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Field Devices for Monitoring Soil Water Content

by

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ACKNOWLEDGEMENTS

This guide was adapted from “Field Devices for Monitoring Soil Water Content” by Rafael Muñoz-Carpena, Univ. of Florida, Bulletin 343. This material is based upon work supported in part by the Cooperative State Research, Education, and Extension Service, U.S. Department of Agriculture under Agreement No. 2004-51130-03114. The U.S. Department of Agriculture prohibits discrimination in all its programs and activities on the basis of race, color, national origin, sex, religion, age, disability, political beliefs, sexual orientation, and marital or family status. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the authors and do not necessarily reflect the view of the U.S. Department of Agriculture.

1. INTRODUCTION

In the context of irrigation water management, measuring and monitoring soil water status is an essential component of best management practices (BMPs) to conserve water and improve water quality. Water content in the soil can be directly determined using the difference in weight before and after drying a soil sample, usually referred to as the gravimetric method. This method expresses gravimetric water content (GWC, g g^{-1}) as weight of water over weight of dry soil, i.e. the ratio of the mass of water present in a sample to the mass of the soil sample after it has been oven-dried at 100-110 C to a constant weight. The *thermo-volumetric method* (or simply *volumetric*) gives volumetric water content (VWC, %) as the volume of water held within a volume of oven-dried undisturbed sample (soil core). Although these direct methods are accurate (±1%) and inexpensive, they are destructive, time and labor-intensive, take time to accomplish (2 days minimum), and do not allow for replication in the same location. Alternatively, many indirect methods are available to monitor soil water content. These methods estimate soil moisture by a calibrated relationship with some other measured variable. The suitability of each method depends on cost, accuracy, response time, installation, intended use, management, and durability.

Depending on the quantity measured, indirect techniques are classified into *volumetric* or *tensiometric* methods (Fig. 1). While the former gives volumetric soil moisture, the latter yields soil suction or water potential (i.e. tension exerted by capillarity). Both quantities are related through the soil water characteristic curve specific for a given soil.

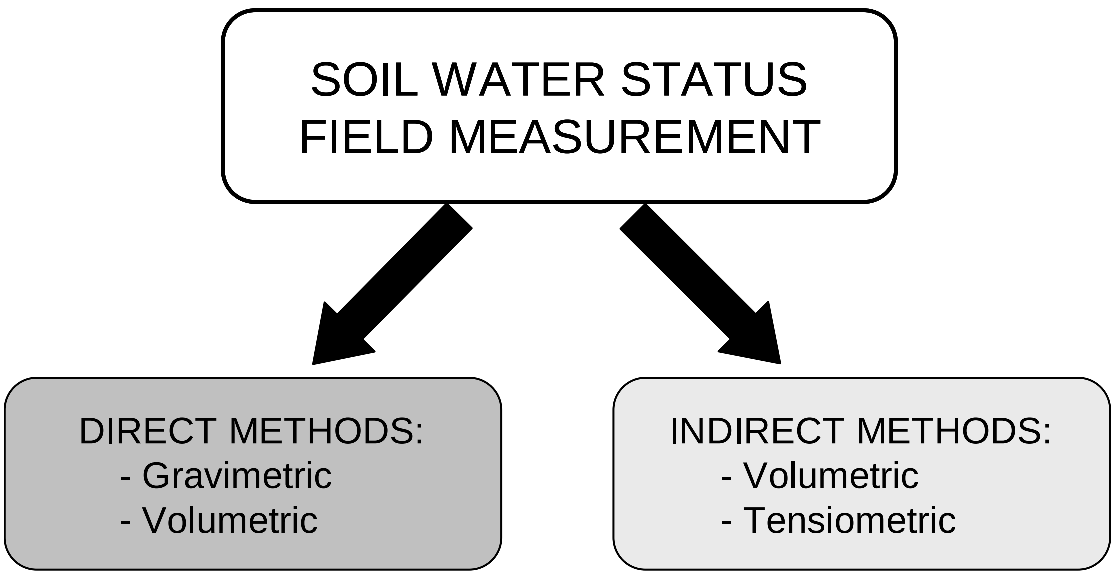


Figure 1. Methods to measure soil moisture.

It is important to remember that every soil has a different curve based on texture, structure, and organic matter content. Therefore, soil curves cannot be related to each other the same way for all soil types (Fig. 2). In addition, this relationship might not be unique and may differ along drying and wetting cycles, especially in finer-textured soils. Several mathematical equations have been proposed to describe the soil characteristic curve that can help to calculate water needed for irrigation.

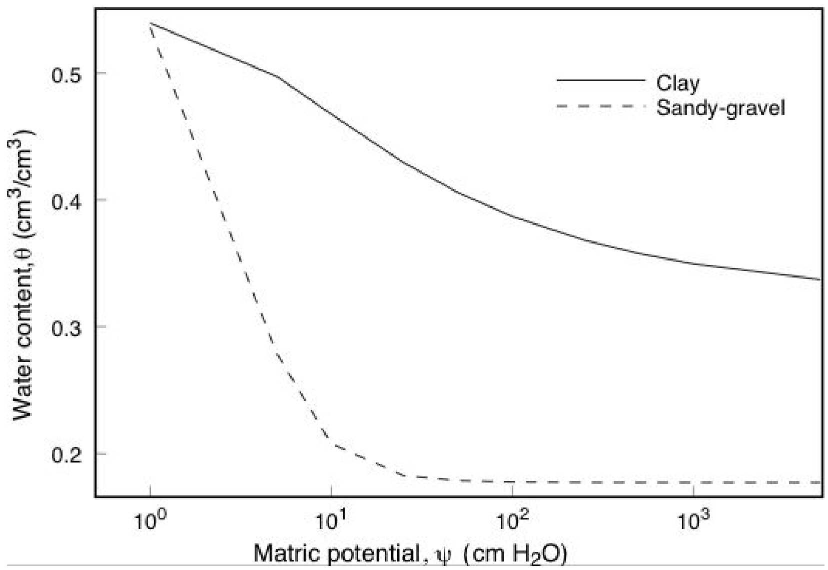


Figure 2. Soil characteristic curves for fine- and coarse-textured soils.

Depending on soil physical properties and the goal of the soil moisture measurement, some devices are more effective than others. First, although volumetric moisture is a more intuitive quantity, water is strongly retained by soil particles in fine-textured soils. Therefore, even if soil volumetric water content is relatively high, the water may not be available to plants. For plant-soil studies, soil suction may be a more useful measurement since it is a measure of the energy plants must invest to extract water from the soil, hence it is a more meaningful measure of plant water stress. Second, the desired sampling frequency is an important factor since response times of different sensors vary over a wide range (i.e. some devices require soil moisture to equilibrate with the sensor matrix). Third, soil physical properties (texture, shrinking/swelling) may influence the suitability of the selected method because some of the sensors require good soil-instrument contact. Furthermore, depending on soil type, precipitation, and evapotranspiration, some instruments might have higher maintenance requirements than others.

Managing irrigation based on soil moisture monitoring is common in agricultural production. Soil moisture monitoring optimizes irrigation by helping an irrigation manager keep soil water content within a target range. This practice reduces the potential for excess soil water and leaching of agrichemicals, but it requires selection of a suitable method for soil moisture estimation (Muñoz-Carpena et al., 2002; 2003). To calculate irrigation volume, suction values from tensiometric methods must be converted to soil moisture through the soil characteristic curve.

2. FIELD METHODS FOR SOIL MOISTURE MEASUREMENT

Most practical techniques for soil water monitoring are indirect (Yoder et al., 1998; Robinson et al., 1999). A review of available techniques is given below, focusing on working principles, advantages and drawbacks.

2.1 Volumetric Field Methods

All methods under this definition estimate the volume of water in a sample volume of undisturbed soil [ft^3 ft^{-3}]. This quantity is useful for determining how saturated the soil is (i.e. the fraction of total soil volume filled with soil solution). When it is expressed in terms of depth [e.g. volume of water in soil down to a given depth over a unit surface area (inches of water)], it can be compared with other hydrological variables like precipitation, evaporation, transpiration, and drainage.

2.1.1. Neutron Moderation

Working principle: Fast neutrons are emitted from a decaying radioactive source ($^{241}Am/^{9}Be$). When they collide with particles with the same mass as a neutron (i.e. protons, H^+), they slow down dramatically, building a "cloud" of "thermalized" (slowed) neutrons. Since water is the main source of hydrogen in most soils, the density of slowed neutrons formed around the probe is proportional to the volume fraction of water present in the soil.

Description: The probe configuration is a long and narrow cylinder containing a source and a detector. Measurements are made by inserting the probe into an access tube that is installed in the soil. The soil moisture can be determined at various depths by placing the probe at different depths in the tube (Fig. 3). Soil water content is obtained from a linear calibration between the count rate of slowed neutrons read by the probe in the field and the soil moisture content obtained from nearby field samples.

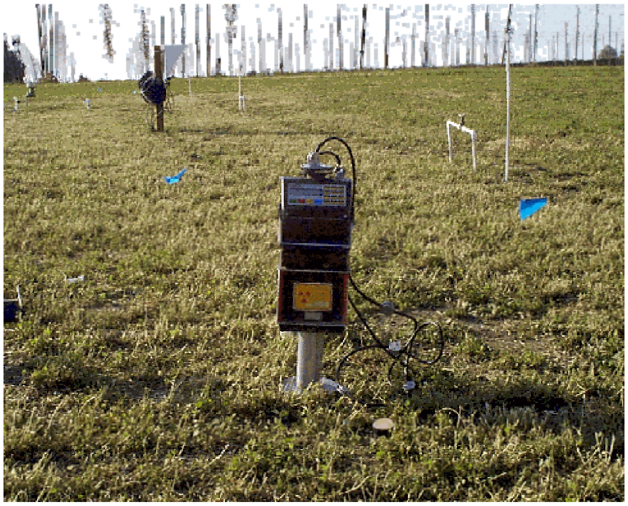


Figure 3. Neutron probe mounted on an access tube.

Advantages

- Robust and accurate (±0.5%).
- Inexpensive per location (i.e. a large number of measurements can be made at different points with the same instrument).
- One probe can measure many different soil depths.
- Large soil sensing volume (sphere of influence with 4 - 16 in. radius, depending on moisture content).
- Not affected by salinity or air gaps.
- Stable soil-specific calibration.

Drawbacks

- Safety hazard, since a radioactive source is involved. (Even at 16 in. depth, radiation losses through soil surface have been detected.)
- Requires certification to use it.
- Requires soil-specific calibration.
- Heavy, cumbersome instrument.
- Takes a relatively long time for each reading.
- Readings close to the soil surface are difficult and inaccurate.
- Manual readings only; cannot be automated due to safety hazard.
- Expensive.
- Sphere of influence may vary for the following reasons:
    a) It increases as the soil dries due to fewer hydrogen atoms. The probability of collision is smaller, so fast neutrons travel further from the source.
    b) It is smaller in fine-textured soils. Since these soils hold more water, the probability of collision closer to the source is higher.
    c) If there are layers with large differences in water content due to changes in soil physical properties, the sphere of influence can have a distorted shape.
- Soils high in organic matter require specific attention and specialized calibration because organic compounds contain significant hydrogen.

2.1.2. Dielectric Methods

The next set of volumetric methods are *dielectric techniques*. They estimate soil water content by measuring the soil bulk permittivity (or dielectric constant), Ka_b, which determines the velocity of an electromagnetic wave or pulse through the soil. In a composite material like the soil that is made of minerals, air and water, permittivity is determined by the relative contribution of each of the components. Since the dielectric constant of liquid water (Ka_w = 81) is much larger than that of the other soil constituents (e.g. Ka_s = 2 - 5 for soil minerals and 1 for air), the total soil or bulk permittivity is governed primarily by the presence of liquid water.

A common approach to establish the relationship between Ka_b and soil VWC is the empirical equation of Topp et al. (1980):

$$VWC = -5.3 \times 10^{-2} + 2.29 \times 10^{-2} Ka_b - 5.5 \times 10^{-4} Ka_b^2 + 4.3 \times 10^{-6} Ka_b^3 \qquad (1)$$

This relationship applies to most mineral soils (independent of composition and texture) and for water volume below 50%. For larger water content, organic soils, or volcanic soils, a specific calibration is required. The above relationship depends on the electromagnetic wave frequency sent by the specific monitoring device. At low frequencies (<100 MHz), it is more soil-specific.

The dielectric methods described below use empirically-calibrated relationships between VWC and the sensor output signal (time, frequency, impedance, wave phase). These techniques are becoming widely adopted because measurements are almost instantaneous, the instruments require minimal maintenance, and they can provide continuous readings through automation.

2.1.2.1. Time Domain Reflectometry (TDR)

Working principle: The soil bulk dielectric constant (Ka_b) is determined by measuring the time it takes for an electromagnetic pulse (wave) to propagate along a transmission line (TL) that is surrounded by the soil. Since the propagation velocity (v) is a function of Ka_b, the latter is proportional to the square of the transit time (t, in seconds) out and back along the TL:

$$Ka_b = (c/v)^2 = [(c \times t)/(2 \times L)]^2 \qquad (2)$$

where c is the velocity of electromagnetic waves in a vacuum (3×10^8 m/s or 186,282 mile/s) and L is the length of the TL embedded in the soil (in m or ft).

Description: A TDR instrument (Fig. 4) requires a device that produces a series of precisely timed electrical pulses across a wide range of high frequencies (e.g. 0.02 - 3 GHz), which travel along a TL comprised of a coaxial cable and a probe. This high frequency provides a response that is less dependent on soil specific properties like texture, salinity or temperature. The TDR probe usually consists of 2 - 3 parallel metal rods that are inserted into the soil and act as waveguides in a similar way as an antenna is used for television reception. At the same time, the TDR instrument uses a device to measure and digitize the energy (voltage) of the TL at intervals down to around 100 picoseconds. When the electromagnetic pulse traveling along the TL finds a discontinuity (e.g. probe-waveguides surrounded by soil), part of the pulse is reflected, producing a change in the energy level of the TL. The travel time (t) is determined by analyzing the digitized energy levels.

Figure 4. Time domain reflectometry (TDR) equipment showing probe versions and readouts.

Soil salinity and/or highly conductive heavy clay soils may affect TDR measurements, since each contributes to attenuation of the reflected pulses. In other words, TDR is relatively insensitive to salinity as long as a useful pulse is reflected (i.e. as long as it can be analyzed). In highly saline soils, using epoxy-coated probe rods may solve the problem. However, this implies loss of sensitivity and change in calibration. In addition to time of travel, other characteristics of the pulse traveling through the soil (e.g. change in size or attenuation) can also be related to soil electrical conductivity. Pulse attenuation has been used in some commercial devices to measure water content and soil electrical conductivity simultaneously.

Advantages

- Accurate (±1%).
- Soil specific-calibration is usually not required.

- Easily expanded by multiplexing.
- Wide variety of probe configurations (various sensing depths).
- Minimal soil disturbance.
- Relatively insensitive to normal soil salinity.
- Can provide simultaneous measurements of soil electrical conductivity.

Drawbacks

- Relatively expensive equipment due to complex electronics.
- Potentially limited applicability under highly saline conditions or in highly conductive heavy clay soils.
- Soil-specific calibration required for soils having large amounts of bound water (e.g. those with high organic matter content, volcanic soils, etc.)
- Relatively small sensing volume (about 1.2 inch radius around length of waveguides).

2.1.2.2. Frequency Domain (FD): Capacitance and FDR

Working principle: The electrical capacitance of a capacitor that uses the soil as a dielectric depends on soil water content. When this capacitor (made of metal plates or rods imbedded in the soil or in access tubes) is connected to an oscillator to form an electrical circuit, changes in soil moisture can be detected by changes in the circuit operating frequency. These changes form the basis of the Frequency Domain (FD) technique used in Capacitance and Frequency Domain Reflectometry (FDR) sensors. In capacitance sensors, a medium's dielectric permittivity is determined by measuring the charge time of a capacitor made with that medium. In FDR, the oscillator frequency is controlled within a certain range to determine the resonant frequency (at which the amplitude is greatest), which is a measure of water content in the soil.

Description: Probes usually consist of two or more electrodes (e.g. plates, rods, or metal rings around a cylinder) that are inserted into the soil. With the ring configuration, the probe is introduced into an access tube installed in the field. When an electrical field is applied, the soil around the electrodes (or around the tube) forms the dielectric of the capacitor to complete the oscillating circuit. In some cases, an access tube is used to allow multiple sensors to measure soil moisture at different depths (Fig. 5).

A soil-specific calibration is recommended because the operating frequency of these devices is generally below 100 MHz. At these low frequencies the bulk permittivity of soil minerals may change and the estimation is more affected by temperature, salinity, bulk density and clay content.

Advantages

- Accurate after soil-specific calibration (±1%)
- Can be used with high soil salinity where TDR fails.
- Better resolution than TDR (avoids the noise that is implied in the waveform analysis performed by TDRs).
- Can be connected to conventional dataloggers (DC output signal).
- More flexibility in probe design (measurements can be made at different depths at the same location compared with TDR that usually measures at a specific depth).

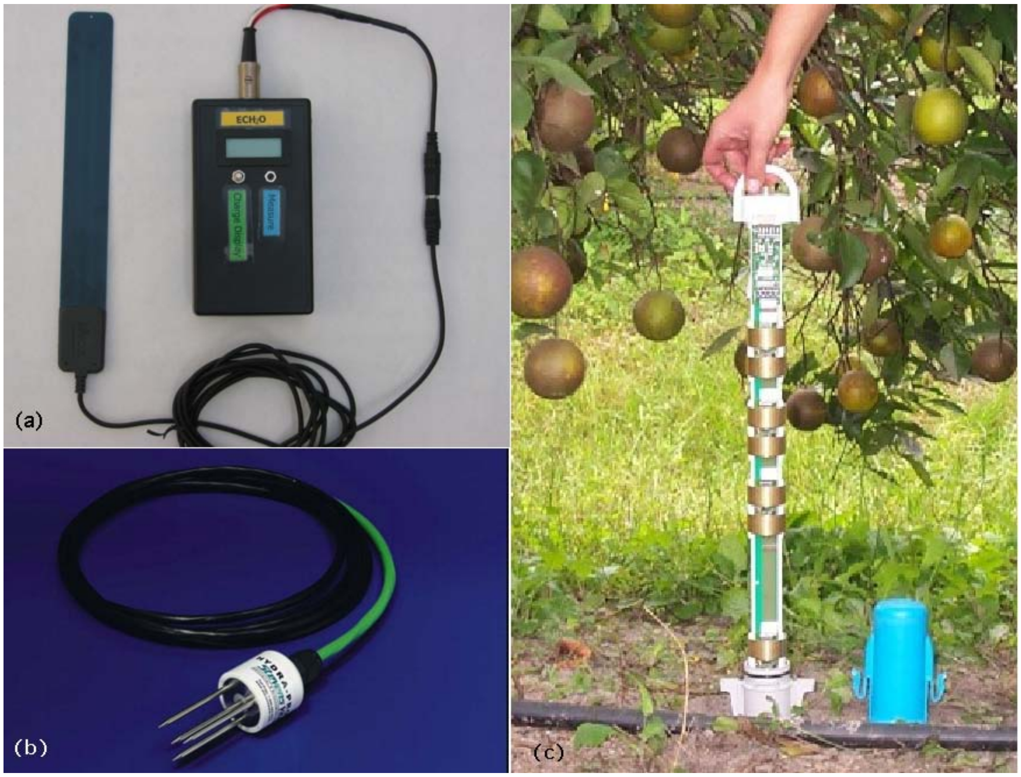


Figure 5. Frequency domain (FD) probes: a) capacitance (plates embedded in a silicon board); b) capacitance (rods); and c) FDR (rings).

- Some devices are relatively inexpensive compared with TDR due to use of low frequency standard circuitry.

Drawbacks

- The sensing sphere of influence is relatively small (about 1.6 in.).
- For reliable measurements, it is critical to have good contact between the sensor (or access tube) and soil. Careful installation is necessary to avoid air gaps.
- Tends to have larger sensitivity to temperature, bulk density, clay content and air gaps than TDR.
- Needs soil-specific calibration.

2.1.2.3. Amplitude Domain Reflectometry (ADR): Impedance

Working principle: When an electromagnetic wave (energy) traveling along a transmission line (TL) reaches a section with different impedance (that has two components: electrical conductivity and dielectric constant), part of the energy transmitted is reflected back to the transmitter. The reflected wave interacts with the incident wave producing a voltage standing wave along the TL, i.e. change of wave amplitude along the length of the TL. If the soil/probe combination causes the impedance change in the TL, measuring the amplitude difference will give the impedance of the probe (Gaskin and Miller, 1996; Nakashima et al., 1998). The influence of soil electrical conductivity is minimized by choosing a signal frequency so the soil water content can be estimated from the soil/probe impedance.

Description: Impedance sensors use an oscillator to generate a sinusoidal signal (electromagnetic wave at a fixed frequency, e.g. 100 MHz) that is applied to a coaxial TL. The TL extends into the soil through an array of parallel metal rods, the outer of which forms an electrical shield around the central signal rod (Fig. 6). This rod arrangement acts as an additional section of the TL, having impedance that depends on the dielectric constant of the soil between the rods.

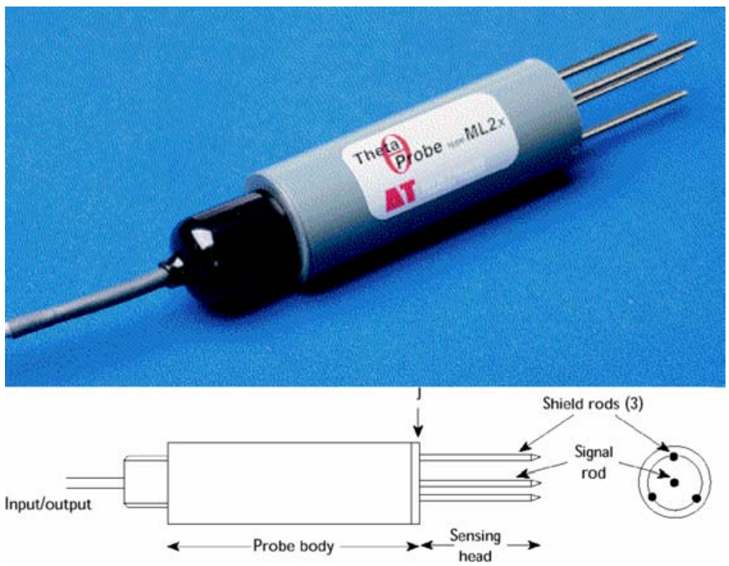


Figure 6. Amplitude domain reflectometry (ADR) probe.

Advantages

- Accurate to within ±1% with soil specific calibration and ±5% without calibrating.
- Allows measurements in saline conditions up to 20 dS/m.
- Minimal soil disturbance.
- Can be connected to conventional dataloggers (DC output signal).
- Inexpensive due to standard circuitry.
- Not affected by temperature.
- In-situ estimation of soil bulk density possible (Wijaya et al., 2002).

Drawbacks

- Soil-specific calibration recommended for reliable measurements.
- Measurement affected by air gaps, stones or channeling water directly onto the probe rods.
- Small sensing volume (0.27 in^3).

2.1.2.4. Phase Transmission

Working principle: After traveling a fixed distance, a sinusoidal wave shows a phase shift relative to the phase at the origin. This phase shift depends on the length of travel along the TL, the frequency, and the velocity of propagation. Since propagation velocity is related to soil moisture content, soil water content can be determined by the phase shift for a given frequency and length of travel.

Description: The probe uses a particular waveguide design (two open concentric metal rings) so that phase measuring electronics can be applied at the beginning and end of the waveguides (Fig. 7).

Figure 7. Phase transmission probe and sensor.

Advantages

- Accurate with soil-specific calibration (±1%).
- Large sensing soil volume (4 - 5 ft^3).
- Can be connected to conventional dataloggers (DC output signal).
- Inexpensive.

Drawbacks

- Considerable soil disturbance during installation due to concentric rings sensor configuration.
- Requires soil-specific calibration.
- Sensitive to salinity levels >3 dS/m.
- Reduced precision due to distortion of pulse during transmission.
- Needs to be permanently installed in the field.

2.1.2.5. Time Domain Transmission (TDT)

Working principle: This method measures the time for an electromagnetic pulse to propagate one-way along a transmission line (TL). Thus, it is similar to TDR but requires an electrical connection at the beginning and end of the TL. Notwithstanding, the circuit is simple compared with TDR instruments.

Description: The probe has a waveguide design (bent metal rods) so that the beginning and end of the transmission line are inserted into the electronic block. Alternatively, the sensor consists of a long band (~3 ft) with an electronic block at both ends (Fig. 8).

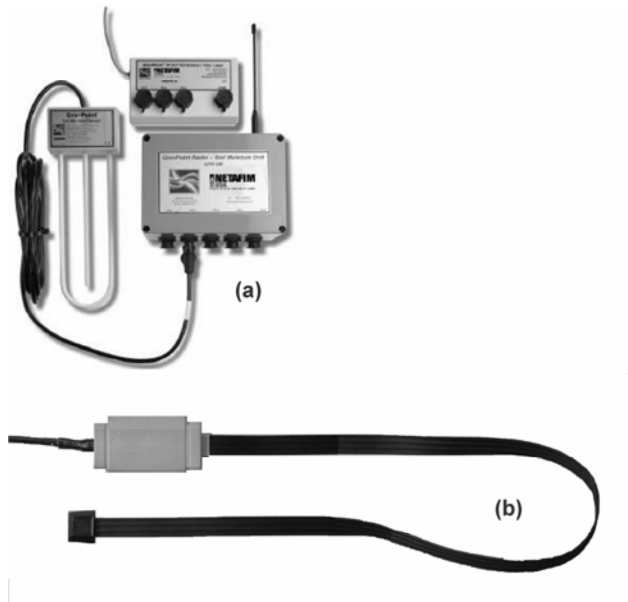


Figure 8. Time domain transmission (TDT) probe.

Advantages

- Accurate (±1 – 2%).
- Large sensing soil volume (0.02 - 0.25 ft^3).
- Can be connected to conventional dataloggers (DC output signal).
- Inexpensive due to standard circuitry.

Drawbacks

- Reduced precision due to distortion of the generated pulse during transmission.
- Soil disturbance during installation.
- Needs to be permanently installed in the field.

2.1.2. Other Volumetric Field Methods

Another interesting technique is Ground Penetrating Radar (GPR). It is based on the same principle as TDR, but does not require direct contact between the sensor and the soil. When mounted on a vehicle or trolley close to the soil surface, it has the potential to provide rapid, non-disturbing soil moisture measurements across relatively large areas, whereas TDR is better for detailed measurements in small areas. Although it has been applied successfully to many field situations, GPR has not been widely used because the methodology and instrumentation are still in the research and development phase (Davis and Annan, 2002). It is likely that small, compact and inexpensive GPR systems will be available in the near future for routine field studies.

New remote sensing (non-contact) methods specially suited to monitor soil moisture across large areas are usually mounted on airplanes or satellites. Among these methods are active and passive microwave and electromagnetic induction (EMI) methods that have been found useful for different applications (Dane and Topp, 2002), and are the subject of current research. The active and EMI methods use two antennae to transmit and receive electromagnetic signals that are reflected by the soil, whereas the passive microwave just receives signals naturally emitted by the soil surface. With microwave methods, typically the signal relates to some shallow depth (< 4 in) below the ground surface so that only a measure of the soil moisture and electrical conductivity of the near-surface soil can be achieved. EMI does not measure water content directly, but rather soil electrical conductivity, and a known calibration relationship between the two is required. Unfortunately, this relationship is site-specific and cannot be assumed.

Other modern techniques to estimate soil moisture and flow are x-ray tomography and nuclear magnetic resonance (NMR). However, their application to field conditions is limited. The reader is referred to other publications for further details (see, e.g., Alvarez-Benedi and Muñoz-Carpena, 2004).

2.2. Tensiometric Field Methods

Tensiometric methods estimate the soil water matric potential, which includes both adsorption and capillary effects of the soil. The matric potential is one component of the total soil water potential that also includes gravitational (position with respect to a reference elevation), osmotic (salts in soil solution), and gas pressure (from entrapped air). The sum of matric and gravitational potentials is the main driving force for soil water movement.

All tensiometric instruments have some type of porous material in contact with the soil through which water can move. In a dry soil, water is drawn out of the porous material, while in a wet soil water moves from the soil into the material. In general, tensiometers do not need a soil specific calibration, but before reading sufficient time must be allowed after field installation so the device and the soil can equilibrate (e.g. overnight).

2.2.1. Tensiometer

Working principle: A sealed, water-filled tube is placed in contact with the soil through a permeable and saturated porous material, and the water inside the tube comes into equilibrium with the soil solution (i.e. it is at the same pressure potential as the water held in the soil matrix). Hence, the soil water matric potential equals the vacuum or suction created inside the tube.

Description: Tensiometers consist of a sealed water-filled plastic tube with a ceramic cup at one end and a negative pressure gauge (vacuometer) at the other. The shape and size of the ceramic cup can be variable and the accuracy depends on the gauge or transducer used (about 1 centibar). Typically the measurement range is 0 - 80 centibars, although there are low-tension versions (0 - 40 centibars) designed for coarse-textured soils (Fig. 9).

Advantages

- Easy to read the manual gauge.
- Up to 4-in. measurement sphere radius.
- Continuous readings possible when using pressure transducer.
- Most models use no electronics, so they do not require a power supply.

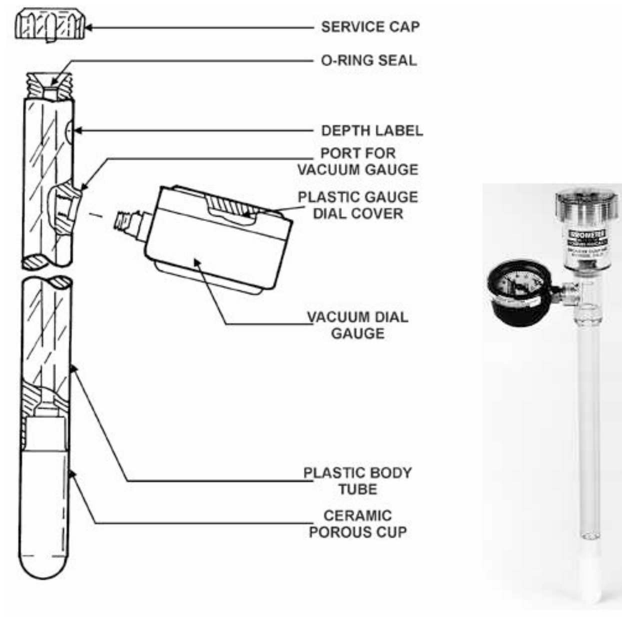


Figure 9. Example of a tensiometer.

- Well-suited for high frequency sampling or irrigation scheduling.
- Minimal skill required for maintenance.
- Not affected by soil salinity, because salts can move freely in and out across the porous ceramic cup.
- Inexpensive.

Drawbacks

- Limited soil suction range (<100 centibars).
- Relatively slow response time.
- Requires intimate contact with soil around the ceramic cup for consistent readings and to avoid frequent discharge (breaking of water column inside).
- Especially in swelling or coarse soils, the ceramic cup can lose contact with soil, thus requiring reinstallation.
- Requires frequent maintenance (refilling) to keep the tube full of water, especially during hot, dry weather.

2.2.2. Resistance Blocks

Working principle: Electrical resistance between electrodes embedded in a porous medium (block) is proportional to its water content, which is related to the soil water matric potential of the surrounding soil. Electrical resistance decreases as the soil and the block lose water.

2.2.2.1. Gypsum (Bouyoucos) Block

Description: A gypsum block sensor is comprised of an electrochemical cell with a saturated solution of calcium sulfate as the electrolyte. The resistance between the block-embedded electrodes is determined by applying a small AC voltage (to prevent block polarization) using a bridge circuit. Since changes in the soil electrical conductivity would affect readings, gypsum is used as a buffer against soil salinity changes (up to a certain concentration). An inherent problem is that the block dissolves and degrades with time (especially in saline soils), and loses its calibration. The block pore size distribution should match the soil texture at the installation site. Readings are temperature-dependent (up to 3% change/°C), so field-measured resistance should be corrected for differences between calibration and field temperatures. Some readers contain manual or self-compensating features for temperature, or the manufacture may provide correction charts or equations. Measurement range is 30 centibars to 15 bars (Fig. 10).

Figure 10. Gypsum (Bouyoucos) resistance block and reader.

Advantages

- Up to 4-in. measurement cylinder radius.
- Minimal maintenance needed.
- Simple and inexpensive.
- Salinity effects buffered up to 6 dS/m.
- Well suited for irrigation where only "full" and "refill" points are required.
- Suited to deficit irrigation.

Drawbacks

- Low resolution, limited use in research.
- Block cannot be used for measurements around saturation (0 – 30 centibars).
- Block properties change with time due to clay deposition and gypsum dissolution. Degradation speed depends on soil type, amount of rainfall and irrigation, and type of gypsum block used.
- Very slow reaction time. Does not work well in sandy soils, where water drains more quickly than the instrument can equilibrate.

- Not suitable for swelling soils.
- Inaccurate readings due to block hysteresis (i.e., at a fixed soil water potential, the sensor can display different resistance when wetting compared with drying).
- Temperature dependent. If connecting to a datalogging system, another variable and sensor for temperature must be added to the system.

2.2.2.2. Granular Matrix Sensors (GMS)

Description: The sensor consists of electrodes embedded in a granular quartz material, surrounded by a synthetic membrane and a protective stainless steel mesh. Inside, gypsum is used to buffer against salinity effects. This kind of porous medium allows measurements in wetter soils and lasts longer than gypsum blocks. However, even with good sensor-soil contact, GM sensors have rewetting problems after they have become very dry because the ability of water films to re-enter the coarse medium from a fine soil is reduced. The GMS material allows soil moisture measurements close to saturation. Measurement range is 10 – 200 centibars (Fig. 11).

Figure 11. Granular matrix sensor (GMS) resistance block and reader.

Advantages

- Reduces problems inherent with gypsum blocks (e.g. loss of contact with the soil due to dissolution and inconsistent pore size distribution).
- Up to 4-in. measurement cylinder radius.
- Minimal maintenance needed.
- Simple and inexpensive.
- Salinity effects buffered up to 6 dS/m.
- Suited to deficit irrigation.

Drawbacks

- Low resolution, limited use in research.
- Slow reaction time. Does not work well in sandy soils where water drains more quickly than the instrument can equilibrate.
- Not suitable for swelling soils.
- If the soil becomes too dry, the sensor must be removed, re-saturated, and re-installed.
- Temperature dependent. If connected to a datalogger, another variable and sensor for temperature must be added to the system.

2.2.3. Heat Dissipation

Working principle: The thermal conductivity of water produces heat dissipation, so a dry material will heat faster than a wet one. In other words, the heat flow in a porous material is proportional to its water content.

Description: A thermal heat probe consists of a porous block containing a heat source and an accurate temperature sensor. The block temperature is measured before and after the heater is powered for a few seconds. Thereby, block moisture is obtained from the temperature variation. Since the porous block in contact with the soil is equilibrated with the soil water, its characteristic curve will yield the soil water potential. Hence, the sensor must be provided with a calibrated relationship between the measured change in temperature and the soil water potential. The measurement range is 10 - 3000 centibars (less accurate for 1000 - 3000 centibar range) (Fig. 12).

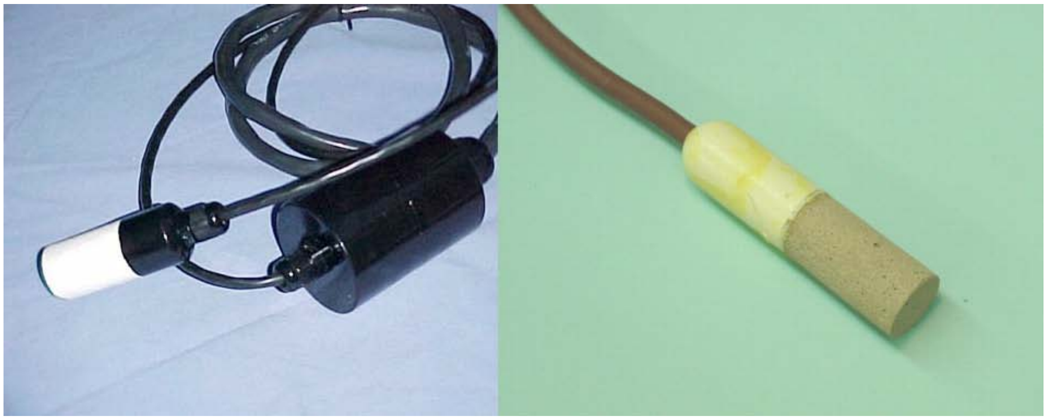


Figure 12. Heat dissipation sensor.

Advantages

- Wide measurement range.
- No maintenance required.
- Up to 4-in. measurement cylinder radius.
- Continuous reading possible.
- Not affected by salinity because measurements are based on thermal conductivity.

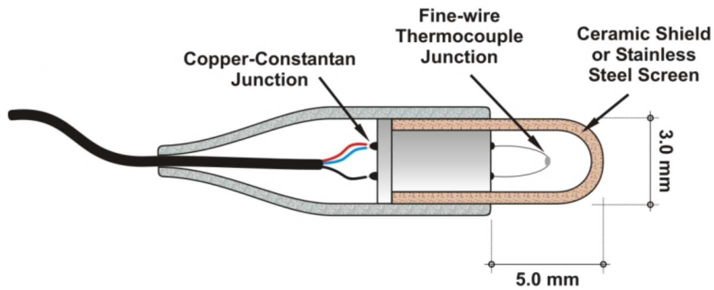
Drawbacks

- Needs a sophisticated controller/logger to control heating and measurement operations.
- Slow reaction time. Does not work well in sandy soils where water drains more quickly than the instrument can equilibrate.
- Fairly large power consumption if read frequently.

2.2.4. Soil Psychrometer

Working principle: Under vapor equilibrium conditions, water potential of a porous material is directly related to the vapor pressure of the air surrounding the porous medium, meaning that soil water potential can be determined by measuring the relative humidity (RH) of a chamber inside a porous cup equilibrated with the soil solution (Campbell and Gardner, 1971).

Description: A soil psychrometer consists of a ceramic shield or screen that forms an air chamber where a thermocouple is located. The screen type is recommended for high salinity environments. RH in the air chamber is calculated from the "wet bulb" vs "dry bulb" temperature difference. Measurement range is 50 - 3000 centibars (less accurate for 1000 - 3000 centibar range) (Fig. 13).



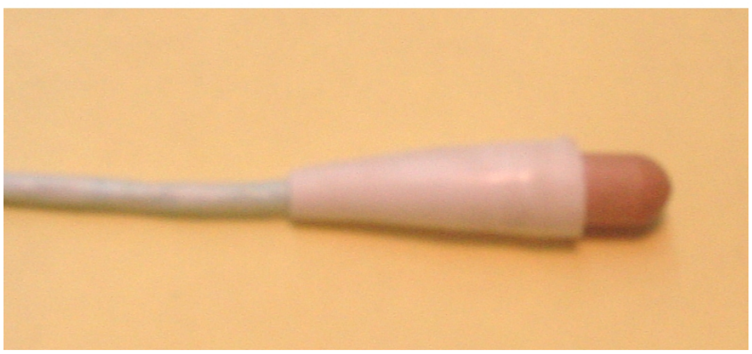


Figure 13. Soil psychrometer.

Advantages

- High sensitivity.
- Scientifically rigorous readings (except in wetter soils).
- Suitable where typical moisture conditions are very dry.

Drawbacks

- Not recommended at shallow soil depths due to high susceptibility to thermal gradient.
- Small sensing volume.
- Very slow reaction time, because it takes time to reach vapor equilibrium.
- Low accuracy in the wet range.
- Specialized equipment is required for sensor excitation and reading.

3. RECOMMENDATIONS AND OUTLOOK

There is a wide range of available methods to measure and monitor soil water content. Often, selecting a technique is not simple because all methods present advantages and disadvantages that can be important for the particular situation. The selection of a suitable method should take into consideration several issues:

- Soil properties (texture, organic matter content, swelling, heterogeneity).
- Application (irrigation scheduling, monitoring, research).
- Plant type (if present).
- Accuracy, depths, and moisture ranges needed.
- Cost (capital and annual cost).
- Skill level required for operation.
- Maintenance.

Tables 1 and 2 display a comparison of the methods presented to provide the reader with a quick reference.

Charlesworth (2000) presents a value selection method suggested by Cape (1997) to decide which soil moisture measuring technique is most applicable to a particular situation. This procedure consists of answering a number of questions (Yes = 1, No = 0) (Table 3). The relative importance of each question is quantified with appropriate weights, and a total relative importance (T) of each sensor for a specific application is obtained by adding the individual scores from all questions and multiplying it by the score for the "effective range of measurement" criterion. This multiplication factor (0 or 1) is a modification of the original method proposed here. It implies that no sensor will be valid for an application if the field measuring range does not match sensor specifications. The total estimated life cost of the sensor (Cost) is estimated from capital, installation, operation, and maintenance costs for the expected life of the sensor (L). The annual cost (A) of the sensor is obtained by dividing Cost by L (A = Cost/L). The final sensor value for the application (V) is obtained by dividing T by A (T/A).

The device with the highest V is more suited to the needs and budget considered. An illustration example is included in Table 3 where the neutron probe is compared with an FDR sensor. Both alternatives include measuring moisture at one point with ten depths. The FDR equipment includes a logger and software for graphical display of information as standard and the neutron probe a built-in display where the moisture values can be read after input of the site-specific calibration, in addition to the count number. For the example application, both devices satisfy the criteria (score = 1) of range of measurement, accuracy, reliability and data handling. On the other hand (score = 0), the FDR calibration strongly depends on soil type, whereas the neutron probe does not allow for quick/frequent readings, does not provide datalogging, and requires a strict maintenance program. Although the cost of installation is similar (both require tubes in the ground), the total cost of the neutron probe is higher, as is the data-collection labor (requires certified personnel). The expected life for both devices is 10 years. The value selection method indicates that FDR is a superior option for this application.

Because of natural and man-induced soil variability, the location and number of soil water monitoring instruments may be crucial. Several factors can affect soil moisture variability, including soil type and intrinsic heterogeneity, plant growth variation, rainfall interception, reduced application efficiency and uniformity in irrigation. In general, zones containing similar representative conditions such as soil type, depth, plant distribution, and sources of water (if irrigation) should be identified, and instruments should be placed in each representative zone.

Since the pressure to manage water more prudently and efficiently is increasing, we expect that research on soil water measurement will continue to produce reliable and low-cost solutions. Future research should focus on developing new techniques or improving the available methods to overcome the main limitation of soil-specific calibration. From a research perspective, a combined device that provides both volumetric and tensiometric in-situ readings would be desirable, since these two variables are often needed in many studies. Further refinement of non-contact and remote sensing techniques shows promise to evaluate large-scale soil moisture distribution and variation.

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Table 1. Evaluation criteria for volumetric soil water monitoring methods.

	Neutron Moderation	TDR	FD (Capacitance and FDR)	ADR	Phase Transmission	TDT
Reading range	0 - 60%	5 - 50%	0 - Saturation	0 - Saturation	5 - 50%	5 - 50% or 0 - 70% Depending on instrument
Accuracy (with soil-specific calibration)	±0.5%	±1%	±1%	±1 – 5%	±1%	±5%
Measurement volume	Sphere (6 - 16 in. radius)	About 1.2 in. radius around length of waveguides	Sphere (about 1.6 in. effective radius)	Cylinder (about 1.2 in.)	Cylinder (4-5 gallons)	Cylinder (0.2 - 1.6 gallons) of 2 in. radius
Installation method	Access tube	Permanently buried *in situ* or inserted for manual readings	Permanently buried *in situ* or PVC access tube	Permanently buried *in situ* or inserted for manual readings	Permanently buried *in situ*	Permanently buried *in situ*
Logging capability	No	Depending on instrument	Yes	Yes	Yes	Yes
Affected by salinity	No	High levels	Minimal	No	>3 dS/m	At high levels
Soil types not recommended	None	Organic, dense, salt or high clay soils	None	None	None	Organic, dense, salt or high clay soils (depending on instrument)
Field maintenance	No	No	No	No	No	No
Safety hazard	Yes	No	No	No	No	No
Application	Irrigation, research, consulting	Irrigation, research, consulting	Irrigation, research	Irrigation, research	Irrigation	Irrigation
Cost (includes reader/logger/interface if required)	$10,000-15,000	$400-23,000	$100-3,500	$500-700	$200-400	$400-1,300

Table 2. Evaluation criteria for tensiometric soil water monitoring methods.

	Tensiometer	Gypsum block	GMS	Heat Dissipation	Soil Psychrometer
Reading range	0 - 80 cbar	30 -200 cbar	10 - 200 cbar	10 - 100 cbar	50 - 300 cbar
Accuracy (with soil-specific calibration)	±1 cbar	±1 cbar	±1 cbar	7% absolute deviation	±2 cbar
Measurement volume	Sphere (>4 in. radius)	Sphere (>4 in. radius)	Sphere (about 0.08 in. radius)		Sphere (>4 in. radius)
Installation method	Permanently inserted into augured hole	Permanently inserted into augured hole	Permanently inserted into augured hole	Permanently inserted into augured hole	Permanently inserted into augured hole
Logging capability	Only when using transducers	Yes	Yes	Yes	Yes
Affected by salinity	No	>6 dS/M	>6 dS/M	No	Yes, for ceramic cup type (use screen type)
Soil types not recommended	Sandy or coarse soils	Sandy or coarse soils, avoid swelling soils	Sandy or coarse soils, avoid swelling soils	Coarse	Sandy or coarse soils, avoid swelling soils
Field maintenance	Yes	No	Medium	No	No
Safety hazard	No	No	No	No	No
Application	Irrigation, research	Irrigation	Irrigation	Irrigation, research	Research
Cost (includes reader/logger/interface if required)	$75-250	$400-700	$200-500	$300-500	$500-1,000

Table 3. Example of the value selection method to choose an appropriate soil moisture sensor (modified from Cape, 1997). The point value for attributes in column (b) is shown in the attributes column. The score in column (c) is calculated for each attribute by multiplying the points in column (b) by the weight assigned to that attribute in column (a). More explanation is given in the text.

Attributes		Weight (a)	Neutron Probe Points (b)	Neutron Probe Score (c)	FDR Points (b)	FDR Score (c)
Effective range of measurement (Point: Yes = 1; No = 0 sensor is not recommended for application and total score T = 0)	Is the soil water sensor (SWS) able to measure all ranges of soil water of interested to you?	-	1		1	
Accuracy (Point: Yes = 1; No = 0)	Is the SWS accuracy enough for your purpose?	14	1	14	1	14
Soil types (for use with range of soils) (Point: Yes = 0; No = 1)	Is the SWS's accuracy affected by the soil type?	11	1	11	0	0
Reliability (Point: Yes = 1; No = 0)	Do you have any personal, other-user or literature-based idea of the reliability of the SWS, and is the failure rate satisfactory to you?	13	1	13	1	13
Frequency/soil disturbance (Point: Yes = 1; No = 0)	Can the SWS provide quick or frequent readings in undisturbed soil?	8	0	0	1	8
Data handling (Point: Yes = 0; No = 1)	Will you have difficulty in reading or interpreting data?	8	1	8	1	8
Communication (for remote data manipulation) (Point: Yes = 1; No = 0)	Does the SWS provide data logging and downloading capabilities and friendly software for analyzing and interpreting the data?	10	0	0	1	10
Operation and maintenance (Point: Give the sensor 1/4 for each Yes answer; No = 0)	Is the SWS calibration universal? Does the SWS have a long life (>5 years)? Is the SWS maintenance-free? Is the SWS easy to install?	10	0 0.25 0 0.25	0 2.5 0 2.5	0 0.25 0.25 0.25	0 2.5 2.5 2.5
Safety (Point: Yes = 0; No = 1)	Does use of the SWS entail any danger?	8	0	0	1	8
Total (T)				51		68.5
Cost (Cost) (in $)				15000		7500
Life (L) (in years)				10		10
Annual cost of sensor (A = Cost/L (in $/year)				1500		750
Value of sensor (V = T/A)				0.034		0.091