elements in the soil with the ability to thermalized fast neutrons, and elements that absorb fast neutrons such as boron, cadmium and chlorine. The calibration procedure consists on compare neutron count ratios taken in a defined soil depth, against water content determined gravimetrically from samples taken nearby at the same soil depth.

The neutron probe allows relatively rapid and repeatable measurements of soil water content to be made at several depths and locations within a field. Repeatable measurements at the same location through the crop growing season, reduces the effect of soil variability on the measurements.

The main advantages of this method are: direct reading of soil water content, large volume of the soil is sampled, one unit can be used in several locations, and is accurate when properly calibrated. The main disadvantages are: individual calibration for each type of soil is required, difficult to use in automatic monitoring, its use near the surface requires spatial technique because of the escape of fast neutrons, and the high cost of the unit. There is also a radiation safety hazard, which requires special licensing, operation training, handling, shipping and storage procedures.

Example 1:

A homogeneous and deep soil has the following parameters: $\theta_{w_FC} = 0.285$ g/g, $\theta_{w_PWP} = 0.140$ g/g, $\rho_b = 1.25$ g cm⁻³. The calibration equation of the neutron probe used to measure soil water content was: $\theta_w = -0.031 + 0.1496 \cdot C.R.$, where θ_w is the gravimetric water content (g/g) and C.R. is the counting ratio of the thermalized neutrons. If the neutron probe gave a reading of 1.452 in a soil depth of 40 cm, determine: depth of total available soil water (TAW), depth of depleted available soil water (DAW) and depth of residual available soil water (RAW). Assume that the density of water is 1 g/cm³.

TAW is calculated using equation (6):

$$TAW = [\theta_{w_FC} - \theta_{w_PWP}] \cdot (\rho_b / \rho_w) \cdot Z$$

Substituting values in the above equation we get:

$$TAW = [0.285 - 0.140] \cdot (1.25 / 1.0) \cdot 40 = 7.25 \text{ cm of water}$$

To calculate the depleted and residual available soil water, the soil water content at the time of measurement must be first calculated, using the calibrated equation of the neutron probe:

$$\theta_w = -0.031 + 0.1496 \cdot C.R$$

$$\theta_w = -0.031 + 0.1496 \cdot (1.452)$$

$$\theta_w = 0.186 \text{ g/g}$$

Similarly, DAW is calculated with equation (7):

$$DAW = [\theta_{w_FC} - \theta_{w_actual}] \cdot (\rho_b / \rho_w) \cdot Z$$

By substituting values we obtain:

$$DAW = [0.285 - 0.186] \cdot (1.25 / 1.0) \cdot 40 = 4.95 \text{ cm of water}$$

RAW is calculated using equation (8)

$$RAW = [\theta_{w_actual} - \theta_{w_PWP}] * (\rho_b / \rho_w) * Z$$

Substituting values:

$$RAW = [0.186 - 0.140] * (1.25 / 1.0) * 40 = 2.30 \text{ cm of water}$$

5. Tensiometers

Soil water tension, soil water suction or soil water potential are all terms describing the energy status of soil water. Soil water potential is a measure of the amount of energy with which water is held in the soil. A water release curve shows the relation between soil water content and soil water tension.

Tensiometers have been used for many years to measure soil water tension in the field. Tensiometers are water-filled tubes with a ceramic cup attached at one end and a vacuum gauge (or mercury manometer) airtight seal on the other end. The device is installed in the soil with the ceramic cup in good contact with the surrounding soil at the desired depth (Figure 5). The soil matric potential is measured by the vacuum gauge as water is pulled out of the ceramic cup into the soil by matric forces. As the soil is rewetted, the tension gradient reduces and water flows into the ceramic cup. As the soil goes through wetting and drying cycles, tension readings can be taken.



Fig. 5. Use of tensiometers to determine soil matric potential at different soil depths.

Commercially available tensiometers use a vacuum gauge to read the tension in a scale from 0 to 100 kPa, although the practical operating range is from 0 to 70 kPa, because once air enters the tube, values are no longer accurate. If the water column is intact, a zero reading indicates saturated soil conditions. Readings of about 10 kPa correspond to field capacity for coarse-textured soils, while readings of around 30 kPa can approximate field capacity for fine-textured soils.

Tensiometer readings can be used as indicators of soil water content and the need for irrigation. When instruments installed at the active root zone of a given crop, reach a certain

reading, they can be used to indicate when to start irrigation, based on soil texture and soil type. Similarly, instruments at deeper depths of the root zone may be used to indicate when adequate water has been applied. However, to determine the depth of water to applied, the curve that relates soil water content against soil water potential for the specific soil must be known.

Careful installation and maintenance of tensiometers is required for reliable results. The ceramic cup must be in intimate and complete contact with the soil. A few hours to a few days are required for the tensiometer to come to equilibrium with the surrounding soil. The tensiometer should be pumped with a hand vacuum pump to remove air bubbles. The length of the tensiometers is from 15 to 120 cm. It is recommended that the tensiometers be installed in pairs, one at 1/3 and the other at 2/3 of the crop rooting depth. They should be installed out of the way of traffic and cultivation. In freezing climates, insulate or remove tensiometers during winter months, because it takes only a small frost to knock the vacuum gauges out of calibration.

Tensiometers have been used to estimate water balance (Devitt *et al.*, 1983), follow capillarity rise above the water table (McIntyre, 1982) and characterize unsaturated soil hydraulic conductivity (Ward *et al.*, 1983). More recently, Zermelo-Gonzalez *et al.* (2007) used tensiometers to schedule irrigation in an orchard of lemon. They found that the highest fruit yield can be obtained when irrigation is applied at a reading of 30 kPa of tensiometers installed at a soil depth of 30 cm.

The main advantages of this method are: direct reading of soil water matric potential, inexpensive, automatic for continuous reading, relatively reliable. The main disadvantages are: requires the soil moisture characteristic curve to relate to soil water content, samples a small portion of soil near the cup may take a long time to reach equilibrium with the soil.

Example 2:

Zermelo-González *et al.* (2007) obtained a calibration equation to get soil moisture content as a function soil tension measured with a tensiometer installed at a soil depth of 30 cm. The equation was: $L = 109.30 - 17.29 \cdot \ln(\text{Tens})$, where, L is the soil water content at a depth of 30 cm (mm/30 cm), Tens is the soil water tension (kPa). If the reading of the tensiometer was 40 kPa, determine the depth of water to be applied to take the soil water content to field capacity, assuming that for that soil and crop (an orchard of lemon) a soil water tension of 15 kPa corresponds to field capacity.

The depth of water to be applied to take the soil water content to field capacity can be calculated with the following relation:

$L_{\text{to_FC}} = L_{15\text{kPa}} - L_{\text{actual_kPa}}$ where: $L_{15\text{kPa}}$ is the soil water content at 15 Kpa (mm/30 cm) and $L_{\text{actual_kPa}}$ is the soil water content that corresponds to the actual reading of the tensiometer (mm/30 cm). substituting the calibration equation in this relation we obtain:

$$L_{\text{to_FC}} = [109.30 - 17.29 \cdot \ln(15)] - [109.30 - 17.229 \cdot \ln(40)]$$

$$L_{\text{to_FC}} = [62.478 \text{ mm}] - [45.519 \text{ mm}]$$

$$L_{\text{to_FC}} = 16.959 \text{ mm/30 cm}$$

6. Porous blocks

Porous blocks are made of materials such as gypsum, ceramic, nylon and fiberglass. Similar to tensiometers, the blocks are buried in intimate contact with the soil at some desired depth and allowed to come to water tension equilibrium with the surrounding soil. Once equilibrium is reached, different properties of the block which are affected by water tension may be measured.

One of the more common types of porous blocks are electrical resistance blocks. Electrodes inside the block are used to measure the resistance to electrical current flow between them. In operation, measurements are made by connecting an ohmmeter to the electrodes of the resistance block. The resistance is proportional to the quantity of water in the block, which is a function of soil water tension. Higher resistance readings mean lower block water content and thus higher soil water tension. By contrast, lower resistance readings indicate higher block water content and lower soil water tension. A Useful technique is to calibrate blocks in soil on a pressure plate apparatus. In this way, resistance, water content and soil water potential can be determined simultaneously on each sample.

Resistance blocks work best in soils drier than -0.05 MPa, making the complementary in the range of operation to soil tensiometers. They are typically accurate to soil matric potentials as low as -2.0 to -3.0 MPa. Because response time of resistance blocks is slow, they are not useful for following rapid wetting events. Significant hysteresis effect may also be found between wetting and drying calibrations. Gypsum blocks require little maintenance and can be left in the field under frizzing conditions. Being made of gypsum, the block will slowly dissolve, requiring replacement. The rate of dissolution depends on soil pH and soil water conditions. Gypsum blocks are best suited for use in fine-textured soils. They are not sensitive to changes of soil water tension from 0 to 100 kPa. High soil salinity affects the electrical resistivity of the soil solution, although the gypsum buffers this effect to a certain degree.

Watermark blocks or granular matrix sensor, is a new style of electrical resistance block. The electrodes are embedded in a granular matrix material, similar to compressed fine sand. A gypsum wafer is embedded in the granular matrix near the electrodes. A synthetic porous membrane and a PVC casing with holes hold the block together. The granular matrix material enhances the movements of water to and from the surrounding soil, making the block more responsive to soil water tensions in the range from 0 to 100 kPa. These sensors have good sensitivity to soil water tension in a range of 0 to 200 kPa. This makes them more adaptable to a wide range of soil textures and irrigation regimes than gypsum blocks and tensiometers.

Readings are taken by attaching special electrical resistance meter to the wire leads and setting the estimated soil temperature. The readings of the Watermark meter are kPa of soil water tension, similar to the tensiometers. Watermark blocks require little maintenance and can be left in the soil under frizzing conditions. The blocks are much more stable and have a longer life than gypsum blocks. Soil salinity affects the electrical resistivity of the soil water solution and may cause erroneous readings. The gypsum wafer in the watermark blocks offers some buffering of this effect.

The main advantages of resistance blocks are: they are calibrated for soil water potential, are reliable, inexpensive, can be automated for monitoring. Disadvantages: requires the soil

moisture characteristic curve to relate to water content, must be calibrated individually, and samples a small volume of soil.

Example 3:

At the agricultural experimental station of Universidad Autonoma Agraria Antonio Narro, in Saltillo, Coahuila, Mexico, a Watermark block was calibrated against gravimetric measurements in a clay loam soil. The calibration was performed at a soil depth of 30 cm where the bulk density was 1.206 g cm³. Determine the depth of available soil water between 20 and 100 kPa, for a soil depth of 30 cm.

The calibration equation of the Watermark block was:

$$\theta_w = 0.215 - 0.0005 \cdot \text{Tens}$$

$$R^2 = 0.853$$

Where: θ_w is the gravimetric water content (g/g), Tens is the soil water tension (kPa).

The depth of available soil water (AW) between two gravimetric soil water contents can be calculated with the following equation:

$$AW = [\theta_{w1} - \theta_{w2}] \cdot (\rho_b / \rho_w) \cdot Z \quad (11)$$

where, θ_{w1} is the initial or higher gravimetric soil water content (g/g), θ_{w2} is the final or lower gravimetric soil water content (g/g) the other variables of equation (10) were previously defined. θ_{w1} and θ_{w2} are calculated by substituting 20 and 100 kPa respectively in the calibration equation of the Watermark block

$$\theta_{w1} = 0.215 - 0.0005 \cdot \text{Tens}$$

$$\theta_{w1} = 0.215 - 0.0005 \cdot (20)$$

$$\theta_{w1} = 0.205 \text{ g/g}$$

$$\theta_{w2} = 0.215 - 0.0005 \cdot \text{Tens}$$

$$\theta_{w2} = 0.215 - 0.0005 \cdot (100)$$

$$\theta_{w2} = 0.165 \text{ g/g}$$

Finally, substituting the value of : θ_{w1} and θ_{w2} in equation (10) the depth of available soil water is obtained:

$$AW = [\theta_{w1} - \theta_{w2}] \cdot (\rho_b / \rho_w) \cdot Z$$

$$AW = [0.205 - 0.165] \cdot (1.206 / 1.00) \cdot 30$$

$$AW = 1.447 \text{ cm}; = 14.47 \text{ mm} / 30 \text{ cm}$$

7. Time domain reflectometry

Time-domain reflectometry (TDR) is a method for measuring soil water content, based in the determination of the dielectric permittivity of the porous media at microwave (MHz-

GHz) frequencies. The method uses equipment developed for testing coaxial cables in the telecommunications industry, which consists of a pulse generator, a sampler that produces a low frequency facsimile of high frequency signals, and an oscilloscope that displays the sampler output. Electromagnetic pulses of frequencies in the 1 MHz to 1 GHz region are sent down to a coaxial transmission line that ends in a parallel pair of stainless steel rods embedded in the soil. The unit samples and displays the reflected pulses, which exhibit perturbations at any point in the transmission line where impedance changes occur, as happens at the juncture of the cable with the steel waveguides. The termination of the transmission line at the end of the waveguides is also clearly visible on the oscilloscope since the remaining energy in the pulse is reflected at that point. The distance on the oscilloscope screen between these two points together with the known length of the waveguides allows calculation of the pulse propagation velocity (V_p), relative to the velocity of electromagnetic radiation in a vacuum ($c=3 \times 10^8 \text{ m s}^{-1}$). From this relation the apparent dielectric permittivity (K_a) can be approximated by the equation:

$$K_a = \left(\frac{c}{V_p} \right)^2 \quad (12)$$

The apparent dielectric permittivity of the soil depends on the volume fraction of the soil constituents and their respective dielectric permittivity. K_a of the dry minerals of the soils varies between 2 and 5, the air has a K_a of 1 while the K_a of water is approximately 80. This shows that K_a for the soil is strongly dependent on soil water content. Topp et al. (1980) found that a third order polynomial equation best fit the data between volumetric water content (θ_v) and the apparent dielectric permittivity of the soil (K_a), over the range of water content from air-dry to saturation.

$$\theta_v = -5.3 \times 10^{-2} + 2.92 \times 10^{-2} K_a - 5.5 \times 10^{-4} K_a^2 + 4.3 \times 10^{-6} K_a^3 \quad (13)$$

Equations 12 and 13 show that the apparent dielectric permittivity of the soil is inversely related to the pulse propagation velocity, i.e., faster propagation velocity indicates a lower dielectric permittivity of the soil and thus lower soil water content. Or, as soil water content increases, propagation velocity decreases, and the dielectric permittivity of the soil increases.

Waveguides inserted into the soil consist of a pair of parallel stainless steel rods spaced between 3 and 5 cm apart. They can be installed in the soil horizontally, vertically at an angle of 45° etc. The TDR soil water measurement system measures the average volumetric soil water content along the length of the waveguide. The volume of soil sampled approximates a cylinder surrounding the waveguide with a diameter about 1.5 times the spacing of the parallel rods.

The waveguides may be permanently installed with wire leads brought to the surface, but this requires care to minimize soil disruption. Horizontal installation yields a depth-specific measurement, while insertion at a 45° angle integrates a larger volume of soil horizontally and vertically. Portable hand push waveguide probes can be used to measure at different locations in the upper soil profile which corresponds to the length of the waveguides. Waveguide must be carefully inserted into the soil with full soil contact along the entire length of the rods. Annular air gaps around the rods will affect readings of the low side. The waveguide rods must remain parallel when they are installed in the soil.

Once properly calibrated and installed, the TDR technique is highly accurate. Precise measurements may be made near the surface, which is an important advantage compared to other techniques such as the neutron probe. Research has shown (Evelt *et al.*, 2001; Pedro-Vaz & Hopmans, 2001) that the dielectric permittivity of the soil is nearly independent of soil type and bulk density and relatively unaffected by soil salinity. Soil salinity or bulk electrical conductivity affects the degree of attenuation of electromagnetic pulse in the soil. Other studies (Jacobsen & Schjonning, 1993) found that inclusion of soil bulk density, clay and organic matter content in the calibration equation improves the correlation, suggesting that complex interactions between the soil components affect the electric properties of the soil.

The CS616 TDR probe (Campbell, Sci., Inc, USA) (Figure 6) consists of two stainless steel rods connected to a printed circuit board. A shielded four-conductor cable is connected to the circuit board to supply power, enable the probe, and monitor the pulse output. The circuit board is encapsulated in epoxy. High-speed electronic components on the circuit board are configured as a bistable multivibrator. The output of the multivibrator is connected to the probe rods which act as a waveguide.

The fundamental principle of CS616 operation is that an electromagnetic pulse will propagate along the probe rods at a velocity that is dependent on the dielectric permittivity of the material surrounding the rods. As water content increases, the propagation velocity decreases because polarization of water molecules takes time. The travel time of the applied signal along 2 times the rod length is essentially measured. The applied signal travels the length of the probe rods and is reflected from the rod ends traveling back to the probe head. A part of the circuit detects the reflection and triggers the next pulse. The Water Content Reflectometer output is essentially a square wave with an amplitude of ± 0.7 volts and a period that fluctuates between 16 and 32 μs , which depends on the volumetric water content and is used for the calibration equation. For soil solution electrical conductivity values less than 2 dS m^{-1} The calibration equation is: $\theta_v = -0.0663 - 0.0063 \cdot t + 0.0007 \cdot t^2$, where θ_v is the volumetric soil water content (m^3/m^3) and t is the period of the square wave (μs).



Fig. 6. CS616 TDR probe for measurement of volumetric soil water content.

The main advantages of this method are: measures water content, samples large soil volume therefore decreases interference due to heterogeneity, can be automated for continuous readout, relatively stable over time. The main disadvantages are: Insertion of rods may be difficult, may sample excessively large soil volume, and requires the use of a datalogger.

Example 4:

A CS616 was used to measure the soil water content of the upper 30 cm of the soil profile in a soya bean crop. If the reading of the probe was 28 μs one day-after irrigation, and 25 μs seven days later, determine the crop evapotranspiration if no rain was observed during the TDR readings.

The volumetric water content one day after irrigation was:

$$\theta_{v_1} = -0.0663 - 0.0063 \cdot (28) + 0.0007 \cdot (28)^2$$

$$\theta_{v_1} = 0.306 \text{ m}^3/\text{m}^3$$

and 7 days later:

$$\theta_{v_7} = -0.0663 - 0.0063 \cdot (25) + 0.0007 \cdot (25)^2$$

$$\theta_{v_7} = 0.214 \text{ m}^3/\text{m}^3$$

The crop evapotranspiration (LamET) was the difference in volumetric water content during the seven days multiplied by the soil depth

$$\text{LamET} = (\theta_{v_1} - \theta_{v_7}) \cdot \text{Soil_depth}$$

$$\text{LamET} = (0.306 - 0.214) \cdot 0.30$$

$$\text{lamET} = 0.0276 \text{ m}$$

$$\text{LamET} = 27.6 \text{ mm}$$

The average daily crop evapotranspiration (LamETprom) during the seven days was:

$$\text{LamETprom} = 27.6/7 = 3.943 \text{ mm}$$

8. Impedance and capacitance methods

The Impedance and capacitance as well as the TDR techniques are electromagnetic (EM) sensors, which principle is based in the significant difference in the dielectric permittivity (K_a) between water, air and mineral particles of the soil. Therefore, is possible to establish a good relation between the soil water content ($\text{m}^3 \text{ m}^{-3}$) and K_a , such as the Topp equation (Equation 12), (Topp *et al.*, 1980).

EM sensors determine K_a of an unsaturated porous medium from different physical principles; transit time, impedance, capacitance, etc. For instance, the TDR (Time Domain Reflectometry) and TDT (Time Domain Transmission) techniques estimate K_a from the relationship between this and the transit time (t_s) of an electromagnetic wave travelling

along the rods of length L of a probe inserted into a porous medium, according to the following equation (Campbell, 1990):

$$Ka = \frac{(ts*c)^2}{(2*L)^2} \quad (14)$$

where, c is the speed of light (m/s) in the vacuum.

Impedance sensors determine the amplitude difference in voltage due to changes in impedance, Z (Ω), between the transmission line of the sensor and the rods that are inserted in the porous media, using the equation (Kelleners *et al.*, 2005):

$$\sqrt{ka} = \frac{c*InvCotan(Z(\Omega))}{2*\pi*L} \quad (15)$$

Capacitance methods, consider the composite media soil-probe as a capacitor whose capacitance, C (F), is proportional to Ka , according to the following equation:

$$C(F) = g(m)*Ka*Ko \quad (16)$$

where, $g(m)$ is a geometric factor and $Ko = 8.54$ is the value of permittivity of the vacuum. The relation obtained between Ka or θ and the signal provided by a given EM sensor is known as the calibration equation. In general, the manufacturer of a specific EM sensor provides signal versus θ equations or signal versus Ka , valid for some conditions of media or soil type. However, because the soil is a heterogeneous porous medium of variable composition and since Ka depends on other variables such as the electrical conductivity of the medium or the frequency of the EM wave, It is recommended to perform a recalibration of the manufacturer equation of the sensor, especially when a more accurate determination of the soil water content is required.

Regalado *et al.* (2010) made a recalibration of the manufacturer equation of nine RM sensors. For the EC10 and EC20 capacitance probes of Decagan Devices, Inc, the manufacturer equations were:

$$\theta_v = -0.376 + 9.36*10^{-4} * S \quad (17)$$

and,

$$\theta_v = -0.290 + 6.95*10^{-4} * S \quad (18)$$

The ML2x impedance probe of Delata -T devices Ltd., the manufacturer equation was:

$$Ka^{0.5} = 1.07 + 6.40*10^{-3}*S - 6.40*10^{-6}*S^2 + 4.7*10^{-9}*S^3 \quad (19)$$

where S is the reading signal of the sensor (mv).

After recalibration in a non saline solution of different values of dielectric permittivity (Ka), the new equations for the EC10 and EC20 capacitance probes were:

$$1/Ka = 0.0589/S^2 - 0.0455 \quad (20)$$

$$1/Ka = -0.2581 + 0.0607*S + 0.2331/S \quad (21)$$

And for the impedance probe was:

$$1/Ka = 0.134/S^{0.5} - 0.105 \quad (22)$$

They also concluded that after recalibration, all sensors behaved correctly under conditions equivalent to those of a non saline soil with sandy texture. Since the sensors studied performed acceptable for the entire range of water content, its suitability for a particular application should be decided according to other specific criteria such as volume of soil explored, robust probes, possibility of automation of the readings, cost, etc.

9. Conclusions

Understanding the soil water holding capacity and the factors affecting the plant available soil water are necessary for good Irrigation management. Adequate soil moisture is critical to plant growth. Too little water, or water applied at the wrong time, causes stress and reduces growth and too much may result in surface runoff, erosion and leaching of nutrients and pesticides.

Different techniques are currently available to directly measure or determine soil water content in a discrete or continuous manner. Some are very simple and others are more complex techniques. The cost of keeping track of soil water content is paid back through the benefits of effective water management, such as energy savings, water savings, water quality improvement, and improvement in quality and yield of harvest.

Successful implementation of any of the methods requires careful attention during the installation, operation, and maintenance of the equipment and sensors. Soil type, soil salinity and irrigation regime are important parameters that must be considered to choose a particular method or technique to get the best results. A routine sampling schedule should be implemented to obtain the most information from any of these methods. The difference in soil water content at a given location from one sampling time to the next often provides more information than random space and time measurements. Soil water should be measured or monitored in at least two depths in the active crop root zone at several locations in a field to obtain a field average.

There have been many advances in electromagnetic (EM) sensor technology (time domain reflectometry (TDR, impedance and capacitance-based approach) which have resulted in sensors that are more robust, less expensive, more suitable for different soil types that can be connected to advanced data loggers for a continuous monitoring of soil water content. Real-time, continuous measurement of soil moisture in the plant rooting zone is very important for determining crop evapotranspiration and the amount of water to apply.

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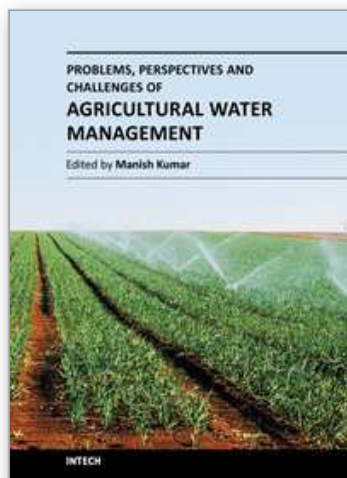
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Food security emerged as an issue in the first decade of the 21st Century, questioning the sustainability of the human race, which is inevitably related directly to the agricultural water management that has multifaceted dimensions and requires interdisciplinary expertise in order to be dealt with. The purpose of this book is to bring together and integrate the subject matter that deals with the equity, profitability and irrigation water pricing; modelling, monitoring and assessment techniques; sustainable irrigation development and management, and strategies for irrigation water supply and conservation in a single text. The book is divided into four sections and is intended to be a comprehensive reference for students, professionals and researchers working on various aspects of agricultural water management. The book seeks its impact from the diverse nature of content revealing situations from different continents (Australia, USA, Asia, Europe and Africa). Various case studies have been discussed in the chapters to present a general scenario of the problem, perspective and challenges of irrigation water use.

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