SOIL-WATER-SOLUTE PROCESS CHARACTERIZATION

An Integrated Approach

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5 Field Methods for Monitoring Soil Water Status

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5.1 INTRODUCTION

In the context of soil research and characterization, often one of the first steps in any study is to quantify the amount of water in the soil in both time and space (see Chapters 3, 4, 6). In the context of water management for irrigation, measuring and monitoring soil water status is an essential component of best management practices (BMPs) to improve the sustainability of agriculture.

Water content in the soil can be *directly* determined using the difference in weight before and after drying a soil sample. This direct technique is usually referred to as the *thermo-gravimetric method* when expressing water content as gravimetric soil moisture θ_m [M^3 M^{-3}], 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 (105°C) to a constant mass. On the other hand, the *thermo-volumetric method* gives the volumetric soil moisture, θ_v or simply θ [L^3 L^{-3}], i.e., volume of water related to the volume of an oven-dried undisturbed sample (soil core). Although these direct methods are accurate ($\pm 0.01\,cm^3cm^{-3}$) and inexpensive, they are destructive, slow (2 days minimum), and do not allow for making repetitions in the same location. Alternatively, many *indirect* methods are available for monitoring soil water content. These methods estimate soil moisture by a calibrated relationship with some other measurable variable. The suitability of each method depends on several issues such as cost, accuracy, response time, installation, management, and durability.

Depending on the quantity measured, indirect techniques are first classified into *volumetric* and *tensiometric methods* (Figure 5.1). While the former gives volumetric soil moisture, the latter yields soil suction or matric potential (i.e., tension exerted by capillarity and adsorptive surface forces). Both quantities are related through the soil water characteristic curve (SWC).

It is important to remember that each soil type (texture/structure) has a different curve; therefore, they cannot be related to each other the same way for all soil types (Figure 5.2). Several mathematical models have been proposed to describe the SWC (see Chapter 3). In addition, this relationship might not be unique and may exhibit hysteresis along drying and wetting cycles, especially in finer soils.

Depending on the soil physical properties and goal of the soil moisture measurement, some devices are more effective than others. First, it must be considered that although volumetric moisture is a more intuitive quantity, in fine-textured soils water is strongly retained by solid particles and therefore may not be available for plant absorption and other processes

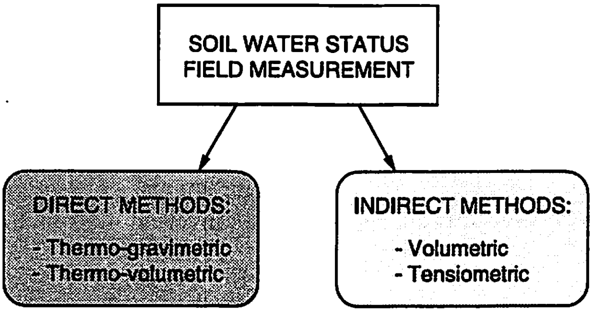


FIGURE 5.1 Methods for measuring soil moisture.

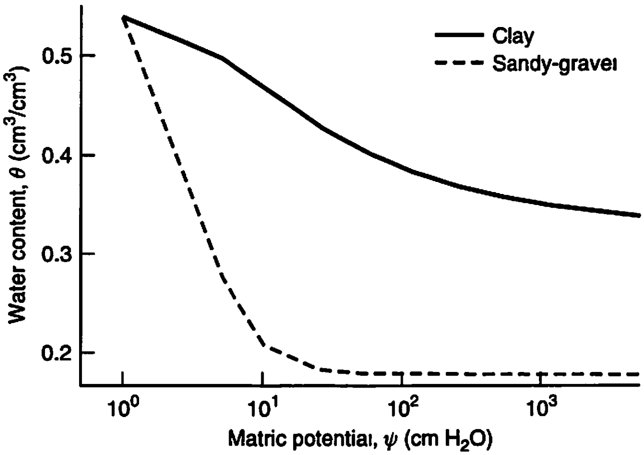


FIGURE 5.2 Measured soil water characteristic curves for two different soil types.

like flow and solute transport. In the case of plant-soil studies, soil suction may be a more useful quantity since it relates to the energy that plants have to invest to extract the water from the soil, and hence it is a more meaningful measure of plant water stress. Second, the desired sampling frequency is an important factor since different sensors' response times 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 require good soil-instrument contact. On the other hand, depending on soil type and hydrologic conditions (precipitation and evapotranspiration), some instruments might have higher maintenance requirements than others.

Irrigation management is a practical application of monitoring soil moisture that is becoming widespread among agricultural growers. Soil moisture–based optimized irrigation consists of keeping the soil within a target moisture range by replenishing the plant water uptake with irrigation. This practice avoids the potential for soil water excess and leaching of agrochemicals present in the soil but requires a suitable method for soil moisture estimation (Muñoz-Carpena et al., 2002, 2003). However, to calculate irrigation requirements, matric potential values from tensiometric methods need to be converted to soil moisture through the SWC.

5.2 METHODS OF CHARACTERIZATION: TRADE-OFFS. COMPARATIVE STUDY

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.

5.2.1 VOLUMETRIC FIELD METHODS

Methods under this definition estimate the volume of water per volume of soil θ [L^3 L^{-3}]. This quantity is useful for determining how saturated the soil is, i.e., fraction of total soil volume filled with the soil aqueous solution. When it is expressed in dimensions of depth or equivalent depth of wetting, d_e, i.e., volume of water in soil down to a given depth over a unit surface area (m), or

$$d_e = \theta d \tag{5.1}$$

where d is the depth increment in meter. d_e can be compared with other hydrological variables such as precipitation, evaporation, transpiration, deep drainage, etc.

5.2.1.1 Neutron Moderation

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

$$CR = m\theta + b \quad \text{and} \quad CR/CS = y\theta \tag{5.2}$$

where CR is the slow neutron count rate in wet soil, CS is count rate in water in a standard absorber (i.e., shield of probe), y is a constant, and m and b are the slope and intercept of the calibration line for the probe. Many

FIGURE 5.3 Neutron probe.

researchers establish calibration curves like the one above in terms of gravimetric water content. This is more convenient because the volume of influence of the neutron probe changes with water content. It is larger when the soil is dry and decreases with increasing water content. In general the radius (r) of the sphere of influence of the probe can be estimated by r (cm) $= 15\ (\theta)^{-1/3}$.

Description: The probe configuration is in the form of a long and narrow cylinder, containing a source and detector. Measurements are made by introducing the probe into an access tube (previously installed into the soil). Therefore, it is possible to determine soil moisture at different depths (Figure 5.3).

Advantages:

- Robust and accurate ($\pm 0.005\,cm^3cm^{-3}$).
- Inexpensive per location, i.e., a large number of measurements can be made at different points with the same instrument.
- One probe allows for measuring at different soil depths.
- Large soil sensing volume (sphere of influence with 10–40 cm radius, depending on moisture content).
- Not affected by salinity or air gaps.
- Stable soil-specific calibration.

Drawbacks:

- Safety hazard, since it implies working with radiation. Even at 40 cm depth, radiation losses through soil surface have been detected.
- Requires certified personnel.
- Requires soil-specific calibration.
- Heavy, cumbersome instrument.
- Takes a relatively long time for each reading.
- Readings close to the soil surface are difficult.
- Manual readings; cannot be automated due to hazard.
- Expensive to buy.
- The sphere of influence may vary according to the following reasons:

a) It increases as the soil dries because the hydrogen concentration decreases, so that the probability of collision is smaller and therefore fast neutrons can travel further from the source.
b) It is smaller in fine texture soils because they can hold more water, and thus the probability of collision 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.

5.2.1.2 Dielectric Methods

The next set of volumetric methods are known as *dielectric techniques*, because all of them estimate soil water content by measuring the soil bulk permittivity (or dielectric constant), ε_b (Inoue, 1998; Hilhorst et al., 2001). This parameter states that the dielectric of a medium is the ratio squared of electromagnetic wave propagation velocity in a vacuum, relative to that of the medium (i.e., ε_b determines the velocity of an electromagnetic pulse through that medium). In the soil the value of this composite property is mainly governed by the presence of liquid water, because the dielectric constant of the other soil constituents is much smaller (e.g., $\varepsilon_s = 2$–5 for soil minerals, 3.2 for frozen or bounded water, and 1 for air) than that of liquid water ($\varepsilon_w = 81$).

A common approach to establish the relationship between ε_b and volumetric moisture (θ) is the empirical equation of Topp et al., (1980):

$$\theta = -5.3 \cdot 10^{-2} + 2.29 \cdot 10^{-2}\varepsilon_b - 5.5 \cdot 10^{-4}\varepsilon_b^2 + 4.3 \cdot 10^{-6}\varepsilon_b^3 \qquad (5.3)$$

This third-order polynomial provides an adequate θ-ε_b relationship for most mineral soils (independent of soil composition and texture) and for $\theta < 0.5\,\mathrm{cm^3 cm^{-3}}$. For larger water content, organic or volcanic soils, a specific calibration is required. In this latter case, this is explained in terms of low bulk densities and large surface areas that result in a greater fraction of bounded water (Regalado et al., 2003). Moreover, high contents of aluminium and iron hydroxides may result in higher permittivity of the solid phase (Dirksen, 1999). It is worth noticing that the θ-ε_b relationship depends on the electromagnetic wave frequency. Thus, at low frequencies (< 100 MHz) it is more soil-specific.

An alternative relationship to the empirical equation is the three-phase mixing model (Roth et al., 1990):

$$\theta = \frac{\varepsilon_b^\beta - (1-\eta)\varepsilon_s^\beta - \eta\varepsilon_a^\beta}{\varepsilon_w^\beta - \varepsilon_a^\beta} \tag{5.4}$$

where η is the soil porosity; ε_w, ε_a, and ε_s are the permittivity of liquid, gaseous, and solid phase, respectively, and β describes the geometry of the medium in relation to the axial direction of the transmission line and, in general, it is considered as a fitted parameter ($-1 \leq \beta \leq 1$). When soil moisture is divided into a mobile and an immobile region, the four-phase mixing model is recommended (Dobson et al., 1985):

$$\theta = \frac{\varepsilon_b^\beta - (1-\eta)\varepsilon_s^\beta - \eta\varepsilon_a^\beta + \theta_{bw}^\beta\left(\varepsilon_{bw}^\beta - \varepsilon_w^\beta\right)}{\varepsilon_w^\beta - \varepsilon_a^\beta} \tag{5.5}$$

where θ_{bw} is the fraction of soil water that is immobile and has a permittivity ε_{bw}. According to Dirksen and Dasberg (1993), it can be obtained from:

$$\theta_{bw} = n\delta\rho_b S_e \tag{5.6}$$

where n is the number of molecular water layers adsorbed at soil particles, δ is the thickness of a monomolecular water layer ($3{\cdot}10^{-10}$ m), ρ_b is the bulk density, and S_e is the specific surface area. Alternatively, the Maxwell–De Loor equation (De Loor, 1964) is based on a theoretical model and contains only physical parameters, although it requires measurement of a significant number of other soil properties.

In addition to these approaches, some of the dielectric methods described below use empirical calibrated relationships between θ and the sensor output signal (time, frequency, impedance, wave phase). These techniques are becoming widely adopted because they have good response time (almost instantaneous measurements), do not require maintenance, and can provide continuous readings through automation.

5.2.1.2.1 Time Domain Reflectometry (TDR)

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

$$\varepsilon_b = \left(\frac{c}{v}\right)^2 = \left(\frac{ct}{2L}\right)^2 \tag{5.7}$$

where c is the velocity of electromagnetic waves in a vacuum ($3 \cdot 10^8$ m/s) and L is the length of the TL embedded in the soil.

Description: A TDR instrument requires a device capable of producing a series of precisely timed electrical pulses with a wide range of frequencies used by different devices (e.g., 0.02–3 GHz), which travel along a TL that is built with a coaxial cable and a probe. The TDR probe usually consists of two or three parallel metal rods that are inserted into the soil acting as waveguides in a similar way as an antenna used for television reception. At the same time, the TDR instrument uses a device for measuring and digitizing the energy (voltage) level of the TL at intervals down to around 100 ps. When the electromagnetic pulse traveling along the TL finds a discontinuity (i.e., probe-waveguides surrounded by soil), part of the pulse is reflected. This produces a change in the energy level of the TL. Thereby the travel time (t) is determined by analyzing the digitized energy levels (Figure 5.4).

Soil salinity or highly conductive heavy clay contents may affect TDR, since it 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 soils with highly saline conditions, using epoxy-coated probe rods can solve the problem. However, this implies loss of sensitivity and change in calibration. On the other hand, pulse attenuation due to soil salinity allows using TDR for quantifying ionic solutes in the soil environment (i.e., electrical conductivity).

In combination with a neutron probe or other technique, which detects total soil moisture, TDR can be used to determine bound or frozen water, because these have much lower permittivity than liquid water.

Advantages:

- Accurate (± 0.01 cm^{3}cm^{-3}).
- Soil specific-calibration is usually not required.
- Easily expanded by multiplexing.
- Wide variety of probes configuration.

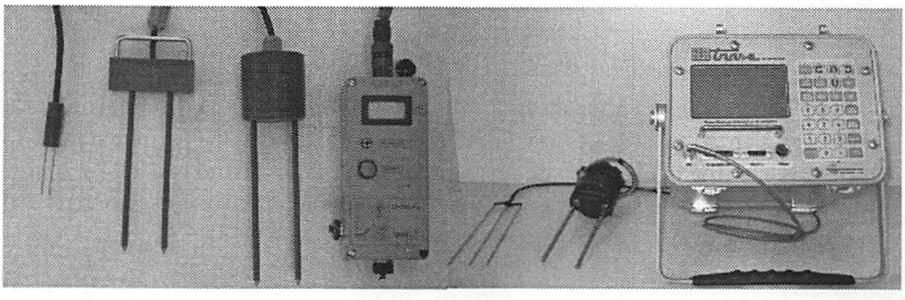


FIGURE 5.4 TDR equipment.

- Minimal soil disturbance.
- Relatively insensitive to normal salinity levels.
- Can provide simultaneous measurements of soil electrical conductivity (see Chapter 10).

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 (i.e., volcanic soils) or high organic matter content.
- Relative small sensing volume (about 3 cm radius around length of waveguides).

5.2.1.2.2 Frequency Domain: Capacitance and FDR

Working principle: The electrical capacitance of a capacitor that uses the soil as a dielectric, depends on the soil water content. When connecting this capacitor (made of metal plates or rods imbedded in the soil) together with an oscillator to form a tuned electrical circuit, changes in soil moisture can be detected by changes in the circuit operating frequency. This is the basis of the frequency domain (FD) technique used in capacitance and frequency domain reflectometry (FDR) sensors. In capacitance sensors the dielectric permittivity of a medium is determined by measuring the charge time of a capacitor in that medium. In FDR the oscillator frequency is swept under control within a certain frequency range to find 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 (i.e., parallel plates, rods, or metal rings along a cylinder) that are inserted into the soil. On the ring configuration the probe is introduced into a access tube installed in the field. Thus, when an electrical field is applied, the soil in contact with the electrodes (or around the PVC tube) forms the dielectric of the capacitor that completes the oscillating circuit. The use of an access tube allows for multiple sensors to take measurements at different depths (Figure 5.5).

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 soil minerals may be changed by soil minerals, and the estimation is more affected by temperature, salinity, bulk density, and clay content. On the other hand, using low frequencies allows for detecting bound water.

Advantages:
- Accurate after soil-specific calibration ($\pm 0.01\ cm^3 cm^{-3}$).

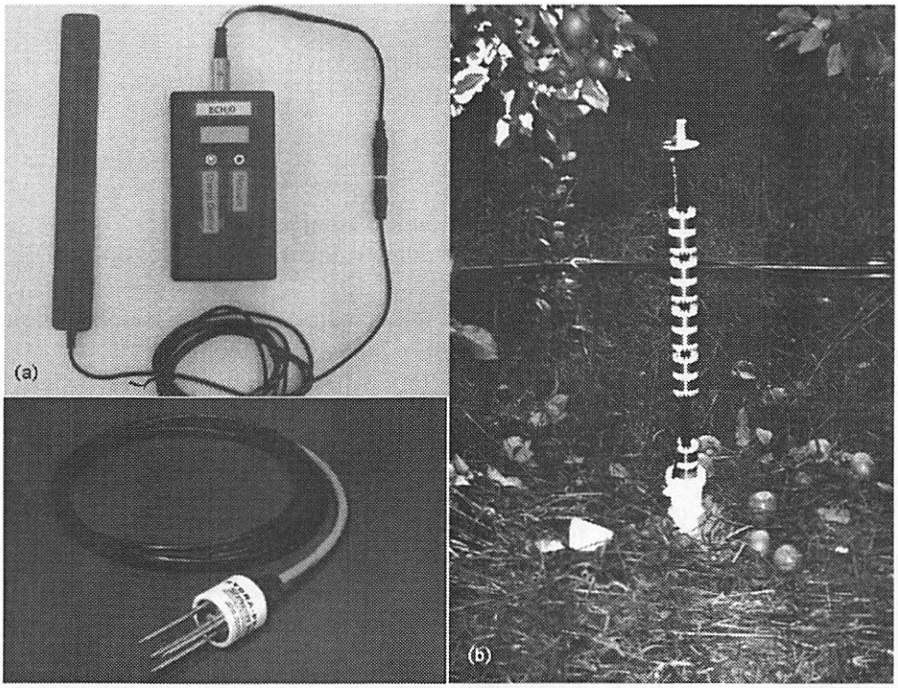


FIGURE 5.5 FD probes: (a) capacitance; (b) FDR.

- Can read at high salinity levels, 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 loggers (DC output signal).
- Flexibility in probe design (more than TDR).
- Some devices are relatively inexpensive compared to TDR due to use of low-frequency standard circuitry.

Drawbacks:

- The sensing sphere of influence is relatively small (about 4 cm).
- For reliable measurements, it is extremely critical to have good contact between the sensor (or tube) and soil.
- Tends to have larger sensitivity to temperature, bulk density, clay content, and air gaps than TDR. Careful installation is necessary to avoid air gaps.
- Needs soil-specific calibration.

5.2.1.2.3 Amplitude Domain Reflectometry (ADR): Impedance

Working principle: When an electromagnetic wave (energy) traveling along a transmission line (TL) reaches a section with different impedance (which has two components: electrical conductivity and dielectric constant), part of the energy transmitted is reflected back into 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 is the cause for 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 the soil electrical conductivity is minimized by choosing a signal frequency so that 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), which is applied to a coaxial TL that extends into the soil through an array of parallel metal rods, the outer of which forms an electrical shield around the central signal rod. 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 5.6).

Advantages:

- Accurate with soil-specific calibration ($\pm 0.01\,cm^3\,cm^{-3}$; $\pm 0.05\,cm^3\,cm^{-3}$ without it).

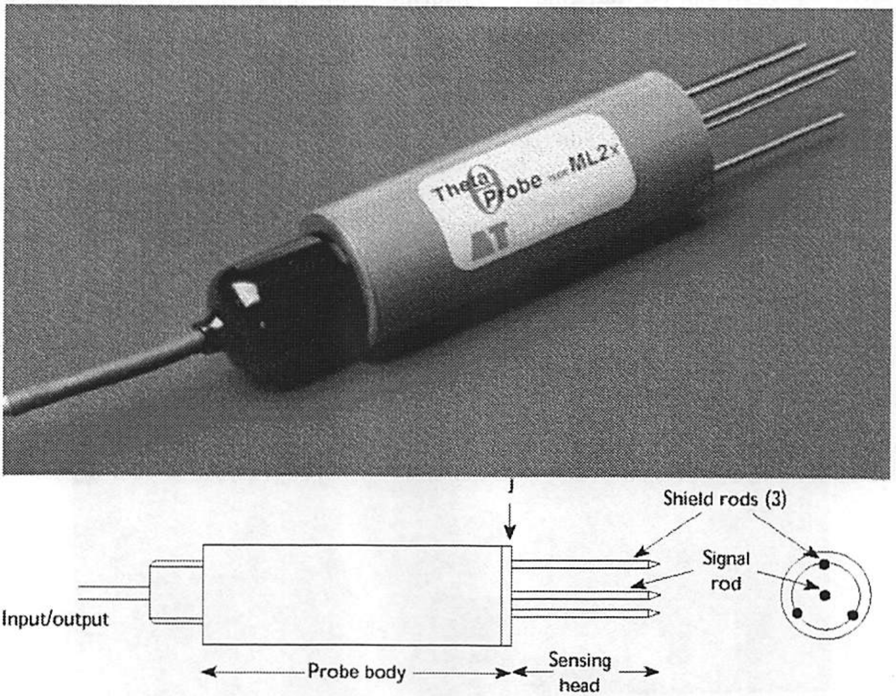


FIGURE 5.6 ADR probe.

- Allows measurements in highly saline conditions (up to 20 dS/m).
- Minimal soil disturbance.
- Can be connected to conventional loggers (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 channelling water directly onto the probe rods.
- Small sensing volume ($4.3\,cm^3$).

5.2.1.2.4 Phase Transmission (Virrib)

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

Description: The probe uses a particular waveguide design (two concentric metal open rings), so that phase-measuring electronics can be applied at the beginning and ending of the waveguides (Figure 5.7).

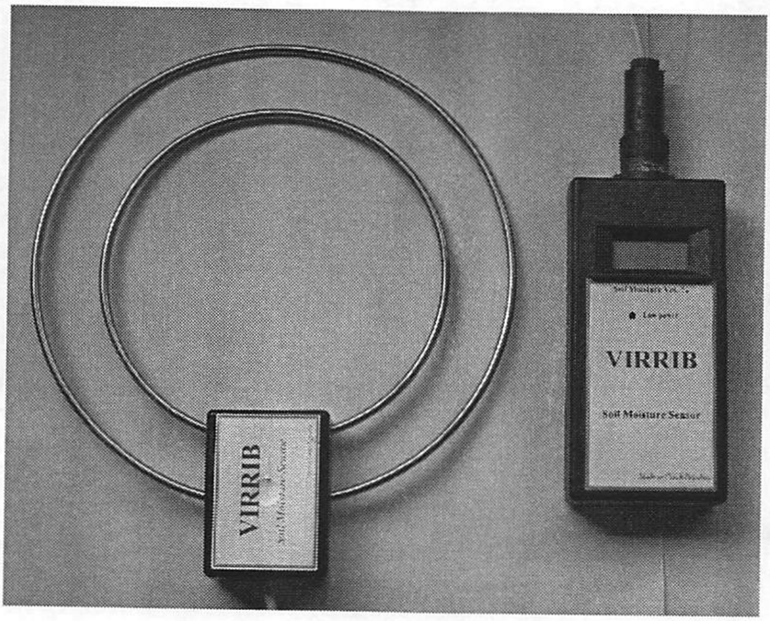


FIGURE 5.7 Phase transmission probe.

Advantages:

- Accurate with soil-specific calibration ($\pm 0.01\ cm^3cm^{-3}$).
- Large sensing soil volume (15–20 L).
- Can be connected to conventional loggers (DC output signal).
- Inexpensive.

Drawbacks:

- Significant soil disturbance during installation due to concentric ring sensor configuration.
- Requires soil-specific calibration.
- Sensitive to salinity levels > 3 dS/m.
- Reduced precision, because the generated pulse becomes distorted during transmission.
- Needs to be permanently installed in the field.

5.2.1.2.5 Time Domain Transmission (TDT)

Working principle: This method measures the one-way time for an electromagnetic pulse to propagate along a transmission line (TL). Thus, it is similar to TDR, but requires an electrical connection at the beginning and ending of the TL. Notwithstanding, the circuit is simple compared with TDR instruments. Recently Harlow et al. (2003) demonstrated two different TDT approaches, showing results comparable with those of FD and TDR techniques.

Description: The probe has a waveguide design (bent metal rods), so that the beginning and ending of the transmission line are inserted into the electronic block. Alternatively, the sensor consists of a long band (~3 m), having an electronic block at both ends (Figure 5.8).

Advantages:

- Accurate (± 0.01–$0.02\ cm^3cm^{-3}$).
- Large sensing soil volume (0.8–6 L).
- Can be connected to conventional loggers (DC output signal).
- Inexpensive due to standard circuitry.

Drawbacks:

- Reduced precision, because the generated pulse gets distorted during transmission.
- Soil disturbance during installation.
- Needs to be permanently installed in the field.

5.2.1.3 Other Volumetric Field Methods

Another interesting technique is ground penetrating radar (GPR). This technique 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

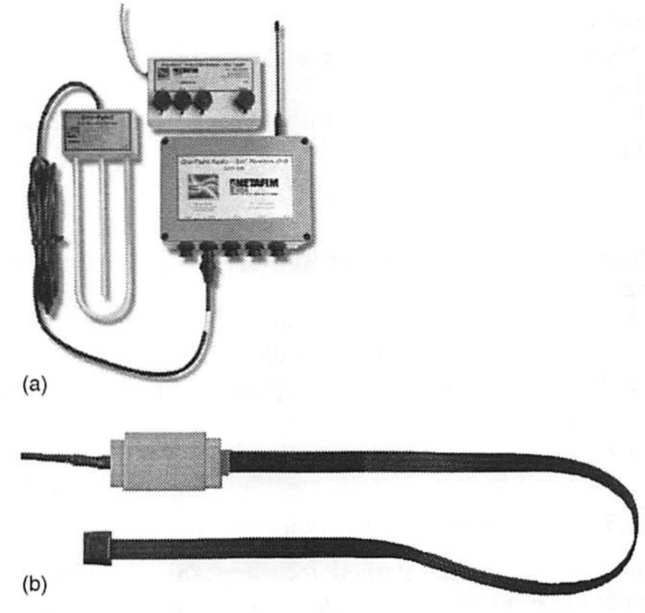


FIGURE 5.8 TDT devices.

trolley close to the soil surface, it has the potential of providing rapid, nondisturbing, soil moisture measurements over relatively large areas. Although it has been applied successfully to many field situations, GPR has not been widely used because the methodology and instrumentation are still only in the research and development phase (Davis and Annan, 2002). It is, however, likely that small, compact, and inexpensive GPR systems will be available in the near future for routine field studies.

It should be mentioned that there are several new remote sensing methods, usually mounted on airplanes or satellites, specially suited for soil moisture monitoring over large areas. Among these methods the active and passive microwave and electromagnetic induction (EMI) methods have been found useful in different applications (Dane and Topp, 2002) and are the subject of much 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. In the microwave methods, the signal typically relates to some shallow depth below the ground surface (<4 in.) 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 non-field techniques for estimating soil moisture and flow [x-ray tomography and nuclear magnetic resonance-(NMR)] are discussed in Chapter 7.

5.2.2 Tensiometric Field Methods

Tensiometric methods estimate the soil water matric potential that includes both adsorption and capillary effects of the soil solid phase. The matric potential is one of the components of the total soil water potential that also includes gravitational, osmotic, gas pressure or pneumatic, and overburden components. The sum of matric and gravitational (position with respect to a reference elevation plane) potentials, i.e., hydraulic potential or total head, is the main driving force for water movement in soils and other porous media (see Chapters 3, 4, and 6).

All available tensiometric instruments have a porous material in contact with the soil through which water can move. Thereby, water is drawn out of the porous medium in a dry soil and from the soil into the medium in a wet soil. It is worth noticing that in general these instruments do not need soil-specific calibration, but in most cases they have to be permanently installed in the field, or a sufficiently long time must be allowed for equilibration between the device and the soil before making a reading.

5.2.2.1 Tensiometer

Working principle: When a sealed water-filled tube is placed in contact with the soil through a permeable and saturated porous material, 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 is equivalent to the vacuum or suction created inside the tube.

Description: The tensiometer consists of a sealed water-filled plastic tube with a ceramic cup at one end and a negative pressure gauge (vacuometer) at the other. Its shape and size can be variable, and the accuracy depends on the gauge or transducer used (about 0.01 bar). Typically the measurement range is 0–0.80 bar, although low-tension versions (0–0.40 bar) have been designed for coarse soils (Figure 5.9).

Advantages:

- Direct reading.
- Up to 10 cm measurement sphere radius.
- Continuous reading possible when using pressure transducer.
- Requires intimate contact with soil around the ceramic cup for consistent readings and to avoid frequent discharge (breaking of water column inside).
- Electronics and power consumption avoidable.
- Well suited for high frequency sampling or irrigation schedules.

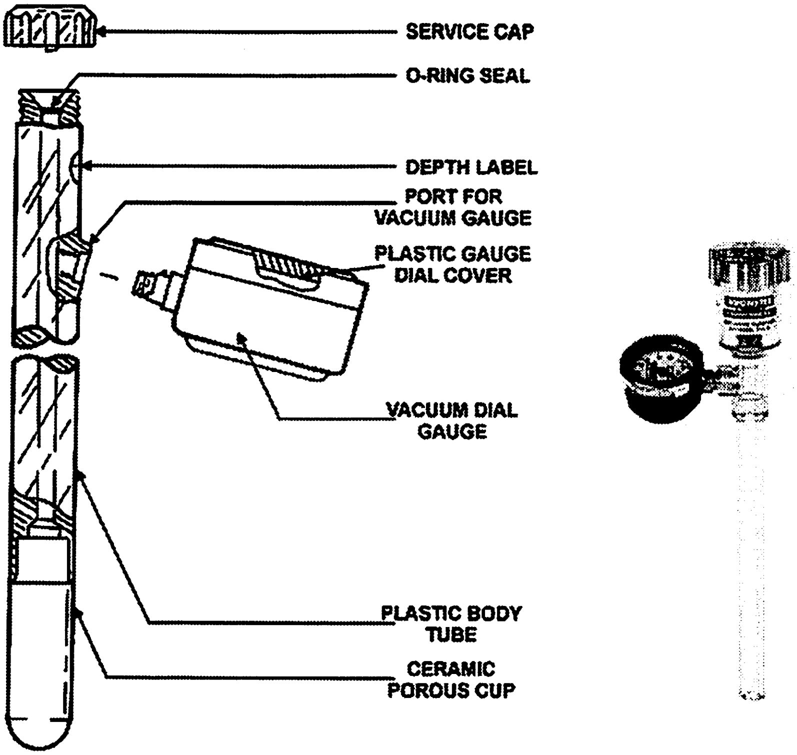


FIGURE 5.9 Tensiometers. (From Smajstrla and Harrison, 1998).

- Minimal skill required for maintenance.
- Not affected by soil salinity, because salts can move freely into and out across the porous ceramic cup.
- Inexpensive.

Drawbacks:
- Limited soil suction range (< 1 bar).
- Relatively slow response time.
- Especially in swelling or coarse soils, the ceramic cup can loose contact with soil, thus requiring reinstallation.
- Requires frequent maintenance (refilling) to keep the tube full of water, epecially in hot dry weather.

5.2.2.2 Resistance Blocks

Working principle: The 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 reduces as the soil, hence the block, dries.

5.2.2.2.1 Gypsum (Bouyoucos) Block

Description: A gypsum block sensor constitutes an electrochemical cell with a saturated solution of calcium sulfate as electrolyte (Bouyoucos and Mick, 1940). The resistance between the block-embedded electrodes is determined by applying a small AC voltage (to prevent block polarization) using a Wheatstone bridge. Since changes to the electrical conductivity of the soil would affect readings, gypsum is used as a buffer against soil salinity changes (up to a certain level). The inherent problem is that the block dissolves and degrades over time (especially in saline soils), losing its calibration properties. It is recommended that the block pore size distribution match the texture of the surrounding soil. The readings are temperature dependent (up to 3% change/°C), and field-measured resistance should be corrected for differences between calibration and field temperatures. Some reading devices contain manual or self-compensating features for temperature or the manufacture provides correction charts or equations. Measurement range is 0.3–2.0 bar (Figure 5.10).

Advantages:

- Up to 10 cm measurement sphere radius.
- No maintenance needed.
- Simple and inexpensive.

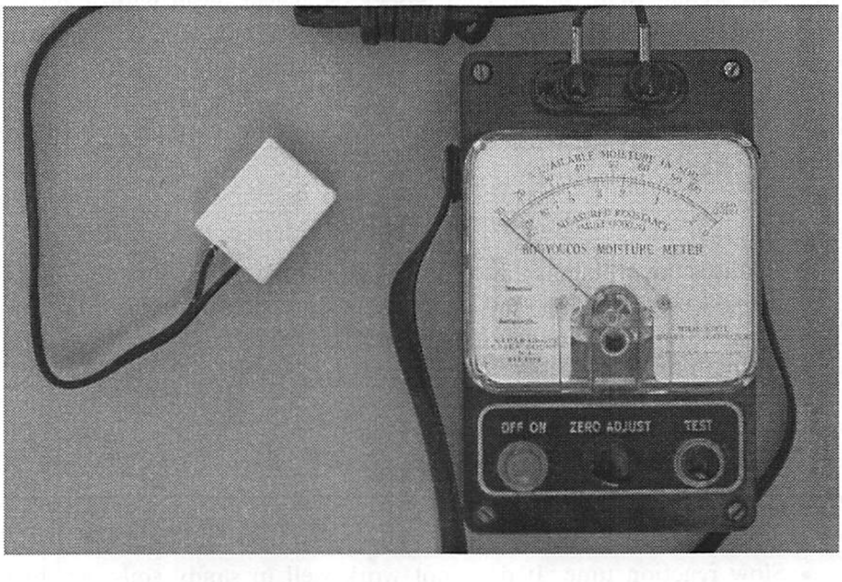


FIGURE 5.10 Gypsum (Bouyoucos) resistance block and reader.

- Salinity effects buffered up to 6 dS/m.
- Well suited for irrigation where only "full" and "refill" points are required.
- Suited to regulated-deficit irrigation.

Drawbacks:
- Low resolution, limited use in research.
- Block cannot be used for measurements around saturation (0–0.3 bar).
- Block properties change with time, because of clay deposition and gypsum dissolution. Degradation speed depends on soil type, amount of rainfall and irrigation, and also the type of gypsum block used.
- Very slow reaction time. It 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 the block hysteresis (at a fixed soil water potential, the sensor displays different resistance when wetting than when drying).
- Temperature dependent. If connected to a logging system, another variable and sensor for temperature must be added to the system.

5.2.2.2.2 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 for measuring in wetter soil conditions and lasts longer than the gypsum blocks. However, even with good sensor-soil contact, GMSs have rewetting problems after they have been dried to very dry levels. This is because of the reduced ability of water films to reenter the coarse medium of the GMS from a fine soil. The GMS material allows for measurements closer to saturation. Measurement range is 0.10–2.0 bar (Figure 5.11).

Advantages:
- Reduces the problems inherent to gypsum blocks (i.e., loss of contact with the soil by dissolving, and inconsistent pore size distribution).
- Up to 10 cm measurement sphere radius.
- No maintenance needed.
- Simple and inexpensive.
- Salinity effects buffered up to 6 dS/m.
- Suited to regulated-deficit irrigation.

Drawbacks:
- Low resolution, limited use in research.
- Slow reaction time. It does not work well in sandy soils, where water drains more quickly than the instrument can equilibrate.

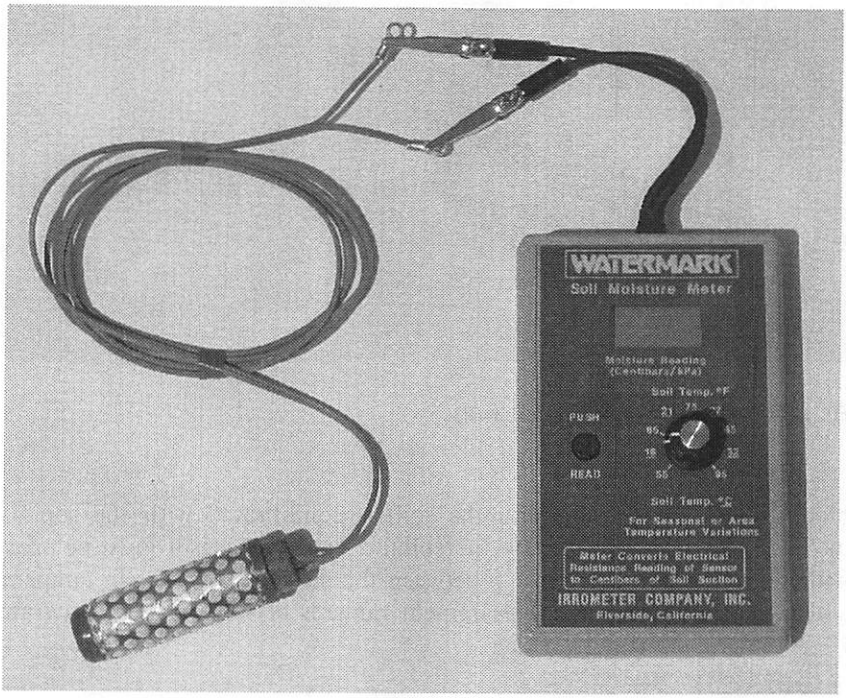


FIGURE 5.11 GMS resistance block and reader.

- Not suitable for swelling soils.
- If the soil becomes too dry, the sensor must be pulled out, resaturated and installed again.
- Temperature dependence. If connected to a logging system, another variable and sensor for temperature must be added to the system.

5.2.2.3 Heat Dissipation

Working principle: The rate of heat dissipation in a porous medium is dependent on the medium's specific heat capacity, thermal conductivity, and density. The heat capacity and thermal conductivity of a porous matrix is affected by its water content. Heat dissipation sensors contain heating elements in line or point source configurations embedded in a rigid porous matrix with fixed pore space. The measurement is based on application of a heat pulse by applying a constant current through the heating element for specified time period and analysis of the temperature response measured by a thermocouple placed at a certain distance from the heating source.

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

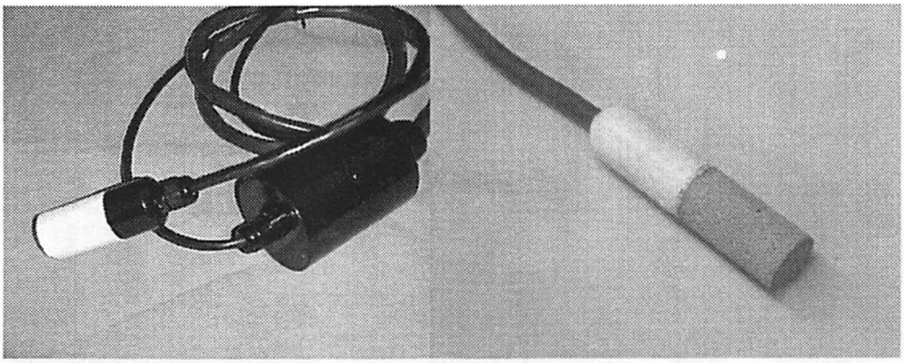


FIGURE 5.12 Heat dissipation sensors.

block, placed in contact with the soil, is equilibrated with the soil water, its SWC will give the soil water potential. Hence, the sensor must be provided with the calibrated relationship between the measured change in temperature and soil water potential. Measurement range is 0.1–30 bar (less accurate for 10–30 bar range) (Figure 5.12).

Advantages:

- Wide measurement range.
- No maintenance required.
- Up to 10 cm measurement sphere radius.
- Continuous reading possible.
- Not affected by salinity because measurements are based on thermal conductivity.

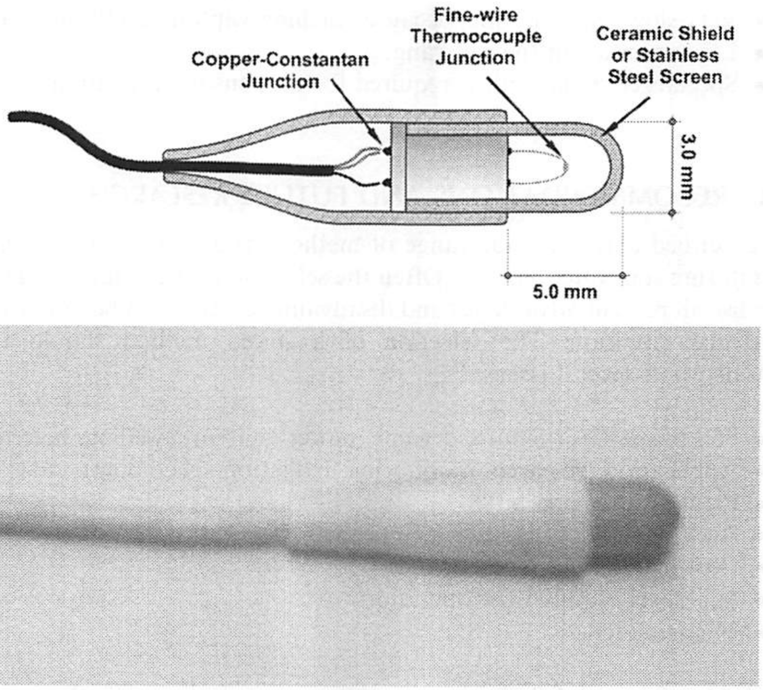
Drawbacks:

- Needs a sophisticated controller/logger to control heating and measurement operations.
- Slow reaction time. It does not work well in sandy soils, where water drains more quickly than the instrument can equilibrate.
- Fairly large power consumption for frequent readings.

5.2.2.4 Soil Psychrometer

Working principle: Under vapor equilibrium conditions, water potential of a porous material is directly related to the vapour pressure of the air surrounding the porous medium according to Kelvin's equation:

$$\phi_m = \frac{RT_a}{M_w} \ln RH \tag{5.8}$$



FIGRUE 5.13 Soil psychrometer.

where ϕ_m is the water potential, R is the gas constant (8.31 J $mol^{-1}K^{-1}$); T_a is the Kelvin temperature of the air, M_w is the molecular weight of water, and RH is the relative humidity. Thereby, the soil water potential is determined by measuring the 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 building an air chamber, where a thermocouple is located. The screen type is recommended for high-salinity environments, Thereby, RH in the air chamber is calculated from the "wet bulb" versus "dry bulb" temperature difference. Measurement range is 0.5–30 bar (less accurate for 10–30 bar range) (Figure 5.13).

Advantages:

- High sensitivity.
- Scientifically rigorous readings (except in wetter soil conditions).
- 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 reaching vapour equilibrium takes time.
- Low accuracy in the wet range.
- Specialized equipment is required for the sensor's excitation and reading.

5.3 RECOMMENDATIONS AND FUTURE RESEARCH

As described above, a wide range of methods is available for measuring and monitoring soil water content. Often the selection of a technique is not simple, because all present advantages and disadvantages, that can be important in the particular situation. The selection of a suited method should take into consideration several issues:

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

Tables 5.1 and 5.2 display a comparison of the methods presented to provide the reader with a quick reference.

Charlesworth (2000) presented a 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 5.3). 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. This implies that no sensor will be valid for an application if the field-measuring range does not match the sensor specifications. The total estimated life cost of the sensor (Cost) is estimated from capital, installation, running, and maintenance costs for the expected life of the sensor (L). The annual cost (A) of the sensor is obtained by A = Cost/L. The final sensor value for the application (V) is obtained by dividing T/A. The device with the highest value V is more suited to the needs and budget considered. An illustration example is included in Table 5.3 where the neutron probe is compared with an FDR sensor. Both alternatives include measuring moisture at one point with 10 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 the site-specific calibration has been input, in addition to the count number. For the example application, both devices satisfy the criteria

TABLE 5.1
Evaluation Criteria for Volumetric Soil Water–Monitoring Methods

	Neutron moderation	TDR	FD (capacitance and FDR)	ADR	Phase transmission	TDT
Reading range	0–0.60 cm^3cm^{-3}	0.05–0.50 cm^3cm^{-3} 0.05–Saturation (with soil-specific calibration)	0–saturation	0–saturation	0.05–0.50 cm^3cm^{-3}	0.05–0.50 cm^3cm^{-3} 0–0.70 cm^3cm^{-3} Depending on instrument
Accuracy (with soil-specific calibration)	±0.005 cm^3cm^{-3}	±0.01 cm^3cm^{-3}	±0.01 cm^3cm^{-3}	±0.01–0.05 cm^3cm^{-3}	±0.01 cm^3cm^{-3}	±0.05 cm^3cm^{-3}
Measurement volume	Sphere (15–40 cm radius)	About 3 cm radius around length of waveguides	Sphere (about 4 cm effective radius)	Cylinder (about 4 cm^3cm^{-3})	Cylinder (15–20 L)	Cylinder (0.8–6 L) of 50 mm 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

(Continued)

TABLE 5.1
Continued

	Neutron moderation	TDR	FD (capacitance and FDR)	ADR	Phase transmission	TDT
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 researcher consultants	Irrigation researcher consultants	Irrigation researcher	Irrigation researcher	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 5.2
Evaluation Criteria for Tensiometric Soil Water–Monitoring Methods

	Tensiometer	Gypsum block	GMS	Heat dissipation	Soil psychrometer
Reading range	0–0.80 bar	0.3–2.0 bar	0.1–2.0 bar	0.1–10 bar	0.5–30 bar
Accuracy (with soil-specific calibration)	±0.01 bar	±0.01 bar	±0.01 bar	7% absolute deviation	±0.2 bar
Measurement volume	Sphere (> 10 cm radius)	Sphere (> 10 cm radius)	Sphere (about 2 cm radius)		Sphere (> 10 cm radius)
Installation method	Permanently inserted into augered hole	Permanently inserted into augered hole	Permanently inserted into augered hole	Permanently inserted into augered hole	Permanently inserted into augered 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	$500–1000

TABLE 5.3
Example of Evaluation Procedure for Choosing Between Alternative Soil Moisture Sensors

Attributes	Weight (A)	Neutron probe Point (B)	Neutron probe Score (C)	FDR Point (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 device able to measure all ranges of soil water of interest to you?		1		1	
Accuracy (Point: Yes = 1; No = 0)	14				
Is the sensor accurate enough for your purpose?		1	14	1	14
Soil types (for use with range of soils) (Point: Yes = 0; No = 1)	11				
Is the sensor's accuracy affected by the soil type?		1	11	0	0
Reliability (Point: Yes = 1; No = 0)	13				
Do you have any personal, other users; or literature-based idea of the reliability of the sensor, and is the failure rate satisfactory to you?		1	13	1	13
Frequency/soil disturbance (Point: Yes = 1; No = 0)	8				
Can the sensor provide quick or frequent readings in undisturbed soil?		0	0	1	8
Data handling (Point: Yes = 0; No = 1)	8				
Will you have difficulty reading or interpreting data?		1	8	1	8
Communication (for remote data manipulation) (Point: Yes = 1; No = 0)	10				
Does the sensor provide data logging and downloading capabilities and friendly software for analyzing and interpreting the data?		0	0	1	10
Operation and maintenance (Point: 1/4 for each Yes answer; No = 0)	10				
Is the sensor calibration universal?		0	0	0	0
Does the sws have a long life (>5 years)?		0.25	2.5	0.25	2.5
Is the sensor maintenance free?		0	0	0.25	2.5
Is the sensor easy to install?		0.25	2.5	0.25	2.5
Safety (Point: Yes = 0; No = 1)	8				
Does use of the sensor entail any danger?		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)			**1500**		**750**
Value of sensor (V = T/A)			**0.034**		$\boxed{\mathbf{0.091}}$

Source: Adapted from Cape, 1997.

(score = 1) of range of measurement, accuracy, reliability, and data handling. On the other hand (score = 0), the FDR calibration is strongly dependent on soil type, whereas the neutron probe does not allow for quick/frequent readings, does not provide datalogging since it cannot be left unattended in the field, and needs an strict maintenance program as a radioactive device. Although the cost of installation is similar (both are 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.

In the context of soil water monitoring, because of the soil's natural and artificially induced variability, the location and number of instruments may be crucial. Several factors can affect soil moisture reading variability: soil type and intrinsic heterogeneity, plant growth variation, rainfall interception, reduced irrigation application efficiency and uniformity, etc. Hence, in general, it is recommended to identify the average (representative) conditions in terms of soil type, depth, plant distribution, and sources of water (if irrigation) and place the instruments in each representative zone.

Since the pressure to manage water more prudently and efficiently is increasing, it is expected 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 actual methods to overcome the main limitation of requiring a 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 state variables are often needed in mass transport studies (see Chapter 3). Further refinement of noncontact and remote sensing techniques shows promise to evaluate soil moisture distribution and variation across large scales.

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