Improving Irrigation Water Use Efficiency: Using Soil Moisture Sensors
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Introduction
Efficient irrigation management provides benefits such as saving fresh water and energy, reducing nutrient leaching, increasing crop yield, and maximizing return on investments. The determination of the right amount and the best timing for irrigation is a challenge.

Soil moisture content is a critical parameter in understanding the water flow in soil. The most direct method to measure the soil moisture content is to weigh a sample of a known volume of soil and then reweigh it after drying in an oven at 105 °C to calculate the mass of water lost by drying (Gardner, 1986). This method allows for calculating gravimetric water content and soil bulk density. The volumetric water content can be calculated by multiplying the gravimetric water content by the soil bulk density (United States Department of Agriculture, Natural Resources Conservation Service, 2011). This soil sample collection method requires intense labor and soil disturbance. It does not measure the soil moisture content continuously. Continuous soil moisture content measurement provides useful information such as how the rainfall and irrigation infiltrate into the soil and how the crop uses the water from different soil depths.

Soil moisture sensors provide an alternative method to measure volumetric water content. Soil moisture sensors are tools that have been widely used for many years for their ability to provide nondestructive continuous data from multiple depths. The description, installation, and data interpretation of two types of common soil moisture sensors are discussed in this bulletin.

How to Describe Soil Moisture Content & Irrigation Needs: Some Basic Terminology
Soil moisture sensors provide indirect measurements of the soil moisture content, based either on the force required to pull water out of the soil (tension) or the electrical properties of the soil, both of which change based on the soil moisture content and soil type. To interpret these sensors, some basic understanding of factors influencing soil moisture depletion and crop water needs is helpful. Figure 1 illustrates the saturation, field capacity (FC), and wilting point (WP) of a soil, which is determined by soil texture. The descriptions of some basic terminologies follow:

saturation: All soil pore spaces are filled with water
field capacity (FC): Maximum amount of water that soil can hold after drainage
wilting point (WP): Soil moisture level where there is no available water for the crop
available water (AW): Difference between FC and WP, often expressed in inches of water per foot of soil
maximum allowable depletion (MAD): Amount of available water that can be safely depleted without causing drought stress, which depends on the crop
and the growth stage. For example, drought-sensitive crops such as onion (25–30%) experience stress earlier than drought-tolerant crops such as soybean (50–65%) (Maughan et al., 2015; Sharma, 2019a). Please find more information on MAD for crops and their growth stage in University of Minnesota Extension’s Basics of Irrigation Scheduling (https://extension.umn.edu/irrigation/basics-irrigation-scheduling#sources-1846810).

soil matric potential (SMP): Physical force required for the plant to move water into its root system

Figure 1. Illustration of saturation, field capacity (FC), and wilting point (WP).

**Types of Soil Moisture Sensors**

**Soil Tension: Tensiometers & WATERMARK Sensors**

Tensiometers, manufactured by IRROMETER (Riverside, CA), are a device that directly measures SMP. WATERMARK sensors, manufactured by IRROMETER, are a solid-state electrical resistance sensing device that also measures SMP. This type of sensor has been used extensively in the agricultural field because it is economical. A WATERMARK sensor reads the resistance changes as the soil tension changes, which depends on the soil moisture content. WATERMARK sensors measure from 0 to 239 kPa. The value of 0 kPa indicates that the soil reached saturation. The measurement of 239 kPa indicates that the soil is dry. A tensiometer can be read manually or connected with a 900M datalogger (Figure 2). Sensor recording intervals can be programmed using WaterGraph software. The 900M datalogger can display the current readings on its screen, which eliminates the need to connect to a laptop to view the current readings. The current retail prices for a WATERMARK sensor, handheld meter, and 900M datalogger is $1,123 ($43, $240, and $840, respectively). This cost is relatively inexpensive compared to Frequency Domain Reflectometry and Time Domain Reflectometry (which will be discussed later). The current retail cost of a tensiometer varies from $95 to $290, depending on the length of the sensor and data output option. The challenge of the tensiometer is that it is not easy to adapt to computer data collection and tends to break the tension at the critical point in sandy soil. Table 1 shows the approximate SMP values for 30%, 50%, and 70% of soil water depletion for each soil type (Irmak et al., 2014).

Figure 2. 900M datalogger (left), tensiometer and suction pump (center), and WATERMARK sensor (right).

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Maughan et al., 2015; Sharma, 2019a.
Table 1. Soil matric potential (SMP) for 30%, 50%, and 70% of soil water depletion for different soil types (Irmak et al., 2014).

<table>
<thead>
<tr>
<th>Soil texture</th>
<th>Depletion in water holding capacity (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30%</td>
</tr>
<tr>
<td>Sand</td>
<td>20</td>
</tr>
<tr>
<td>Loamy sand</td>
<td>25</td>
</tr>
<tr>
<td>Sandy loam</td>
<td>28</td>
</tr>
<tr>
<td>Silt loam</td>
<td>80</td>
</tr>
</tbody>
</table>

How do I know when to irrigate when using a soil tension sensor?

The threshold to trigger irrigation depends on the crop type, growth stage, soil water holding capacity, and capacity of the irrigation system. The exact irrigation timing will also depend on projected precipitation and evapotranspiration.

Figure 3 shows an example of the change of the WATERMARK sensor readings affected by irrigation and rainfall. In this example, the soil type was sandy loam, and the irrigation trigger was scheduled when the WATERMARK sensor was reading at 50 kPa (approximately 50% water depletion).

Table 2. Soil water deficits (in./in.) for different soil tensions, excerpted from the University of Minnesota Extension (Sharma 2019b).

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Soil water deficits (in./in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30 kPa</td>
</tr>
<tr>
<td>Sand</td>
<td>0.025</td>
</tr>
<tr>
<td>Loamy sands</td>
<td>0.033</td>
</tr>
<tr>
<td>Sandy loams</td>
<td>0.041</td>
</tr>
<tr>
<td>Loams</td>
<td>0.017</td>
</tr>
</tbody>
</table>

Figure 3. Example of WATERMARK sensor data with an irrigation trigger point of 50 kPa.

How much irrigation water should I apply based on soil tension measurements?

Knowing soil types (especially texture) is important for irrigation scheduling because soil water holding capacity is largely determined by soil types. Fine-textured soil has a much higher water holding capacity than coarse-textured soil. Also, higher values of organic matter typically increase water holding capacity. Table 2 describes soil water deficits (in./in.) and the associated SMP of different soil types (Sharma 2019b). For example, for the sandy loam soil shown in Figure 3, the SMP at the time of the first irrigation was 50 kPa, suggesting a water deficit of 0.058 in./in. (see Table 2). Therefore, if the crop had a root system of around a 24 in. depth, you would need to irrigate with about 1.4 in. of water assuming there is no rain in the forecast.
However, note that both soil type and sensor readings often vary with depth. Therefore, ideally sensors are placed at multiple depths in the crop rooting zone, and changes in soil texture with depth are taken into consideration to calculate irrigation needs. The example in Figure 4 shows sensor readings and associated depletion in available water at different depths. For a crop with a 3-foot root zone, the total water deficit would be 1.29 in. based on the sensor readings. This means that up to 1.29 in. of rainfall, irrigation, or both could be added to the field before water would be leached out of the bottom of the root zone. Figure 5 shows another calculation example for a tomato. In this example, 0.80 in. of irrigation could be added to the soil, assuming there is no rain in the forecast.

**Figure 4.** Example of the amount of irrigation calculation using WATERMARK sensor for a corn. A represents 0–18 in. depth (loamy sand), B represents 18–30 in. depth (loamy sand), and C represents 30–42 in. depth (sand). ¹Please refer to Table 2.
Figure 5. Example of the amount of irrigation calculation using WATERMARK sensors for a tomato. A represents 0–9 in. depth (loamy sand), B represents 9–15 in. depth (loamy sand), C represents 15–21 in. depth (sand), and D represents 21–24 in. depth (sand). Please refer to Table 2.

Volumetric Water Content: Frequency Domain Reflectometry

Frequency Domain Reflectometry (FDR) sensors measure soil water content using the dielectric properties of soil which are highly dependent on moisture content. An example of dielectric permittivity is shown in Table 3. The changes in the permittivity correlate with changes in the circuit frequency, which also relates to soil moisture content.

Table 3. Example of dielectric permittivity.

<table>
<thead>
<tr>
<th>Material</th>
<th>Dielectric permittivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>1</td>
</tr>
<tr>
<td>Soil Minerals</td>
<td>3-7</td>
</tr>
<tr>
<td>Organic Matter</td>
<td>2-5</td>
</tr>
<tr>
<td>Ice</td>
<td>5</td>
</tr>
<tr>
<td>Water</td>
<td>80</td>
</tr>
</tbody>
</table>
A common FDR sensor is the EC-5, manufactured by MeterGroup (Pullman, WA), which outputs the value as volumetric water content (VWC) (%). The EC-5 measurements can be recorded using a ZL6 datalogger (Figure 6). Up to six sensors can be connected to the datalogger, and the measurement interval can be programmed using Zentra Utility software. The current retail prices of an EC-5 sensor and ZL6 is $860 ($110 and $750, respectively). The dataloggers can use a remote monitoring system at an additional cost of the cellular service subscription fee of $175/year/datalogger (as of 2020). The advantages of the remote monitoring system are that it allows for downloading the data remotely using a computer with an internet connection and the ability to see whether there are any problems with sensors without having to visit the field.

The Drill and Drop soil probe, manufactured by Sentek Technologies (Stepney, Australia), measures soil moisture levels every 4 in. up to 4 ft. soil depth (Figure 7). This sensor also uses FDR technology and measures the soil dielectric by placing the soil between two electrical plates to form a capacitor. The current retail price of a Drill and Drop soil probe with cellular capability is $3,059 and the annual cellular service subscription fee is $285/year/probe. The collected data displays on IrriMAX Live website, which provides both raw data (Figure 8) and a composite result (Figure 9).
How do I know when to irrigate when using an EC-5 sensor?

Table 4 shows the volumetric water content levels of FC, WP, and AW for each soil type; however, these values may vary depending on site-specific conditions. As shown in Table 4, AW in finer textured soil is much higher than coarse-textured soil. This means that finer textured soil can hold much more water than coarse-textured soil.

Typically, irrigation is recommended at 30–60% depletion of available water in soils, depending largely on the crop’s tolerance to drought stress, crop stages of development, and the capacity of the irrigation system. Table 4 provides the ranges of recommended irrigation trigger points for each soil type. Irrigation water should be applied when the volumetric water content sensor reads the values within the suggested value range. Irrigation trigger timing should be determined with consideration of projected precipitation and evapotranspiration, and the capacity of the irrigation system.

Table 4. Field capacity (FC), wilting point (WP), available water (AW), and recommended irrigation trigger point for different soil types.

<table>
<thead>
<tr>
<th>Soil texture</th>
<th>FC (%)</th>
<th>WP (%)</th>
<th>AW (%)</th>
<th>Trigger Point Range (Irrigate when VWC falls below these values)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>9.4</td>
<td>5</td>
<td>4.4</td>
<td>6.8–8.1</td>
</tr>
<tr>
<td>Loamy sand</td>
<td>12</td>
<td>5.7</td>
<td>6.3</td>
<td>8.2–10.1</td>
</tr>
<tr>
<td>Sandy loam</td>
<td>17.9</td>
<td>8.1</td>
<td>9.8</td>
<td>12.0–15.0</td>
</tr>
<tr>
<td>Loam</td>
<td>31</td>
<td>14</td>
<td>17</td>
<td>20.8–25.9</td>
</tr>
</tbody>
</table>

An example of irrigation triggers using an EC-5 is shown in Figure 10. In this example, the irrigation trigger point was set to 14.5% for sandy loam soil. When the soil moisture level was approaching the irrigation trigger level, the irrigation was applied.

Table 4. Example of EC-5 volumetric water content sensor data (sandy loam soil).

How much irrigation should I apply based on volumetric water content measurements?

The total amount of water needs for soil can be calculated using the volumetric water level data. Ideally, several soil moisture sensors should be installed to the depth used for water management purposes. Figure 11 shows an example of a calculation of the amount of irrigation that could be applied to corn using volumetric water content sensors. This example assumes that the root depth for this corn is 3 ft. and soil textures are loamy sand, loamy sand, and sand for 0–18, 18–30, and 30–36 in. depth, respectively. Three soil moisture sensors are installed at 12, 24, and 36 in. depth, and readings from soil
moisture sensors are 8%, 9%, and 7%, respectively. Since these values are below the trigger point for their soil type (see Table 4), irrigation should be applied but how much irrigation water is needed? Please see Figure 11 for detailed calculations. Based on the volumetric water content sensor data, the available water in the crop root zone is 2.94 in. Based on the field capacity of each soil texture, the maximum water holding capacity in this crop root zone is 4.16 in. The difference between maximum water holding capacity and calculated available water in the root zone is the amount of irrigation that could be applied. Therefore, approximately 1.22 in. of water could be applied to the field, assuming there is no rain in the forecast.

**Figure 11.** Example of the amount of irrigation calculation using volumetric water content sensors for a corn. A represents 0–18 in. depth, B represents 18–30 in. depth, and C represents 30–42 in. depth. ¹FC for loamy sand is 12%. ²FC for sand is 9.4%.
Figure 12 shows another example of a calculation of the amount of irrigation that could be applied to tomato using volumetric water content sensors. This example assumes that the root depth for this tomato is 2 ft. and soil textures are loamy sand and sand for 0–15, and 15–24 in. depth, respectively. Four soil moisture sensors are installed at 6, 12, 18, and 24 in. depth. A sensor at 6 in. depth is beneficial, especially for shallow-rooted vegetable crops or crops at early growth stages. The readings from soil moisture sensors are 8%, 9%, 7%, and 7% for 6, 12, 18, and 24, respectively. Since these values are below the trigger point for their soil type (see Table 4), irrigation should be applied but how much irrigation could be applied? Please see Figure 7 for detailed calculations. Based on the volumetric water content sensor data, the available water in the crop root zone is 1.89 in. Based on the field capacity of each soil texture, the maximum water holding capacity in this crop root zone is 2.64 in. The difference between the maximum water holding capacity and calculated available water in the root zone is the amount of irrigation that could be applied. Therefore, approximately 0.75 in. of water could be applied to the field, assuming there is no rain in the forecast.

**Figure 12.** Example of the amount of irrigation calculation using volumetric water content sensors for a tomato. A represents 0–9 in. depth, B represents 9–15 in. depth, C represents 15–21 in. depth, and D represents 21–24 in. depth. \(^1\)FC for loamy sand is 12%. \(^2\)FC for sand is 9.4%.
Sensor Placement and Installation

Sensor placement considerations:

- Sensors should be installed between plants for row crops and between the center of root mass for fruits and vegetables.
- Sensors should not be placed close to a wheel track or lane edge.
- Locations that are not representative of the majority of the field’s irrigation, such as under the end gun or cornering arm, and near the center pivot point should be avoided.
- The depth of the sensors should be considered based on the crop’s root depth. Typical installation depths are $\frac{1}{3}$, $\frac{2}{3}$, and the bottom of the crop’s full root depth. For example, a placement for corn would be at 12 in., 24 in., and 36 in. deep. Additional sensors at multiple depths can help better understand the water movements of the soil. The sensor at the bottom of the root zone can help the farmer to determine when to turn the irrigation off based on the spike (Figure 13).
- A set of sensors in a field can provide valuable information. Several sets of sensors can be used for variable soil texture, topography, and crops within a field.

Soil Tension: WATERMARK Sensor

Figure 14 shows the installed 900M datalogger and WATERMARK sensors.

1. Attach the WATERMARK sensor to the end of a piece of $\frac{3}{4}$ in. PVC pipe using glue with the sensor cable running through the pipe. The PVC pipe length is determined by the sensor depth.
2. Soak the WATERMARK sensor in water overnight.
3. Use a $\frac{3}{4}$ in. diameter hollow pipe to make a hole for the sensor. Mix a slurry of water and soil from the bottom of the hole. Place the mixture in the hole for better contact between the sensor and surrounding soil.
4. Insert the sensor into the hole firmly to ensure good contact with the soil.
5. Backfill the hole with the soil profile from the hollow pipe and pack the soil carefully.

![Figure 13. Soil moisture sensor data in a commercial corn field. Typical root depth is 36 in. The 36 in. depth sensor shows a spike, indicating over-irrigation.](image)

Because the soil moisture sensor measures only a small volume of soil surrounding the sensor, the installation should be performed carefully. There must be good contact between the sensor and soil to avoid creating an air gap. The detailed procedure for each sensor installation is described below.

Volumetric Water Content: FDR

Figure 15 shows the installed EC-5 sensor.

1. Dig a hole or trench large enough to provide sufficient access to the desired depth. A post hole digger can be used effectively for this purpose for depths up to 2 feet in most soil types.
2. Insert the sensor horizontally into the trench.
3. Backfill the trench with the same soil profile and pack the soil carefully.
Low-Cost Remote Monitoring System

The Michigan State University irrigation team developed a low-cost remote monitoring system (LOCOMOS) that can continuously measure soil moisture levels at multiple depths and leaf wetness duration, and display the collected data to a website for improving irrigation water use efficiency and disease management. In 2019, the team installed and tested nine LOCOMOSs across Michigan. Figure 16 shows installed LOCOMOSs in soybean fields at Sturgis, Michigan. A future plan is to develop a smartphone app that can analyze and interpret the data from the LOCOMOS for Michigan farmers with real-time irrigation advice.
References


Michigan State University

Irrigation Websites

Biosystems & Agricultural Engineering: Irrigation: [https://www.egr.msu.edu/bae/water/irrigation/](https://www.egr.msu.edu/bae/water/irrigation/)

MSU Extension: Irrigation [https://www.canr.msu.edu/irrigation/](https://www.canr.msu.edu/irrigation/)