Soil Water Sensors for Irrigation Management

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Introduction

This Nebraska Extension Circular addresses different methods and instruments for measuring soil water status for irrigation management. The advantages and disadvantages of each method are discussed.

Overview

Accurate quantification of soil water status is important for proper irrigation scheduling as well as other hydrological and environmental assessments. Soil water status refers to the amount of water held within a unit of soil at a distinct period in time. Soils range in their ability to hold and transport water due to differences in soil physical and chemical properties. For irrigation purposes, soil water is most critical between two points referred to as field capacity (FC) and permanent wilting point (PWP), which are the upper and lower limits, respectively, of a soil's available water holding capacity (AWHC). Field capacity is the amount of water remaining in the soil profile after water freely drains following a wetting event; whereas, PWP is the amount of water in the soil profile that is unavailable for plant uptake.

The Nebraska Extension Circular EC2009, *Basic Soil and Water Resources and Irrigation Engineering/Agricultural Water Management and Related Terminology* reports the estimated FC and PWP values for different soil textures. AWHC ranges between 0.27 in/ft for sand to 2.40 in/ft for silt soils. Consequently, the accuracy of soil water sensors can impact irrigation management at different magnitudes depending on soil texture. For example, a sensor with error of ±0.10 in/ft would not be well suited for a sandy soil that has low AWHC, but would perform satisfactorily for a silt loam soil that has high AWHC.

Soil Water Content

Soil water content can be defined on a volume "volumetric water content" or mass "gravimetric water content" basis. Volumetric water content (θ_v) is the volume of water (V_w) present in a bulk volume of soil (V_b) and is calculated as:

$$\theta_v = \frac{V_w}{V_b} \qquad \text{(Equation 1)}$$

whereas gravimetric water content (θ_g) is the ratio of mass of water (m_w) to mass of solids (m_s), and is calculated as:

$$\theta_g = \frac{m_w}{m_s} \qquad \text{(Equation 2)}$$

The relationship between θ_v and θ_g is as follows:

$$\theta_v = \theta_g \times \frac{\rho_b}{\rho_w} \qquad \text{(Equation 3)}$$

where ρ_b is the soil bulk density (lb ft^{-3}) and ρ_w is the density of water (~ 62.4 lb ft^{-3}). For irrigation management, θ_v is typically used instead of θ_g, since θ_v can be defined in terms of depth of water, which is analogous to irrigation application depth.

Volumetric water content is directly measured using the gravimetric method, which includes removing a known volume of soil (V_b), drying the soil at 221°F (105°C) until a constant weight is achieved, determining the volume of water loss (V_w) by recording the weight of the soil prior to and following drying, and then solving for equation 1 by dividing V_w by V_b.

Soil Matric Potential

Soil water status can also be described in terms of matric potential (Ψ_m), which is a measure of how tightly the water is held within the soil. In other words, Ψ_m describes the amount of work that the crop root system would have to exert on the soil to uptake water. It can be measured using a hanging water column or a pressure plate apparatus. These methods use a porous plate that allows water—but not air—to transfer across the membrane. The porous plate will come into equilibrium with the soil, and the corresponding tension (or pressure) can be measured using a vacuum gauge or pressure transducer.

Soil Water Sensors and Methods

Direct methods for quantifying soil water status can be destructive, tedious, time consuming, expensive, limited by physical constraints, and are noncontinuous in nature. Consequently, other methods and technologies have been developed to estimate soil water status. Some of these sensors and methods that have been used for irrigation management include:

- Appearance and Feel
- Neutron Gauge
- Capacitance Probes (installed within access tubes)
- Time Domain Reflectometry
- Tensiometers
- Electrical Resistance Sensors

These are "indirect" soil water monitoring methods, which means that they do not directly measure soil water status, but instead estimate θ_v or Ψ_m from another property using a calibration equation (commonly referred to as a "factory" calibration). Factory calibrations are often performed under controlled laboratory conditions, which may or may not be representative of field conditions. The derived factory calibration equations, which are usually embedded into the sensor electronics and/or data logger, are typically developed by pooling a range of soil textures together and fitting a response curve to the data. More recently, soil specific curves are being developed by manufacturers to improve the performance of their factory calibrations. In some instances, it may be necessary to develop a field calibration for a sensor type to improve its performance for a specific soil type.

Indirect soil water sensors can be susceptible to various factors, such as soil temperature, soil physical and chemical properties, wetting and drying cycles, etc., which can affect sensor performance as well as the accuracy of the supplied factory calibration equations. Unfortunately, due to differences in sensor technology, different sensors will not necessarily respond the same to an influencing factor. Physical attributes can vary across sensors, such as sensing volume, sensor spacing, response time, and operational range and frequency. As a result, when selecting a soil water sensor for an intended use, it is important to understand how the sensor works. In addition, the following can be used to help infer what sensor is best for your operation, including convenience and product support, financial cost, remote access capability, sensor accuracy, susceptibility to influencing factors, the number of sensors required, sensor spacing, sensing volume, and integration with other sensors. A brief overview and descriptions of some different types of sensors and methods are presented below. The reader is directed to the manufacturer's website to obtain additional information on a sensor type and the manufacturer's services.

Appearance and Feel Method

The appearance and feel method consists of viewing and feeling the soil to make an inference of soil water status to determine whether or not irrigation is required *(Figure 1).* It is often the least accurate method because it does not provide a quantitative assessment of soil water, but rather a subjective and qualitative assessment. The accuracy or success of using this method relies on the ability of a user to view and feel the soil. It becomes even more challenging when working with layered soils or different soil textures due to differences in soil properties. It is one of the least costly methods because it only requires a hand probe or auger to remove soil at a depth of interest. Similar to the gravimetric method, it is labor intensive, time consuming, and is a point-in-time measurement. Consequently, due its inaccuracy the authors do not recommend the use of this method for irrigation management and scheduling decisions. However, it can be used in conjunction with other sensor technologies to observe relative differences in soil water status in areas of the field where sensors are not installed.

Neutron Gauge

The neutron gauge is the most accurate indirect soil water sensor available. It comprises a neutron source and a detector that is connected to a cable. The source and detector are lowered into permanently installed (during the growing season) access tubes (usually aluminum) to a desired depth where a measurement can be taken. The access tubes are typically installed using a Giddings probe (Giddings Machine Company, Windsor, CO) *(Figure 2A).* The nuclear source emits fast

Figure 1. Demonstration of the process of using the hand feel method for a qualitative assessment of soil water status.

neutrons, approximately 17,000 neutrons per second, where they are thermalized (slowed down) by colliding with hydrogen atoms (water) present in the soil (Rudnick et al., 2015). The sphere of influence depends on θ_v and the sensing radius (R, inch) can be estimated as follows (IAEA, 1970):

$$R = 5.9(\theta_v)^{-1/3} \qquad \text{(Equation 4)}$$

Neutron gauges are for the most part not affected by temperature and salinity; however, they can be influenced by organic matter content, soil texture, and other chemical elements. Therefore, field calibration using the gravimetric method is still recommended. A field calibration consists of comparing the count ratio, which is the neutron count (thermalized neutrons) divided by the standard count to the gravimetric determined θ_v. The calibration equation has a linear relationship expressed as:

$$\theta_v = a \times \left(\frac{Neutron\ Count}{Standard\ Count}\right) + b \qquad \text{(Equation 5)}$$

The standard count is used to monitor the performance and verify that the neutron gauge is operating without faults. It should be taken with the probe locked in the shielding unit at an elevated surface, with a height of 2 ft minimum but ideally a height of 3 ft or greater *(Figure 2B).* This ensures that the standard count will not be affected by soil, vegetation, and/or other factors. Following the standard count, field measurements can be taken by placing the neutron gauge on an access tube and lowering the source to a desired depth *(Figure 2C).* Neutron gauges can be susceptible to neutron scattering outside of the soil when taking near surface readings (i.e., less than 12 inches), which can reduce sensor accuracy. However, a field calibration can be developed to improve sensor performance when taking shallow measurements. Care must be taken during in-field measurements to prevent damaging or breaking plants. The user should also confirm that all tubes are absent of water prior to lowering the source into the access tubes.

Neutron gauges are not typically an option for on-farm irrigation management due to the radioactive source, which requires proper training, licensing, and safety measures when handling, storing, and transporting the instrument. In addition, a neutron gauge is expensive, which further limits its use for on-farm irrigation management. However, due to its known accuracy, it is commonly used for research applications and can be used as the standard to calibrate other soil water sensors.

Capacitance Probes Installed Within Access Tubes

Capacitance probes are a form of electromagnetic (EM) sensors that indirectly measure θ_v based on the dielectric properties of the soil medium. Soil medium is made of three components: liquid, gas, and solid particles, all of which have different dielectric constants. A substance's dielectric constant is defined as the ratio of that substance's dielectric permittivity to that of free space. It is not constant, but varies with the frequency of the EM sensor (Radcliffe and Šimůnek, 2010). The dielectric constant of water is approximately 80 at 20°C, whereas air has a dielectric constant of 1.0, and soil minerals have dielectric constants between 2.7 and 5.0. Due to the relative values of the constants, an increase in capacitance means an increase in soil water content. The performance of capacitance sensors can be susceptible to soil salinity, temperature, and clay content.

Capacitance probes usually consist of capacitors (i.e., pairs of metal rings) located along the length of the probe *(Figure 3)* and are placed within a plastic access tube. The placement of the capacitors along the probe shaft can vary depending on the manufacturer, but are usually placed in 4-inch increments. A capacitor emits an EM field that extends outside of the access tube, commonly called the fringing field,

Figure 2. Installation of an access tube (A), standard count measurement (B), and in-season field measurement of a CPN 503DR Hydroprobe™ (neutron gauge) (C).

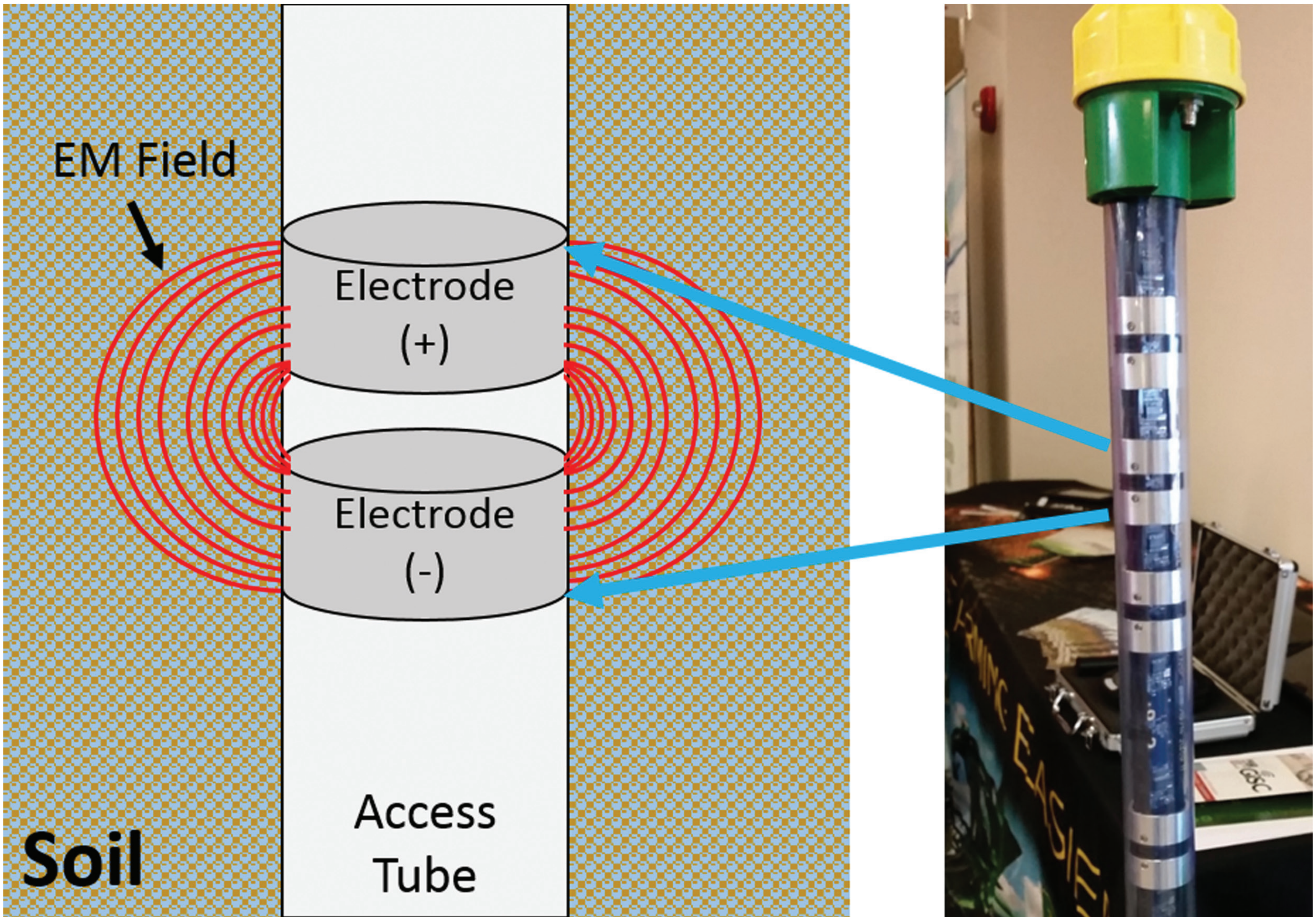

Figure 3. Capacitors located within a John Deere Field Connect™ capacitance probe with an illustration of a capacitor's electromagnetic (EM) field penetrating the soil.

into the soil such that the capacitance is influenced by the soil bulk electrical permittivity and thus by soil water content (Evett and Cepuder, 2008).

The sensing volume is dependent on soil water content; however, the measuring radius of some capacitance probes is less than that of a neutron gauge and/or by gravimetric sampling, which can make calibrating the sensors troublesome (Evett and Cepuder, 2008). Nevertheless, most capacitance probes follow the trends in wetting and drying cycles, which if coupled with known information on soil and crop type, can be effectively used to schedule irrigation even if a field calibration cannot be performed.

Proper installation of capacitance probes is extremely important to prevent air gaps between the probe and soil, which can result in false readings. To prevent this from occurring, some companies use a slurry (i.e., mixture of soil and water) during installation. Unfortunately, the structure of the soil slurry is not representative of the surrounding soil, which can change the soil's AWHC and adversely impact the sensor readings.

Depending on the unique situation, using or not using a slurry may be appropriate. For example, if a producer cannot avoid air gaps when attempting a dry install (i.e., no slurry), the slurry method might be a more appropriate option. Capacitance probes can also be affected by high θ_v areas surrounding the capacitors since EM fields will radiate preferentially into more conductive (wetter) soil peds. This can cause a sensor to read higher soil permittivity and water content, compared with the average water content surrounding the probe (Evett et al., 2009).

Capacitance probes have several advantages, which can include remote access capability, compatibility with additional instrumentation such as a weather station, continuous monitoring capability, fast sensor response time, and information on root activity by observing changes in sensor readings over time. In addition, several companies that deploy capacitance sensors offer technical support, which can include installation and maintenance of the product as well as data interpretation. It should be noted that other capacitance-based sensors exist besides those that consist of an access tube. Examples of such sensors are those developed by Decagon Devices (Decagon Devices, Inc., Pullman, WA), which consist of steel electrodes that are inserted directly into the soil.

Time Domain Reflectometers

Time domain reflectometry (TDR) sensors estimate soil water content by propagating an electromagnetic wave along a cable attached to a sensor with rods (usually two or three) inserted into the soil (i.e., waveguide). The electrical pulse travels the length of the waveguide and then is reflected back after reaching the end of the probe. For estimation of soil water content, the travel time of the pulse along the sensor rods is required.

To obtain the travel time of the pulse, an oscilloscope or equivalent electronic device is used to construct a waveform by capturing the pulse reflected from many points along the waveguide at very small time increments (Evett and Heng, 2008). Similar to the capacitance sensors described previously, TDR operates based on the dielectric constant of the soil medium. As the dielectric constant of the soil increases, the travel time decreases, and therefore, θ_v can be estimated using a calibration equation. The apparent permittivity response of the TDR method is less sensitive to bulk electrical conductivity as compared with other EM-based sensors, since it operates at a higher frequency, which has led to the success of TDR for estimating θ_v (Robinson et al., 2003). TDR probes can be installed vertically, horizontally, or diagonally, and they provide an average θ_v value across the length of the probe. The sensing volume is approximately 0.4 inches (1 cm) above and below the plane of the sensor. To mitigate the effects of air gaps on sensor performance, careful installation is necessary.

A conventional TDR system has a probe, cable tester such as the Tektronix® 1502C *(Figure 4A),* and a data logger with firmware. Historically, the cost of a TDR system hindered the use of TDR for estimation of θ_v for irrigation purposes. Recently, the cost of a TDR system has decreased, allowing the systems to be more competitive for irrigation purposes. In addition, a newly developed TDR sensor (TDR-315™) by Acclima, Inc. is available that has all necessary electronics embedded in the sensor head to generate the pulse and construct the waveform *(Figure 4B).* The raw data is processed in the sensor head and the final estimation of θ_v, soil temperature, permittivity, electrical conductivity (EC), and temperature corrected EC is transmitted to the data logger using the SDI-12 protocol (http://www.sdi-12.org/).

Figure 4. A Tektronix's 1502C cable tester that can be used in a conventional TDR system (A) and a TDR-315 sensor manufactured by Acclima, Inc. that has all electronics embedded in the sensor head to generate the pulse, construct the waveform, and process the data (B).

Tensiometers

Tensiometers measure soil matric potential and are developed for field applications. They consist of a water-

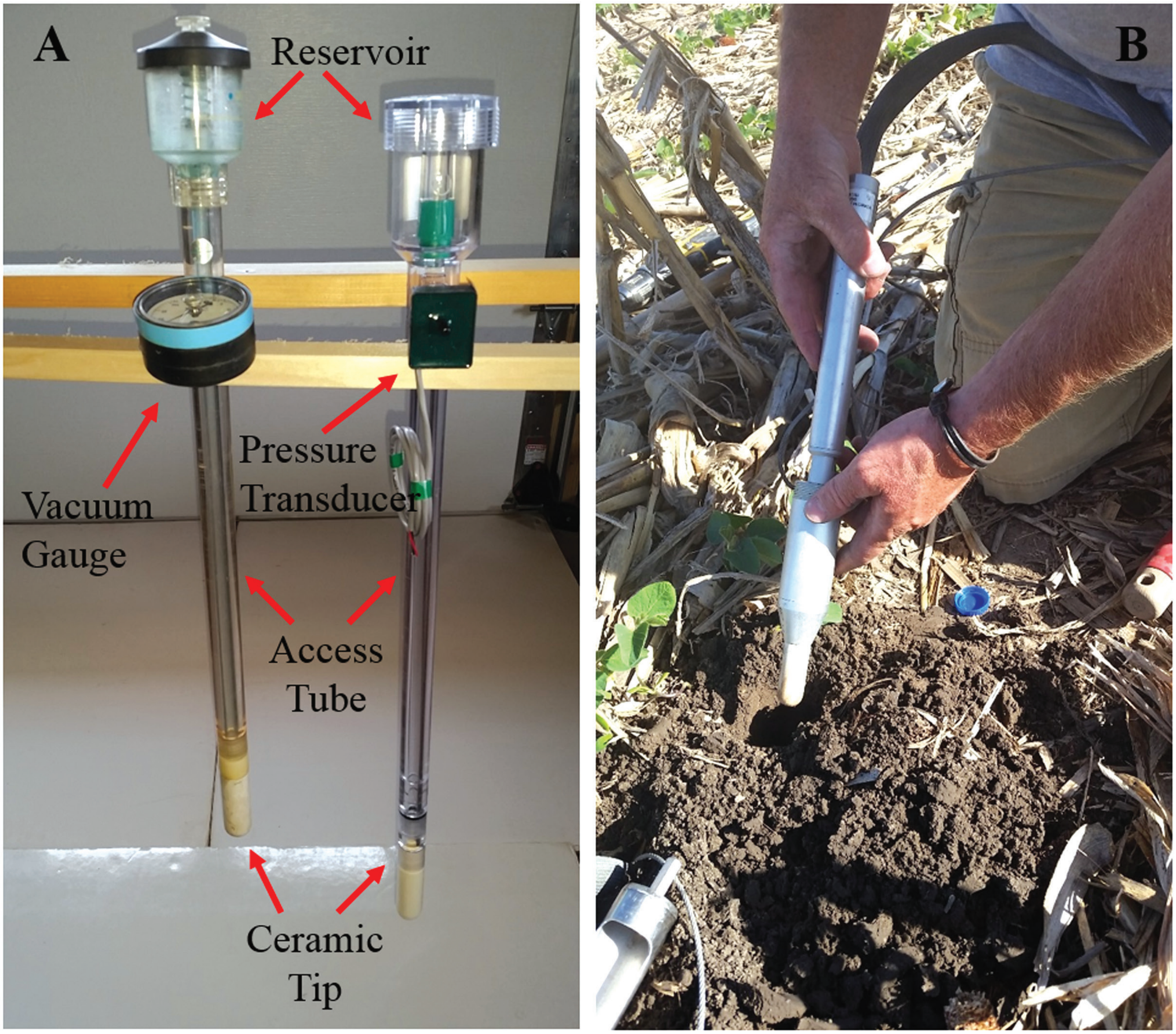

Figure 5. Two traditional tensiometers, one with a vacuum gauge (Soil Moisture Equipment Corp., Santa Barbara, CA) and the second with a pressure transducer (Irrometer Co., Inc., Riverside, CA) (A), and a tensiometer developed by Hortau, San Luis Obispo, CA) (B).

filled tube with a hollow ceramic tip, which is placed in the soil at a desired depth *(Figure 5)*. The sensor will equilibrate with the soil by pulling water out of the tube as the soil dries or pulling water into the tube as the soil wets so good soil contact is required. This process creates or releases tension within the water-filled tube. The tension can be measured and recorded manually (vacuum gauge) or by using a data logger (pressure transducer).

The operational range of a tensiometer depends on elevation relative to mean sea level, but usually ranges between 0 and 75 centibars (cb). Matric potential is influenced by textural classification, since fine-textured soils can hold water at greater tensions as compared with coarse-textured soils, the operational range may not be appropriate for irrigation purposes across all soil textures or management practices such as deficit irrigation.

As described in the Nebraska Extension Circular EC783, *Principles and Operational Characteristics of Watermark® Granular Matrix Sensor to Measure Soil Water Status and Its Practical Applications for Irrigation Management in Various Soil Textures*, the irrigation trigger point to prevent water stress for corn changes across soil textures. A higher tension value is required for silt and clay-based soils as compared to sandy soils. For example, Hastings, Crete, and Holdrege silt loam soils have a suggested irrigation trigger point range from 90 to 110 cb, which is at or above the measurable range of tensiometers, as compared to a Valentine fine sand that has a suggested irrigation trigger point range from 20 to 25 cb.

However, tensiometers may be appropriate for fine-textured soils when frequent irrigation events are required to maintain high soil water status.

Additional factors to consider when using tensiometers include: the sensor is measuring soil tension and not water content and therefore a soil water retention curve will be required to convert between the two; routine maintenance to refill the access tube if/when tension is broken; potential lag time for the sensor to equilibrate with the surrounding soil following a wetting event; and susceptibility of hysteresis. Hysteresis refers to the nonunique relationship between θ_v and Ψ_m (i.e., nonunique soil water retention curve), and considerable variation in θ_v can exist for the same Ψ_m depending on the soil wetting and drying history. This nonunique relationship, which is often described as the ink-bottle effect, is a result of a soil's pore shape since draining of pores (i.e., drying) involves smaller pore radii, and filling of pores (i.e., wetting) involves larger pore radii (Radcliffe and Šimůnek, 2010).

Well-maintained tensiometers can be highly accurate and provide reliable information for scheduling irrigation. They do not require soil specific calibrations nor are they affected by changes in temperature and salinity. Depending on the construction of the tensiometer, it may or may not be insensitive to osmotic potential (Young and Sisson, 2002), which is the effect of solutes on the energy of water. Therefore, under saline conditions the crops may be experiencing greater stress than what is indicated by certain tensiometers.

Figure 6. A Watermark Granular Matrix sensor and gypsum blocks.

Electrical Resistance Sensors

Electrical resistance sensors are used to estimate soil tension (i.e., negative of Ψ_m) and are comprised of two nonconnecting electrodes embedded in a porous media (usually gypsum). A current is applied across the two electrodes, which is affected by soil water content. As soil water content increases, the resistance between the electrodes decreases. The sensor outputs a voltage that is proportional to the resistance in the porous medium, and the resistance value can be converted to Ψ_m using a calibration equation. Several calibration equations relating resistance to Ψ_m are addressed by Irmak and Haman (2001). Gypsum blocks are an early version of an electrical resistance sensor *(Figure 6)*. They are encapsulated in gypsum; sensitive to saline soil water; and decompose rapidly in high salt and soil water content conditions. This causes the gypsum blocks to vary from sensor to sensor and for each sensor over time. Consequently, the authors do not recommend their use in scheduling and managing irrigation.

Watermark Granular Matrix sensors (Irrometer Co., Inc., Riverside, CA) were developed to minimize the negative effects of salt and high soil water content on the sensor by covering the gypsum material with a granular matrix, wrapping it in a synthetic membrane, and surrounding it with a perforated stainless steel shell *(Figure 6)*. The manufacturer specifies the sensor to operate in the range of 0 to 239 kPa when connected to a Watermark data logger, which can alleviate the concerns associated with using a tensiometer.

Watermark sensors are relatively inexpensive as compared with other soil water sensors. As a result, Watermark sensors have been widely adopted for irrigation and research applications in a wide range of soil and vegetation types. However, similar to the tensiometer, Watermark sensors require good soil contact, have a potential lag time for the sensor to equilibrate with the surrounding soil following a wetting event, and are susceptible to hysteresis.

In addition, Watermark sensors are moderately affected by soil temperature. However, as described in the Nebraska Extension Circular EC783, *Principles and Operational Characteristics of Watermark Granular Matrix Sensor to Measure Soil Water Status and Its Practical Applications for Irrigation Management in Various Soil Textures*, the soil temperature within a growing season does not fluctuate much, and therefore, the effects of temperature are often negligible for irrigation purposes. The reader is directed to EC783, which has a more comprehensive explanation of proper installation, maintenance, and data interpretation of the Watermark sensor for irrigation management and scheduling decisions.

Summary

Direct measurement of soil water status can be destructive, tedious, time consuming, expensive, limited by physical constraints, and provides only a point-in-time value. Therefore, other methods and technologies have been developed to estimate soil water status. These indirect technologies vary in their method for estimating soil water status, and as a result, can range in their performance as well as be impacted by different factors.

When selecting a soil water sensor for an intended use, it is important to understand how a sensor works so that one can compare advantages and disadvantages across sensors. In addition to sensor accuracy, the following can also be used to help decide which sensor is best for an intended use: convenience, financial cost, remote access capability, product support, susceptibility to influencing factors, how many sensors are required (more than one is recommended), sensor spacing, sensing volume, response time, and integration with other sensors.

A general overview of various technology types and methods for estimating soil volumetric water content (θ_v) or matric potential (Ψ_m) has been discussed within this publication. However, it does not serve as a comprehensive review of all indirect sensor types, nor does it completely describe differences across sensors for the same technology type (e.g., comparing a capacitance probe across companies). The reader can obtain additional information describing the differences across sensor technologies in the References section. Also, the reader is directed to the manufacturers' websites to obtain copies of their manuals for information on a specific sensor.

Disclaimer

Reference to commercial products or trade names is made with the understanding that no discrimination is intended of those not mentioned and no endorsement by Nebraska Extension is implied for those mentioned.

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