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METHODS AND TECHNIQUES FOR SOIL MOISTURE MONITORING

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Combining effective irrigation management strategies with more efficient irrigation systems and soil moisture monitoring can lead producers to use water more efficiently and reduce energy used for irrigation.

Excessive irrigation not only increases the cost of production from additional pumping and electricity use but also causes excessive fertilizer loss to runoff and leaching, without an economic increase in production. Excessive runoff can also increase the topsoil erosion and can be harmful to the environment if fertilizers and pesticides move to sensitive environments. By subjecting soil and plant canopies to frequent and prolonged wet conditions, excessive irrigation can decrease harvestable yield due to greater occurrence and severity of disease, anaerobic soil conditions, nutrient deficiencies, and inability to operate farm machinery in the fields. On the other hand, providing insufficient water for the crop limits ***transpiration*** and ***photosynthesis*** and, in turn, hinders crop growth and reduces yield and crop quality.

Wiser irrigation scheduling methods can achieve efficient irrigation management. Methods range from monitoring crop water use (aka crop evapotranspiration) based on weather data, monitoring soil moisture status, to monitoring crop indicators such as canopy temperature. For more information on crop evapotranspiration, please refer to University of Wyoming extension bulletin "*Evapotranspiration: Basics, Terminology, and its Importance*, B-1293". A combination of the above is best to accurately determine when to irrigate and how much water to apply; however, to schedule irrigation, producers need to know how to interpret sensor readings, which requires an understanding of basic soil water concepts, available soil moisture sensors, sensor technology and their installation procedures. For basic soil water concepts please refer University of Wyoming extension bulletin "*Irrigation Management: Basics of Soil Water*, B-1330".

This bulletin focuses on different methods and techniques of soil moisture measurement and how producers and water managers can determine soil moisture.

UW College of Agriculture and Natural Resources Extension

SOIL MOISTURE MONITORING

Soil moisture monitoring is divided into two broad categories – direct and indirect monitoring (Yoder et al., 1998). Direct methods measure soil **volumetric water content**. These methods are destructive, tedious, time-consuming, and non-continuous.

In contrast, indirect soil moisture monitoring methods measure volumetric water content using related properties based on a calibration equation. Various factors such as soil physical and chemical properties, soil temperature, and the accuracy of the **factory calibration equation** can affect the performance of indirect sensors. Depending on the sensor's technology (such as **sensor response time, sensing volume, operational range**, etc.), different soil moisture monitoring devices respond differently in different soil environments.

The following provides a brief description of each soil moisture monitoring method and how sensors operate in order to know which sensors are suitable in your production setting and operation.

FEEL AND APPEARANCE METHOD

This method includes the collection of soil samples at different locations and depths in the field to view and feel the soil by crumbling the sample into small pieces and then squeezing it by hand to form a ball. The soil is then ribboned between thumb and the forefinger. The cohesiveness of the ball is an indication of soil wetness, with ribbon length positively correlated to the soil water content.

This method requires a great deal of judgment and experience to make a good estimate of soil water content. In general, this is the least accurate method as it provides a subjective assessment of soil moisture. Nevertheless, the method is widely used. This method is low cost, as it requires only a soil hand probe or auger to remove the soil sample from different depths. Considering the spatial variability of soil in a field, this method can be used for irrigation management, especially if measurements are validated against a more accurate method periodically. This method becomes more challenging when working with layered soil (different soil texture at different depths) due to the difference in soil physical properties among layers. Another disadvantage of this method is the needed experience before confidence is gained and accuracy achieved. For more information on this method, please visit USDA-NRCS Program Aid Number 1619: *Estimating Soil Moisture by Feel and Appearance*, https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs144p2_051845.pdf.

GRAVIMETRIC METHOD

This is a direct measure of soil moisture and does not require sensors. It involves collecting soil samples at different locations and depths using a soil probe or soil auger (Figure 1). The soil is then sealed in an airtight container or plastic bag so moisture is not lost before weighing (if taking multiple soil samples in a field, place the soil sample sealed in an airtight container or plastic bag and store in an airtight ice chest). After determining wet weight, the soil is placed in an oven for 24 hours at 220°F, and the dry soil sample is reweighed to determine the amount of water lost. This method also requires the use of bulk density of the soil to covert the gravimetric water content to volumetric water content.

For example, if a wet soil sample weighs (M_{ws}) 120 grams prior to being disturbed, and the dry weight (M_{ds}) after 24 hours drying at 220°F is 100 grams, and the bulk density (ρ_b) is 1.25 grams/cm^3, the mass and volumetric water content can be calculated using equations:

$$\text{Mass Water Content} \quad (\theta_m) = \frac{(M_{ws} - M_{ds})}{M_{ds}}$$

$$\text{Mass Water Content} \quad (\theta_m) = \frac{120 - 100}{100}$$

$$\text{Mass Water Content} \quad (\theta_m) = \frac{20}{100} = 0.20 \text{ gram of water per gram of dry soil}$$

$$\text{Volumetric Water Content} \quad (\theta_v) = \frac{\rho_b}{\rho_w} \times \theta_m \quad (\rho_w = \text{density of water, 1 gram per cm}^3)$$

$$\text{Volumetric Water Content} \quad (\theta_v) = \frac{1.25}{1} \times .20 = 0.25 \text{ cm}^3 \text{ of water per cm}^3 \text{ of soil}$$

While fairly simple, this method is also accurate and is a standard method for measuring soil moisture content, meaning it is often used to validate or calibrate other methods. The method can give an accurate measure of volumetric water content within 1 percent if the **bulk density** is known and a reliable balance is used for weighing. However, because of its high labor requirement and time-consuming nature, producers do not use the method on a regular basis. Another limitation is measurements are not instantaneous, since it takes 24 hours to completely dry the soil.

Figure 1. *(a) Soil sample extraction from different depths using a 5-foot soil probe in a producer's field near Powell, and (b) wet soil sample weighing and data recording in the laboratory.*

TENSIOMETER

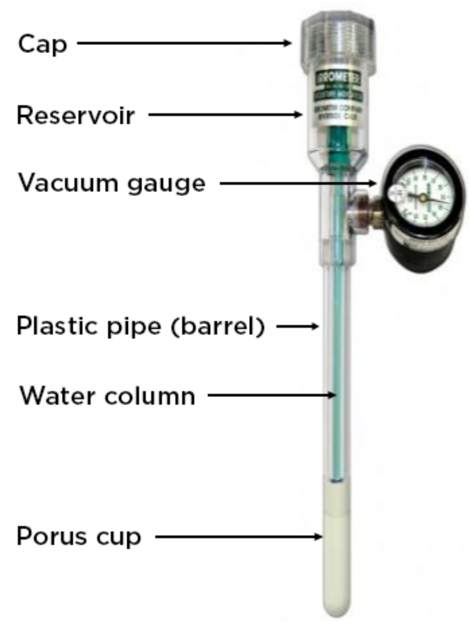


Figure 2. *Traditional tensiometer with vacuum gauge.*

A tensiometer measures the **soil matric potential**, which is also referred to as soil water suction or soil water tension (negative pressure). Tensiometers are mostly used in horticultural crops and consist of an airtight, water-filled cylindrical tube with a porous cup attached on the lower end and a vacuum gauge at the top (Figure 2).

The tension measured by tensiometer is equivalent to the force or energy that a plant has to overcome to extract water from the soil, and the force that determines the moisture distribution and transport within the soil. The porous cup must be in good contact with the soil at the desired depth. If installed this way, water in the porous cup will form an equilibrium with water in the soil, and water will be drawn into or pulled out of the porous cup as the soil becomes wetter or drier. This process creates and releases the suction force in the cup. The force is transmitted through the water column inside the plastic tube and causes a tension reading on a vacuum gauge (recorded manually or automatically using a pressure transducer connected to a data logger).

In general, the operational suction scale on the vacuum gauge of most commercial tensiometers ranges from 0 to 80 centi bar (cbar, which is 1/100 of a bar) of tension. However, a higher range is required for silt and clay soils as compared to sandy soils. For silt loam soils, the suggested irrigation trigger point ranges from 80 to 110 cbar, which is at or above the operating range of tensiometers as compared to fine sandy soils, with irrigation trigger points ranging from 20 to 30 cbar.

The cost of a traditional tensiometer generally ranges from $60 to $80 depending on the length, which varies between 6 to 48 inches. Tensiometer manufacturer companies in the U.S. include Irrometer company (http://www.irrometer.com/), Soil Moisture Equipment Corp. (http://www.soilmoisture.com/home.php), and Hortau (https://hortau.com/).

For installation, the end of the tensiometer containing the porous cup is inserted at the desired depth through a pilot hole made with a soil probe. Soaking the porous cup in water for several hours before installation is important. After installation, the plastic tube is filled with water and allowed to equilibrate with soil water for about 24 hours. Routine maintenance is required to refill the plastic tube. In general, tensiometers do not require soil-specific calibration and work well with changes in soil temperature and salinity.

ELECTRICAL RESISTANCE SENSORS

Similar to tensiometers, electrical resistance block sensors measure soil tension. Each sensor consists of two electrodes enclosed in a block of porous material (usually gypsum) (Figure 3), also referred to as gypsum blocks or moisture blocks. They operate on the principle that water conducts electricity and dry soil does not. With good contact with the surrounding soil, water suction of the porous block forms an equilibrium with the soil water suction of the surrounding soil. As the soil moisture changes, the water content in the porous block also changes, which affects the electrical resistance between the two electrodes. For example, as the water content of the porous block decreases, the electrical resistance between the two electrodes increases. When electrical current is applied to one electrode, the sensor provides a voltage output, which is proportional to the resistance in the porous block. This voltage output can be further converted to matric potential using a calibration equation.

Figure 3*. Traditional (a) gypsum block and (b) Watermark granular matrix electric resistance sensor.*

One limitation of gypsum blocks is that the gypsum matrix is a very fine-textured material and sensitive to saline soil water, which causes them to decompose rapidly in high salt and high soil moisture conditions. In a gypsum block, electrical resistance/ matric potential varies not only from block to block but also for each block over time. These sensors are not recommended for use in irrigation scheduling. The usable range is limited to high soil water tensions (dry soil), usually greater than 50 cbar. Generally, at a normal site (with few irrigation events), a gypsum block may last two to three years; however, an annual replacement may be required in areas with frequent irrigation or high water tables.

To overcome the limitations of gypsum blocks in saline and wet conditions, Watermark Granular Matrix Sensors (Irrometer company http://www.irrometer.com/) were developed using a porous ceramic external shell with an internal matrix structure containing two electrodes (Figure 3b). A synthetic membrane and perforated stainless-steel casing or shell for protection against deterioration surrounds the matric material. These features provide more stability to the sensors and prevent the sensors from dissolving over time under high salt and soil moisture conditions. Matric potential readings can be recorded with either a handheld meter or using a Watermark monitor data logger. Handheld meters generally operate from 0 (near saturated) to 199 cbar (dry soil) compared to Watermark Monitor data loggers that have a measurement range of 0 to 239 cbar.

Watermark sensors are relatively inexpensive compared to other soil moisture sensors with cost ranges from $25 to $35 per sensor, with an additional cost for a portable handheld meter ($185 to $250) and Watermark Monitor data loggers ($350-$400) for continuous monitoring. Due to their large measurement range (0 to 239 kPa), these sensors have been widely used for irrigation scheduling over a wide range of soil and vegetative applications.

A typical sensor average matric potential and soil temperature output during a sugarbeet growing season in a Garland silt loam soil is presented in Figure 4. The average matric potential values were calculated by averaging sensor readings measured at 12, 24, and 36 inches of soil depth. Downward arrows in Figure 4 indicate an irrigation or rainfall event, which causes matric potential to decrease. The performance of Watermark sensors can also be slightly affected by variations in soil temperature. Under factory settings, sensors are calibrated for a default temperature of 70ºF. However, soil temperature in an irrigated field within a growing season does not fluctuate much, and thus the effect of soil temperature on soil matric potential is negligible (Figure 4). If the user has soil temperature measurements, it is recommended to adjust the matric potential reading for temperature fluctuation according to the equation:

$$SMP_{adj} = SMP + (T_s - 70°F) \times 0.01$$

Where, SMP_{adj} = adjusted soil matric potential; *SPM* = actual soil matric potential reading; T_s = soil temperature (°F).

Attaching the Watermark sensors to 7/8-inch thin wall PVC pipe using a PVC glue to provide a proper fit is recommended. This set-up permits easy pushing and pulling of the sensors into the access hole during installation and removal. Figures 5 and 6 show materials and step-by-step instructions to prepare and install Watermark sensors in a field.

Use the PVC cap to close the top of the PVC pipe to prevent water (rain or irrigation) from entering. New sensors must be soaked in irrigation water overnight, let dry until evening, wet again for 30 minutes, let dry overnight, and wet again before installation. This procedure helps improve the sensor response to irrigation. It is important to check the wet

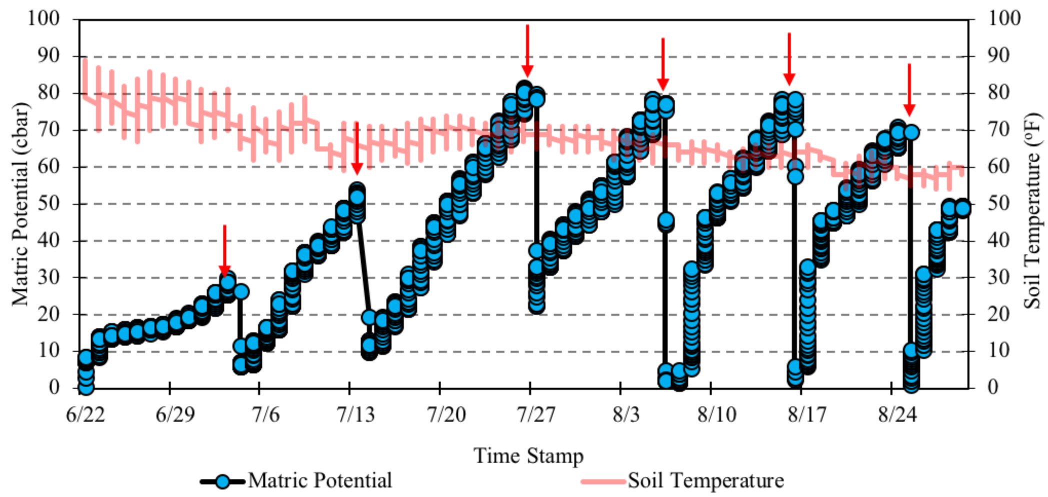


***Figure 4**. Watermark sensor average matric potential output installed 1-foot and 2 feet in a sugarbeet field and soil temperature output installed at 1-foot depth at Powell Research and Extension Center near Powell in Garland silt loam soil in 2016. Red arrows indicate an irrigation (I) or rainfall (R) event, which causes matric potential to decrease.*

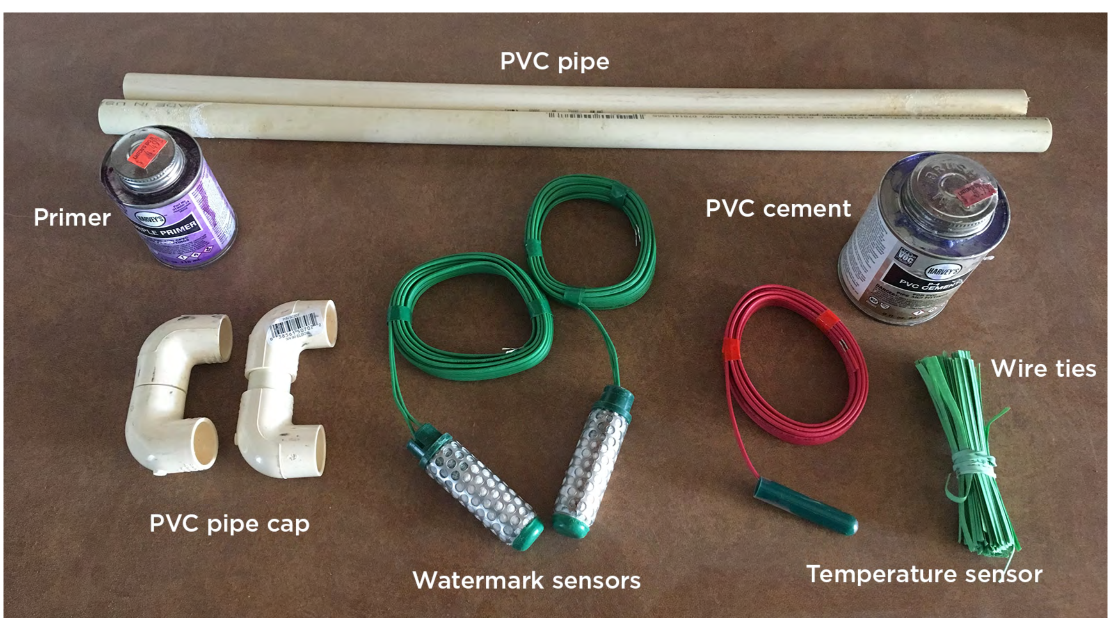
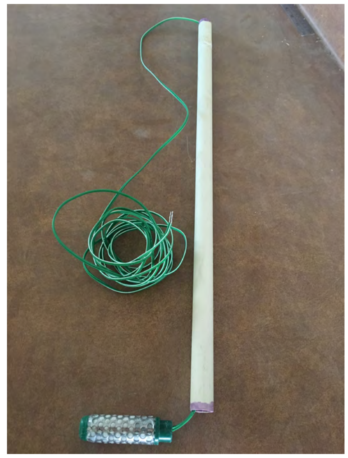


***Figure 5**. Materials required to prepare the Watermark sensors before field installation.*

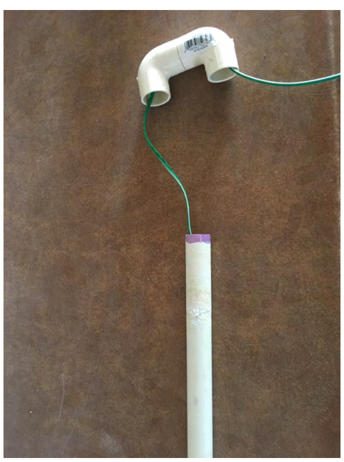
Step 1. Prime the one end of the PVC pipe and let it dry.



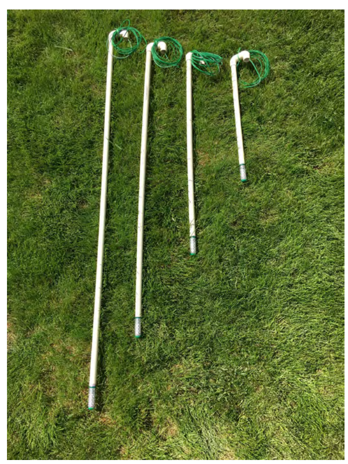
Step 2. Thread sensor wire through PVC pipe.

Step 3. Apply glue to the plug of the sensor.

Step 4. Insert the sensor into the PVC pipe.

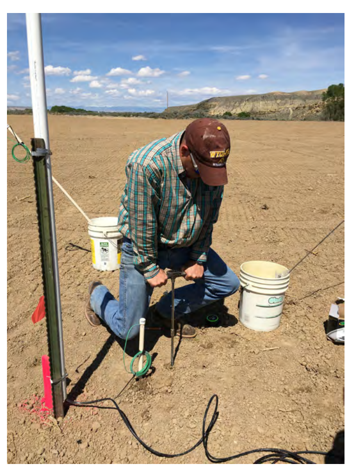


Step 5. Connect the PVC cap to the other end.



Step 6. Place the sensor in the sun and let it dry.

Step 7. Put the sensors in water before installation.



Step 8. Sensor installation in field using soil probe.

Figure 6. *Preparing and installing Watermark sensors in a field.*

Figure 7. *A typical installation of Watermark sensors at different depths with (a and b) wired and (c) wireless monitoring systems in sugarbeet, alfalfa seed, and dry bean fields in the Big Horn Basin.*

sensor reading before installation (generally between 0 to 10 kPa). If the sensors read greater than 10 kPa, they may need to be replaced. When sensors are soaked in water, some amount of water will rise in the PVC pipe due to capillary action. Removing this water before installation is critical. Otherwise, the water in the PVC pipe will slowly wet the watermark sensors causing the sensor to read wet soil moisture. A typical installation of Watermark sensors with wired and wireless monitoring systems in sugarbeet, alfalfa seed, and dry bean production fields is presented in Figure 7.

For data monitoring, a handheld meter, Watermark monitor data logger, or a wireless mesh network can record soil moisture and other sensor data. When using the handheld meter, take readings two or three times per week then plot the data on graph paper (provided by the manufacturer) to record the matric potential readings and determine the next irrigation (Figure 8).

A Watermark monitor data logger is also available to monitor the soil matric potential and other data, such as soil temperature, continuously. Up to eight sensors (Watermark sensors plus temperature sensors) can be attached to each data logger, and readings can be recorded at different time intervals ranging from 1 minute to 24 hours. Note if the data logger is programmed to read and record data for the shorter interval (1 minute or 15 minutes), the data logger memory will fill up quickly. For hourly measurements, the data logger memory can record up to 170 days when using all eight ports. The more advanced option is the wireless mesh network data collection system that automatically records soil moisture and other sensor data. This data can be viewed in real time on the web or downloaded in the field. It includes sensor nodes, data logger, battery, and solar panel (Figure 8). For more information on this method, please visit installation and operating instructions available at http://www.irrometer.com/pdf/Instruction%20Manuals/IRROmesh/745%20IRROmesh%20Manual-WEB.pdf.

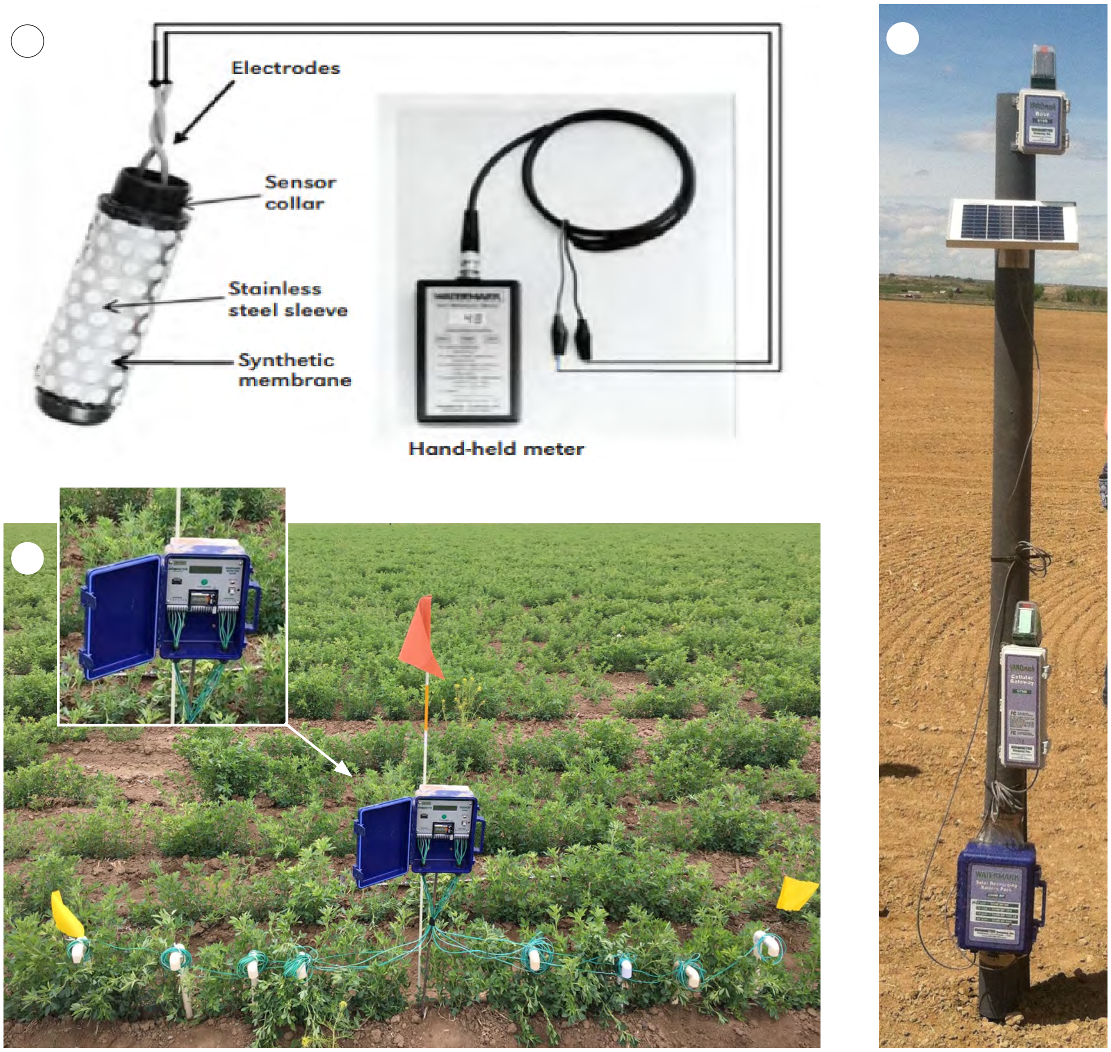


Figure 8. *Watermark monitoring systems (a) Watermark sensor attached to handheld meter (adapted from Irmak, 2016) (b) eight Watermark sensors attached to Watermark monitoring data logger and (c) wireless mesh data monitoring system sensor node, data logger, and cell gateway battery pack powered by solar panel.*

ELECTROMAGNETIC SOIL MOISTURE SENSORS

Common types of commercially available electromagnetic sensors include (a) Frequency Domain Reflectometry (FDR) or capacitance (C), (b) Time Domain Reflectometry (TDR), (c) Amplitude Domain Reflectometry (ADR)/Impedance, and (d) Time Domain Transmission (TDT). Table 2 highlights the advantages and disadvantages of each sensor technology. These sensors indirectly measure volumetric soil moisture content based on the dielectric and electric properties of the soil medium (**soil bulk permittivity** or **soil dielectric constant**, Ka) that determines the storage and dissipation of the magnetic and electric energy of soil components, which is related to soil moisture content (Muñoz-Carpena, 2004).

Soil medium is generally composed of three components, soil particles, water, and air, all of which have different dielectric constants. The dielectric constant for soil particles generally ranges from 3 to 5, whereas air and water have a dielectric constant of 1 and 80, respectively. Since the dielectric constant of water is much larger than that of other soil constituents, the total permittivity of the soil is mainly governed by the presence of soil water content.

The following section describes the basic principle and description of the sensors. 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.

Table 1. *Commercially available electromagnetic sensors with manufacturer, type, and output to volumetric water content.*

Sensor	Manufacturer	Type	Sensor Output*
CS 650/655	Campbell Scientific (https://www.campbellsci.com/soil-water-content)		
TDR	Ɛ, ECb, T		
CS 616	Campbell Scientific	TDR	Period (µs)
Theta Probe	Delta-T (https://www.delta-t.co.uk/product-category/soil_science/soil_moisture_sensors/)		
I	Voltage		
Field ScoutTDR 100	Spectrum Technologies (https://www.specmeters.com/soil-and-water/soil-moisture/soil-moisture-sensors/)		
TDR	Ɛ, ECb		
ML3	Delta-T	I	Voltage, T
5TE	Decagon (https://www.metergroup.com/environment/products/)		
C	Ɛ, ECb, T		
10HS	Decagon	C	Voltage
GS1	Decagon	C	Voltage
TrueTDR-315	Acclima (http://www.acclima.com/products.html)		
TDR	Ɛ, ECb, T		
Hydra Probe	Stevens (https://www.stevenswater.com/products/)		
I	Ɛ, Ɛ', Ecb		
PR1/PR2 Probe	Delta-T	C	Voltage
Diviner 2000	Sentek (http://www.sentek.com.au/products/soil-moisture-triscan-sensors.asp)		
C	Count		
TriSCAN	Sentek	C	Count
EnviroSCAN	Sentek	C	Count
Digital TDT	Acclima	TDT	Ɛ, ECb, T

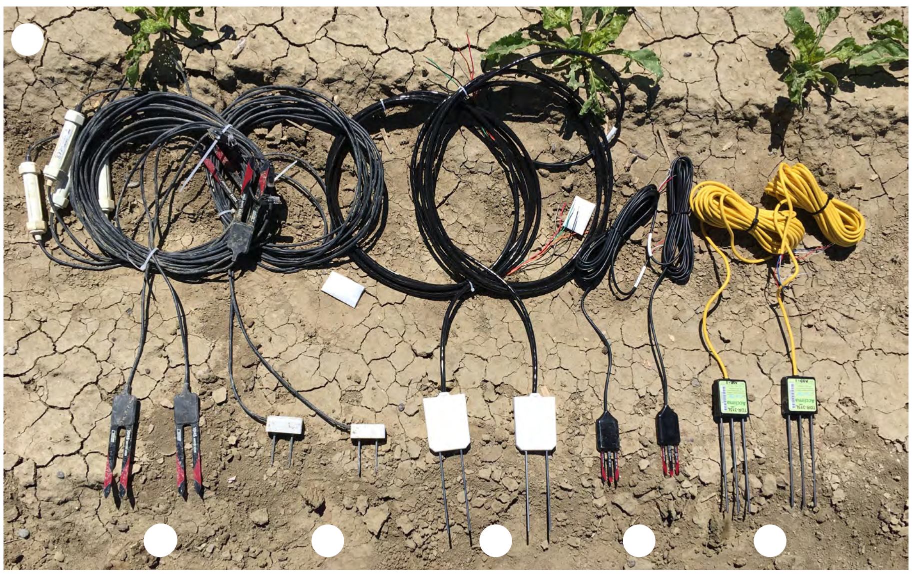
* Ɛ = real dielectric permittivity, Ɛ' = imaginary dielectric permittivity, ECb= electrical conductivity, T = temperature, TDR = time domain reflectometry, I = impedance, C = capacitance, TDT = time domain transmission

FREQUENCY DOMAIN REFLECTOMETRY (FDR) OR CAPACITANCE SOIL MOISTURE SENSORS

These sensors are comprised of a capacitor that uses soil as a dielectric, which depends on the soil water content. Generally, these sensors are in the form of (i) a pair of parallel stainless-steel rods or (ii) a pair of metal rings attached along the length of a PVC pipe, which act as an electrode (Figure 9). The capacitor along the length of the PVC pipe is designed typically to have multiple sensors along the length of the pipe usually at an interval of 4 inches (however, it can vary depending upon the manufacturer) and thus allow simultaneous measurements of soil moisture at different depths.

When an oscillating frequency is applied to the electrodes, the soil around the electrodes (or around the tube) forms the dielectric of the capacitor that completes the oscillating circuit. The changes in soil moisture can be detected by changes in the operating frequency. In capacitance sensors, as the capacitor emits an electromagnetic field in the soil, it

Figure 9*. Different types of electromagnetic sensors. (a) Pair of parallel stainless steel rods attached to data-logger. (b) A pair of metal rings attached along the length of a PVC pipe installed in a sugarbeet field at the Powell Research and Extension Center.*



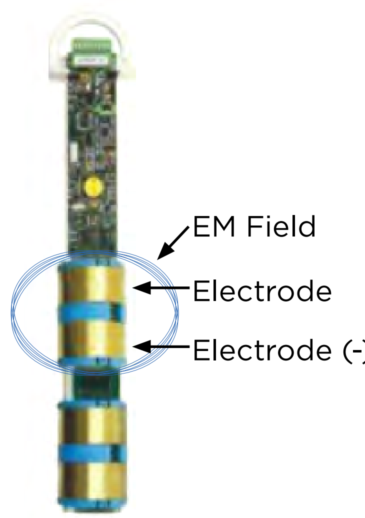
1. Decagon 10HS (C) 2. Decagon GS1 3. (C) Campbell Scientific CS655 (TDR) 4. Decagon GS1 (C) 5. Acclima TDR-315L (TDR)*

Data logger

Crop Metric Sentek TriSCAN probe (C)

AquaSpy probe

John Deer Field Connect probe (C)



Capacitor

* C = capacitance, TDR = time domain reflectometry

measures the permittivity of a soil medium by measuring the charge time of a capacitor made with that medium and thus the soil water content (Evett and Cepuder, 2008).

In FDR sensors, the oscillator frequency is applied 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. 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. Some example of capacitance-based sensors includes Decagon 5TE, Decagon 10HS, Delta-T PR1/PR2 probes, Sentek TriSCAN etc.

TIME DOMAIN REFLECTOMETRY (TDR) SOIL MOISTURE SENSORS

With TDR, soil moisture is measured by estimating the travel time of a fast rise step voltage pulse traveling along a transmission line built with a coaxial cable and a probe. It consists of two or three parallel rods inserted into the soil acting as waveguides. An electromagnetic wave is passed through the soil via the rods from a transmission line. Similar to the FDR technique, the speed and strength of the wave after it travels from one rod to the other is directly related to the dielectric properties of the soil, and hence, its soil moisture content. As the dielectric constant of the soil increases, the travel time decreases, and soil moisture content can be estimated using the calibration equation (Topp et al., 1980).

In general, TDR instrumentation requires a device capable of generating a series of timed electrical pulses with a wide range of high frequencies. This high frequency provides a permittivity response less dependent on soil specific properties like texture, salinity, or temperature as compared to other techniques (Evett and Heng, 2008). TDR sensors can be installed vertically, horizontally, or diagonally as they provide an average soil moisture content across the length of the probe. In the past, the high cost of TDR sensors hindered their use for estimating soil moisture content for irrigation; however, with recent advances in technology and a reduction in cost, these sensors are now frequently being used for irrigation purposes. Some commercially available TDR sensors are the Acclima TDR-315 and the Campbell Scientific CS 650/655. Each have all the necessary electronics embedded in the sensor head to generate the voltage pulse and transfer the processed data to the data logger (Figure 9).

Stevens Hydra probe

Acclima TDT soil moisture sensor

Figure 10. *(a) Amplitude Domain Reflectometry (ADR) or Impedance and (b) Time Domain Transmission (TDT) soil moisture sensors.*

AMPLITUDE DOMAIN REFLECTOMETRY (ADR)/IMPEDANCE SOIL MOISTURE SENSORS

The ADR or impedance method of soil moisture measurement requires an oscillator to generate an electromagnetic signal (sinusoidal signal at a fixed frequency) propagated through the sensor with rods (usually two or three) inserted into the soil. When this electromagnetic signal reaches a section with a different impedance, part of the signal reflects back to the transmitter. The reflected wave interacts with the incident wave and measures the change in the wave amplitude of the reflected signal in volts and gives the impedance of the probe and both real and imaginary dielectric permittivity, which in turn is used to measure the soil moisture content (Gaskin and Miller, 1996; Nakashima et al., 1998). Some commercially available ADR or impedance sensors include Stevens Hydra Probe, Delta-T ML3 and Delta T Theta Probe (Figure 10).

TIME DOMAIN TRANSMISSION MOISTURE SENSORS

This method of soil moisture monitoring is very similar to the TDR technique, except it measures only the one-way time for an electromagnetic pulse to propagate along the transmission line (pulse along a looped or closed circuit) (Figure 10). The metal rod is designed in such a way that the beginning and end of the transmission line are inserted into the electronic block. It measures the time from the start to the end of the loop for the propagation of an electrical pulse. The relationship between the one-way transmission time and the dielectric constant is further used to quantify the actual soil moisture content. This technique is relatively new and has been developed over the last 10 years. Some commercially available TDT sensors include Acclima TDT soil moisture sensors and Acclima 2-wire TDT sensors.

INSTALLATION OF ELECTROMAGNETIC SENSORS

The sensor design determines the methods to install electromagnetic sensors. Many sensors come with manufacturer recommendations for installation. For example, capacitance or TDR sensors with stainless-steels rods can be installed by simply pushing the sensor rod in the soil to the desired depth. This can be done either (i) by digging a trench or hole and installing sensors horizontally toward the crop root zone at different depths or (ii) by using an auger or soil sampling probe to bore a hole and install sensors vertically until they reach the bottom of the hole. The latter approach requires specific sensor holding tools for installation at a deeper depth. An alternative is to use PVC pipe and gluing the electromagnetic sensor at one end of the PCV rod, similar to Watermark sensors (Figure 6).

Multi-depth capacitance sensors (Figure 9b) are inserted in a PVC pipe (usually provided by the manufacturer). A soil auger or sampling probe can be used to make a bore that accommodates the length of the tube. Care must be taken when drilling the hole. Do not install the sensor in an oversize hole as it may cause voids and air gaps. To prevent air gaps, some users use a mixture of soil and water during the installation; however, in many cases, the structure of the slurry does not match the surrounding soil, which may adversely affect the sensor reading. The majority of multi-depth sensors come in different access tube diameters and lengths. Follow the manufacturers' recommendations for installation.

NEUTRON SCATTERING

This method is considered to be the most accurate indirect method of soil moisture monitoring. Neutron probes consist of a neutron source, detector, and an electronic counting scale, which are connected together by an electric cable. Measurements at desired depths are made by lowering the probe down an access tube installed vertically in the soil. High-energy neutrons are emitted by a radioactive source (Americium 241/Beryllium) in all directions into the soil where they collide with hydrogen atoms of water (i.e., H_2O) in the soil (IAEA, 1970). Through repeated collisions, the speed of the neutron is attenuated or slowed down. Thus, the rate of attenuation is dependent on the amount of water present.

A detector near the source counts the number of slow-moving neutrons over a period ranging from 15 seconds to 2 minutes. These raw counts are then transmitted to the microprocessor and converted using a calibration equation (provided by the manufacturer or developed by field calibration) into a volumetric water content value.

Neutron gauges are not typically used for on-farm irrigation management due to their radioactive source; however, due to its accuracy, this method is commonly used for research applications and to calibrate other soil moisture sensors. Keeping radiation exposure to a minimum and avoiding physical damage to the instrument is important. Radioactive material can be a potential health hazard. Proper training in handling, storing, and transporting and licensing are required before use. A badge (received after training and licensing) must be worn by operators to monitor exposure levels. The operator is also required to maintain a daily use log for the neutron moisture meter. A leak test must be performed semi-annually.

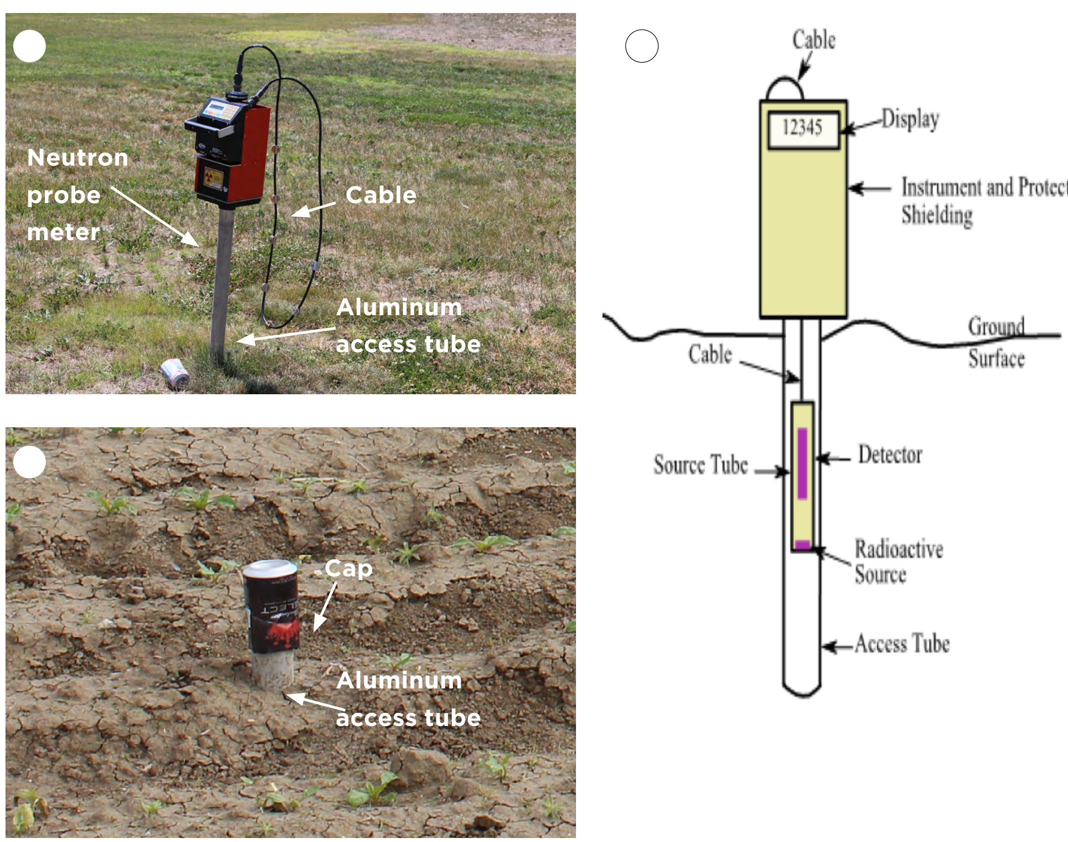


Figure 11. *Neutron probe (a) standard count measurement, (b) access tube with the top cover installed at Powell Research and Extension Center and (c) illustration of neutron probe unit in the field. (Adapted from UC drought management Neutron probe meter.)*

Typical installation includes access tube installations by placing them in snug-fitting holes, pre-drilled by a soil tube or auger, which are either hand or machine-operated (Giddings probe; Gidding Machine Company, Windsor, CO). Ideal tubes have a minimal wall thickness, just large enough for the probe to fit into without an air gap and are of a material that will not thermalize neutrons. Other factors for the choice of access tube material include cost, durability, and availability. In general, aluminum is the best material choice, although brass, steel, and stainless steel have also been used successfully. It is important not to install the access tube in an over-sized hole as it may create voids and air gaps adjacent to the access tube. It is also important to cover the access tube from top (using an inverted can) to avoid any accumulation of water inside the access tube (Figure 11).

CONSIDER THE FOLLOWING BEFORE SELECTING AND INSTALLING MOISTURE SENSORS

Cost and support

Initial cost of the sensors is an important factor when considering the moisture sensor. Table 2, page 16, highlights the approximate initial cost for each sensor technique. In general, low-cost sensors tend to be read manually compared to automated sensors that include the cost of a data logger for continuous data monitoring. The cost further depends on whether moisture sensors are connected to a data logger or irrigation controller via direct connection (wired) or remotely (wireless). Many manufacturers now offer technical support, which includes installation, maintenance, and data interpretation.

Placement and number of soil moisture sensors

It is recommended users install sensors at places within a field that have average soil and surface conditions, avoiding field edges, and unusually wet or dry areas. Web Soil Survey (https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm) is a free online tool that provides soil data, including soil type as well as soil physical and chemical properties. This information can be used to find the location with average soil conditions. For sensor placement, considering crop type and rooting depth is important. For deep-rooted plants (rooting depth > 2 to 3 feet) such as corn and alfalfa, install soil moisture sensors at three depths (1 foot, 2 foot, and 3 foot, for example). The number of sensors can be reduced to two depths for shallow-rooted crops.

Table 2. Summary of advantages and disadvantages of each soil moisture monitoring technique and its associated cost.

Monitoring Technique	Advantages	Disadvantages	Cost
Feel and Appearance	• Least-costly method • Multiple locations	• Subjective and qualitative assessment; not quantitative. • Difficult when working with layered soils • Time-consuming and labor-intensive	• Labor
Gravimetric	• Accurate • Inexpensive • Multiple locations	• Time-consuming and labor-intensive • Time delay	• Labor, drying oven, weighing balance
Tensiometer	• Inexpensive • Widely used and accepted • Not affected by salinity • Continuous reading possible using transducer • High-frequency sampling • Minimal skill required • Easy to install	• Small operative range (0 to 85 cbar) • Slow response time • Need good contact between sensor and soil • Requires frequent maintenance (refilling) to keep the tube full of water • Operating range works for sandy soils but not for fine-textured soils	• $60-$80 (requires 3-4 sensors) • Plus $140-$155 if installed with transducer
Electrical Resistance	• Large sample area • Can be used in moderately saline soils • Simple and inexpensive • Easy to install • Best suited for irrigation management	• Not recommended for sandy soils because of slow response time as water moves fast in sandy soil • Performs poorly in soils that shrink and swell • Affected by soil temperature fluctuation	• $20 per sensor (3-4 required per location • Plus $200 for hand manual reader and $500 for data logger
Frequency Domain Reflectometry (FDR)	• Remote access capability • Fast response time • Accurate after soil-specific calibration (±1%) • Compared to TDR, FDR can be used in high saline soils • Flexibility in probe design • Moderately inexpensive compared to TDR	• Small sensing area (1.6 inches) • Need good contact between the sensor (or access tube) and soil • Careful installation is required to avoid air gaps • Sensitive to soil temperature, bulk density, clay content, and air gaps • Need soil-specific calibration	• $250 to $300 per sensor (3-4 required per location) • Plus $500-$2500 for data logger • $500-$1000 access tube installation kit
Time Domain Reflectometry (TDR)	• Accurate (±1%) • Soil-specific field calibration is usually not required • Not easily influenced by moderate soil salinity • Remote access capability	• Small sensing area (0.4 inches) • Need good contact between sensor and soil • Expensive	• $250-$300 per sensor (requires 3-4 sensors per site) • Plus $1,000-$3,000 for data logger
Neutron Scattering	• Accurate and reliable • Unaffected by salinity • Large sample area	• Soil-specific field calibration is required • Highly regulated • Expensive • Safety hazard • Heavy and cumbersome • Reading close to soil surface is difficult and not accurate • Manual reading	• Neutron probe (>$10,000) • Plus $10-$20 per access tube

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GLOSSARY

Bulk density: Soil bulk density is defined as the ratio of the mass of the dry soil to the total volume occupied by the soil including the volume of the pores. The total volume includes the volume of soil particles plus the volume of void space.

Dielectric constant: The measure of ease in which a wave of electromagnetic energy can move through the material

Factory calibration equation: Factory calibration means the fine-tuning process (measure the output of a sensor in response to an accurately known input) of sensors during manufacturing process. Factory calibration is generally performed under controlled laboratory conditions, which may or may not represent field conditions.

Permittivity: Property of the material that affects the forces between two changes points in the material.

Photosynthesis: The process by which plants use the energy from sunlight to produce glucose and oxygen from carbon dioxide and water.

Sensor operational range: The maximum and minimum value range across which a sensor works.

Sensor response time: The time required for a sensor output to change from its previous state to a new value.

Sensor sensing volume: The volume of soil around the sensor across which a sensor measures moisture.

Soil matric potential: A measure of the energy status of soil water relative to that of water at a standard reference, generally expressed in the units of pressure. It indicates the ability and the amount of energy that plants have to overcome to extract water from a soil profile.

Transpiration: The biological-associated evaporation of cellular water from within the plant leaves. It is defined as the process of movement of moisture through the plant roots to stems and leaves to the atmosphere through plant leaf stomata. Stomata are the microscopic pores on a leaf surface through which the plant transfers water and gas to the atmosphere. This process is important for leaf cooling.

Volumetric water content: The amount of water held in a unit volume of soil at any given time.

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