UNDERSTANDING CROP IRRIGATION

A3600-02

Methods to Monitor Soil Moisture

John Panuska, Scott Sanford and Astrid Newenhouse

Advancements in soil moisture monitoring technology make it a cost-effective risk management tool.

A major challenge facing Wisconsin growers is the need to conserve and protect natural resources amid increasing food demand, rising production costs and climate extremes. Growers need to use every opportunity possible to optimize production efficiency to address these and other challenges and maintain yields. Water stress is one of several factors that can reduce crop yield and quality. Keeping the proper amount of water available in the root zone is essential to any successful crop production operation.

Irrigation has become an increasingly important risk management tool for growers. An understanding of soil moisture management is key for growers to make irrigation management decisions. The recommended approach for optimal root zone soil water management includes irrigation water management (scheduling) and soil moisture monitoring. Recent advancements in soil moisture monitoring technology make it a cost effective risk management tool.

Types of equipment

There are several aspects of soil moisture monitoring equipment: configuration, measurement science, and data management. The advantages and limitations along with specific equipment examples of each aspect are presented and discussed in this publication.

Figure 1
Portable soil moisture sensor

Courtesy of Spectrum Technologies, Inc.

Spectrum Fieldscout™ TDR 300

Figure 2
Stationary moisture sensors

Francisco Arriaga

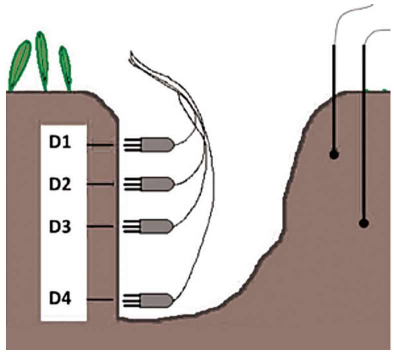
Sensors installed at several depths.

Sensor configuration

Soil moisture sensors measure the amount of water in the soil. They are either stationary at fixed locations and depths or portable as handheld probes. With a portable sensor (Figure 1) you can take measurements at several locations, but you may need to dig a hole to get readings deeper in the soil profile. Stationary sensors (Figure 2) are placed at several predetermined locations and depths. These locations should have soil water holding characteristics that represent the whole field or to be more conservative, use the soil with the lowest water holding capacity. The primary drivers of soil water holding capacity are soil texture and soil organic matter content. Both can vary significantly even within a single field. Different soil textures have different soil water holding capacity. This difference is illustrated by the volume of water held at field capacity. Field capacity is the maximum moisture content held by a soil without drainage. Finer grained "heavier" soils (clays, loams and silt loams) have greater water holding capacity than "lighter" coarse-grained soils (sandy loams and sands). When the soil moisture value exceeds field capacity, water moves deeper into the soil profile (leaching), which in turn removes water-soluble nutrients and pesticides from the root zone. Table 1 summarizes the field capacity values for several soil textural classes. Clay soil, for example, holds much more water than a sandy loam soil. For additional information on how soil textural differences and root zone depth impact irrigation water application strategies, see UW–Extension publication A3600, *Irrigation Water Management in Wisconsin–The Wisconsin Irrigation Scheduling Program (WISP)*.

In cases where a single field contains both heavy and light soils, it is recommended that the area containing each soil type be monitored and managed for irrigation as a separate unit. Field mapping technologies, such as electromagnetic conductivity (EM) mapping are also available to help identify differences in water holding capacity. This type of mapping can help growers identify representative locations for sensors. For more discussion on EM mapping, see Kachanoski et al. (1988). Once a location has been selected, place the sensors between plants within a crop row at their desired depths. Flag the sensors so field equipment operators can see where they are and prevent damage to them.

Figure 3
Stationary soil moisture sensors installed at several depths



Source: UW-Madison CEE class

Table 1
Field capacity by soil texture class

SOIL TEXTURE	Field Capacity (% by volume)
SAND	9
LOAMY SAND	13
SANDY LOAM	21
LOAM	27
SILT LOAM	33
SANDY CLAY LOAM	26
CLAY LOAM	32
CLAY	40

Source: Cambell and Norman (1998)

Measurement science and sensor technology

Soil water tension sensors

Soil water tension is a measurement of the attraction or adhesion of water to soil particles. A plant must overcome the soil water tension to extract water from the soil. Soil water tension is the force of capillarity or surface tension pulling water into soil pores. Soil tension (suction) can be measured using an instrument called a tensiometer, which is a vertical water-filled tube with a porous tip that is placed in direct contact with the soil. The tube is sealed; as the soil draws water out of the porous tip a vacuum is created. This vacuum level is measured by a mechanical or electronic vacuum gauge connected to the tube. Drier soils create greater suction, therefore when the potential of the soil to hold water is satisfied (near saturation), the suction approaches zero. A tensiometer typically measures vacuum in units of pounds per square inch (psi) or centibars (cb). Centibars are numerically equal to kilopascals (kpa). A suction of approximately 33 cb is typically used as field capacity for irrigation purposes.

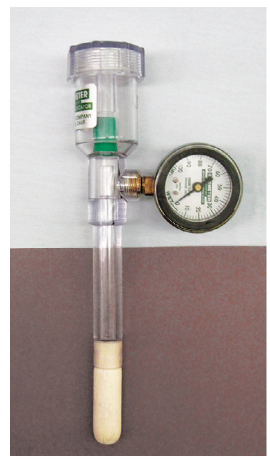
A few companies manufacture soil moisture tensiometers in the U.S., such as IRROMETER™ Company (Figure 4) and Soilmoisture Equipment Corp. Tensiometers with an electronic vacuum gauge can be connected to a data logger to record values on a predefined time period. The lower part of Figure 4 with the brown background is the portion of the sensor that would be inserted into a hole in the soil.

An alternative to a tensiometer is to use an electronic sensor that can be read manually with a reader or a data logger to measure soil water tension. Figure 5 shows a Watermark™ sensor which measures changes in electrical resistance that are converted to vacuum in centibars/kilopascals to mimic a tensiometer's reading.

TENSIOMETERS

- **Mechanical sensor cost is about $80-160**
- **One-time cost of hand-operated vacuum pump used for device installation is about $86**
- **Insert in crop row or field**
- **Displays vacuum in centibars/kilopascals**
- **Must be removed from soil over the winter**
- **May require refilling with water periodically**
- **Reads vacuum using a mechanical gauge or optional electronic gauge or vacuum transducer and data logger**

Figure 4
Irrometer™ tensiometer



WATERMARK™ SENSOR

- **Sensor cost is about $35–60**
- **An electronic tensiometer measures electrical resistance and converts to read in vacuum in centibars/kilopascals like a tensiometer**
- **Requires a data logger/reader – cost is about $300**
- **According to Chávez et al. (2011), the accuracy is ±11% volumetric moisture content**
- **Can be permanently installed (through winter) in soil, no water refilling needed**
- **Egert et al. (1992) report that readings can vary between sensor units, so this sensor is better suited for relative, not absolute, moisture readings**

Figure 5
Watermark™ sensor

John Panuska photos

Electromagnetic sensors

Capacitance and Time Domain Reflectometry (TDR) sensors are electronic devices that can be either portable or stationary. Both measure the storage and dissipation of the electrical and magnetic energy (dielectric permittivity) of the soil, which is calibrated to moisture content. They read instantly and can accurately measure over a wide range of soil textures and moistures.

CAPACITANCE SENSORS

Capacitance sensors can use a pair of parallel stainless steel rods (wave guides) (Figure 8), a single-piece insert (Figure 6), or can also be fully contained within a PVC pipe (Figure 7) which is installed vertically into a soil bore hole. Systems using the PVC pipe design typically have multiple sensors mounted along the length of pipe, thus allowing simultaneous soil moisture measurement at several depths. Capacitance sensors require a data logger and/or display unit.

- **Requires electronic reader or data logger costing about $400-600**
- **In-soil single sensor unit cost about $100**
- **Multi-sensor units cost $1,000 and up**
- **Displays percent volumetric soil moisture**
- **Can remain in soil through winter**
- **Accuracy: ±3 to 5% volumetric moisture**

Figure 6
Capacitance-type soil moisture sensors

a) Spectrum SM100 Waterscout®
b) Decagon Echo® EC-5

Figure 7
Multi-depth capacitance soil moisture sensor in PVC pipe

Systems using the PVC pipe design typically have multiple sensors mounted along the length of pipe, 48 inches long in the above example (the cut-out shows sensors inside), thus allowing simultaneous soil moisture measurement at several depths.

TIME DOMAIN REFLECTOMETRY (TDR)

The in-soil part of a TDR sensor for both the in-place and handheld units look the same and are typically a pair of wave guides which are connected to a data logger and/or a display unit (Figure 8). Wave guide rods are available in various lengths from 1 to 8 inches (short for shallow-rooted crops such as turf and longer for deeper-rooted crops). You can change the wave guides but this requires recalibratiing the reader by taking one reading with the rods in the air and another in distilled water. To get a value for a location at a specific depth, the rods should be installed horizontally at that depth.

- **Requires electronic reader or data logger costing about $800 - 1,200**
- **In-soil portion of sensor costs about $60**
- **Displays percent volumetric soil moisture**
- **Can remain in soil through winter**
- **Accuracy: ±1 to 3% volumetric moisture**

Figure 8

In-soil wave guides for the Spectrum TDR 300® soil moisture sensor

John Panuska

Data management

There are several options for reading and recording data from the sensors. Data can be displayed directly using a reader (Figure 9), stored in a data logger directly (Figure 10), or transmitted via radio or cellular link (telemetry) to a remote location. Some data loggers have displays that show the current value without needing a computer or reader (Figure 11). This is convenient when scouting fields. Telemetry-based systems can provide readings remotely in near real time, while for loggers and

Figure 9

Reader

ProCheck Reader and Decagon Echo® EC-5

Figure 10

Data loggers

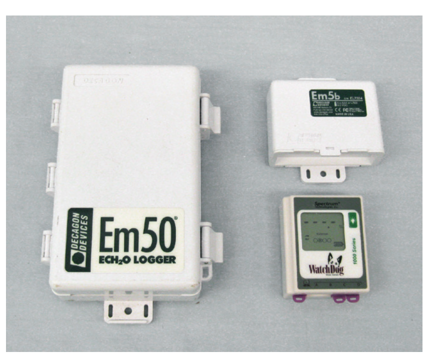


Figure 11

Data logger with display

Scott Sanford photos

Spectrum SM 100 Waterscout® Sensor and Watchdog® data logger with readout display systems, you must go to the sensor in the field to retrieve the data (Figure 12). Telemetry-based systems can be configured in several ways. One configuration option uses a single data logger for 1 to 6 sensors that uploads data after each reading or on a daily basis. Another system configuration has wireless connections among data loggers in a field that transfer the data to a central controller which in turn uploads by a cellular link, radio signal or satellite communications to a secure website. You can then access the data from a computer or mobile device.

Figure 12
AquaSpy™ probe with telemetry

Scott Sanford

There are vendors that offer irrigation and data management services to create a more complete soil water management system. Services may include data telemetry, data post processing, system monitoring with notification, soil moisture sensor installation and removal, weather stations, variable rate irrigation (VRI) prescriptions, field soils mapping and automated pivot control. A basic service package typically includes installing soil moisture sensors in fields and uses a combination of crop ET estimates, soil moisture measurements and weather forecasts to make irrigation application recommendations to the grower.

You can also convert soil moisture tension data that is expressed in centibars into percent volumetric moisture content values, which offer a more descriptive way to compare among soils. If you know your soil type (texture), you can use a soil water release curve to approximate the volumetric soil moisture content. A soil water release curve is typically developed in a soil physics lab for the specific soil in question and its shape is determined by soil texture. Refer to the UW–Extension web page "Understanding Crop Irrigation" (online at fyi.uwex.edu/cropirrigation) for information on how to approximate the volumetric soil moisture content of your soil.

Installing stationary sensors

Soil water tension sensors (Watermark™ and tensiometer sensors) must have constant soil contact and are only installed in a stationary location. Soak the sensors in clean water overnight before installation. At the location, drive a stake in the ground and then pull it out to form a hole, or use an auger to bore a hole into the soil to the desired depth. The hole diameter should be slightly smaller than the sensor (it must fit snugly). Mix a few ounces of water with some soil to make a slurry and put it in the bottom of the hole before you insert the sensor. After inserting the sensor, backfill the hole with crumbled soil if needed. If you use a sensor tube, mound soil up around the tube to prevent surface water inflow between the tube and the undisturbed soil. Within a day the sensor should equilibrate with the surrounding soil and provide accurate values.

Install capacitance and TDR sensors by simply pushing the in-soil part of the device into the soil at the desired depth while being careful to avoid rocks. This can be accomplished in two ways:

1) dig a trench or hole and install the sensors horizontally in the sidewall of the hole; or

2) use an auger or soil sampling probe to bore a hole to the desired sampling depth and install the sensor vertically in the bottom of the hole.

Capacitance sensors are very sensitive to the soil conditions in the area immediately surrounding the sensor. Rocks, voids or variations in the soil will affect sensor readings. For blade-type sensors installed horizontally, the blade should be oriented vertically so water will not pool on the sensor blade. After you have installed the sensor, carefully backfill the access hole while maintaining the textural characteristics of the undisturbed soil profile near the sensor.

Multi-depth capacitance sensors are mounted inside a PVC tube. Use an auger to make a hole to a depth that accommodates the length of the tube and then insert the tube into the ground. Follow manufacturer's recommendations for installation. Several manufacturers offer instructional installation videos on their websites.

Digging holes or trenches to install individual sensors horizontally can be time-consuming and a significant amount of work. Another installation method for some types of sensors (Watermark,™ Spectrum Waterscout,® Decagon H20 Echo® EC-5) is to attach the sensor to a ½-inch inside diameter Schedule 40 PVC pipe up to 3½ feet long. Attach the sensor to one end of the pipe (Figure 12). Run the reader wire through the pipe from below so it exits at the top. Attach a cap or two elbows to the top to prevent water from running down the inside of the pipe and distorting the measurement.

Bore a ⅞-inch-diameter hole in the soil to the desired depth using a soil sampling auger or a wood auger drill bit on a power drill. Gently push the sensor into the soil at the bottom of the bore hole. If the ground is hard, you can press a blade in the bottom of the hole to form a slot for the sensor blade or use some water to soften the soil. A paste or slurry isn't needed around a capacitance or TDR sensor. The soil should be tamped in around the pipe and mounded at the ground surface to prevent surface water inflow around the pipe. The bore hole can also be drilled at a slight angle to reduce the chances of water tracking into the soil next to the pipe and affecting the sensor reading. Place colored marker tape around the top of the pipe or paint it a bright color to find it quickly and to help field equipment operators see where they are located and prevent damage to them. This method also makes sensor removal much easier: pull the pipe out of the soil by hand unless the ground is very dry.

If the ground is too dry, you may need to dig or wait for a soaking rain to remove the sensor. For row crops, place the sensors in the row so they don't get in the way of field cropping operations such as spraying or cultivation.

For stationary sensors it is recommended that a minimum of two sensors be installed at each site – one shallow sensor at 25-30% of the root zone depth and one deep at 65-80% of the root zone depth. Start irrigating when the shallow sensor indicates low soil moisture content. The deep sensor

Figure 13
Stationary sensors mounted in the end of a ½-inch PVC pipe

John Panuska

indicates when irrigation water has reached the lower root zone and enough water was applied. The deep sensor can also be an indication of the depth to which rain water has percolated or if leaching has occurred. Leaching carries water-soluble nutrients and pesticides out of the root zone, deeper into the soil profile and possibly into groundwater, so it should be avoided if possible.

Table 2 contains typical plant root zone depths and suggested sensor depths for several crops, assuming there are no obstructing layers (hard pan or rock) in the soil profile. Because individual root zone depths can vary, field verification is recommended. Dig down to see how deep your crop's root zone is.

Table 2
Root zone, management and sensor depths for common crops

CROP	Max. Root Depth (in)[1]	Irrigation Water Mgt. Depth (in)[2]	Shallow Sensor (in)[3]	Deep Sensor (in)[3]
BROCCOLI & CAULIFLOWER	24	12-18	12	20-24
STRAWBERRY	12-24	12-18	6	12
POTATO	24-36	12-18	8-10	18
TOMATO & CANTALOUPE	36	12-24	18	36
BUSH BEAN	24-36	18-24	10	18
SOYBEAN	48-60	30-36	12-18	30-36
SMALL GRAINS	48	30-36	18	36
SWEET CORN	24-36	24-36	12	24-30
FIELD CORN	48	30-36	12-18	30-36
PUMPKINS/WINTER SQUASH	36-48	30-36	18	36
ESTABLISHED ALFALFA	60	36-48	18	36

Sources:

1. USDA – NRCS Part 652 – Irrigation Guide, 1997, Chapter 3, Table 3-4
2. Depth at which the water content should be managed for optimum crop production
3. Soil Moisture Basics, Irrometer Co., www.irrometer.com/basics.html

Jeff Vanuga, USDA-NRCS

Rainfall and irrigation water application monitoring

Water inputs from rainfall and irrigation are a critical component of the root zone water balance. Root zone input (rainfall and irrigation) and loss (evapotranspiration and leaching) data can be fed into soil moisture tracking software such as the Wisconsin Irrigation Scheduling Program (WISP) (www.wisp.cals.wisc.edu) to predict root zone soil moisture.

Soil moisture tracking software simplifies the calculations of daily water balance and is also a good record-keeping tool. At least one rain gauge, and preferably three, should be located within each irrigation unit. An irrigation unit is the area under a center pivot or an area that has significantly different soil water holding characteristics from another area within a field. Rain gauges can be used to gather data on both natural rainfall and irrigation. An inexpensive manual rain gauge placed under a center pivot is a good way to check your system's water application rate.

Both manual and automated rain gauges are available. Manual rain gauges cost $20-$50 per unit and should have an opening of at least 2 inches. Automatic recording rain gauges are also readily available and cost $100-200 per unit depending on the features available. Automatic recording rain gauges collect rainfall using a funnel and direct it into a small tipping bucket measuring device. This two-sided bucket typically contains the volume equivalent of 0.01 inches of rainfall on each side. When one side of the bucket fills, it dumps out and the other side begins to fill, while a manual or electronic counter records the number of tips. For soil moisture monitoring systems using a data logger, the rain gauge can be connected to the same data logger used for soil moisture monitoring. Like soil moisture sensors, wireless rain gauges are also available.

Conclusions

Spatial and temporal variations in rainfall along with soil characteristics impact crop root zone water content and therefore crop yields and quality. Soil moisture sensors are one of several tools available to growers to help manage root zone moisture on irrigated fields.

Under-irrigation harms yields and quality, while over-irrigation increases pumping costs and leaches nutrients and pesticides out of the root zone, thus increasing groundwater contamination risk and the risk of plant fungal diseases. Soil moisture monitoring and tracking (scheduling) helps growers make informed water application decisions that can help optimize soil moisture conditions. This in turn can reduce production cost and improve crop yield and quality while reducing the risk of groundwater contamination.

Over the past 5 to 10 years the cost of soil moisture monitoring equipment has come down while quality and sophistication of the tools have increased. There is now a soil moisture monitoring technology for every budget and management system. Available equipment spans the range from simple mechanical sensors to multi-depth continuous recording electronic sensors with web-based data access. Given the climate and environmental challenges facing growers, it makes sound business sense to use readily available technologies to optimize production efficiency. Soil moisture monitoring is one of those technologies.

Visit the UW–Extension web page "Understanding Crop Irrigation" (fyi.uwex.edu/cropirrigation) for links to suppliers, the WISP software and more information.

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