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Irrigation Monitoring with Soil Water Sensors

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Monitoring the water content of your soil will help you decide how much water to apply and when to apply it. Soil water sensors can give the information you need to:

- optimize production
- conserve water
- reduce environmental impacts
- save money

Monitoring the soil's moisture will help you schedule irrigation in order to avoid applying too little or too much water; which under irrigation will reduce crop yields. Overirrigation can also:

- increase water and energy costs
- leach fertilizers below the root zone
- erode soil
- move soil particles and chemicals to drainage ditches
- result in unnecessary labor costs

By understanding basic soil water concepts, the strengths and weaknesses of different types of soil water sensors, and methods of installing them, you can irrigate crops more efficiently, improve water conservation, and make your farm more profitable.

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Basic concepts

To figure out when and how much to water, you need to know your field's: **field capacity, plant available water,** and the **permanent wilting point** (Fig. 1). These levels of soil water content can be expressed in inches of water per foot of soil (Table 1) as well as in bars.

- **Field capacity** is the amount of water in the soil when water draining from a heavy irrigation changes from fast to slow. This is the point when all the gravitational water has drained. Medium to heavy (loam to clay) soils normally reach field capacity 2 to 3 days after irrigation. In these soils, the soil water tension at field capacity is about 0.3 bars (30 centibars) of tension. In sandy soils, which drain more quickly, field capacity measures about 0.1 bar (0.1 bars = 10 centibars).
- **Permanent wilting point** is the soil water content from which plants cannot recover overnight after drying during the day. This parameter has been determined in greenhouse experiments, and can vary with plant species and soil types. The permanent wilting point occurs at water tensions between 10 and 20 bars. An average of 15 bars is generally used. The water in the soil at and below the permanent wilting point is called hygroscopic water. Hygroscopic water is held tightly on the soil particles below permanent wilting point and cannot be extracted by plant roots (Fig. 1).
- **Plant available water** is the soil water content between field capacity and the permanent wilting point. This level of water content, usually expressed in inches of water per foot of soil depth, depends on the soil's bulk density, texture, and structure. Again, the approximate amount of plant available water varies in different soil textures.

  Volumetric water content (θ) is another measure used to describe the amount of water in the soil. This is the direct measurement used to calibrate other soil water sensing techniques.

$$\theta = \frac{\text{Volume of water}}{\text{Volume of soil}}$$

Values of θ are always less than 1 and can be expressed a depth of water per unit depth of soil. For example, it can be expressed as foot per foot, and used to calculate irrigation depth.

Table 1. Soil water content parameters for different soil textures.

Soil Texture	Field Capacity (in./ft)	Plant available water (in./ft)	Permanent wilting point (in./ft)
Sand	1.2 (0.10)*	0.7 (0.06)	0.5 (0.04)
Loamy sand	1.9 (0.16)	1.1 (0.09)	0.8 (0.07)
Sandy Loam	2.5 (0.21)	1.4 (0.12)	1.1 (0.09)
Loam	3.2 (0.27)	1.8 (0.15)	1.4 (0.12)
Silt loam	3.6 (0.30)	1.8 (0.15)	1.8 (0.15)
Sandy clay loam	4.3 (0.36)	1.9 (0.16)	2.4 (0.20)
Sandy clay	3.8 (0.32)	1.7 (0.14)	2.2 (0.18)
Clay loam	3.5 (0.29)	1.3 (0.11)	2.2 (0.18)
Silty clay loam	3.4 (0.28)	1.6 (0.13)	1.8 (0.15)
Silty clay	4.8 (0.40)	2.4 (0.20)	2.4 (0.20)
Clay	4.8 (0.40)	2.2 (0.18)	2.6 (0.22)

*Numbers in parentheses are volumetric water contents expressed as foot of water per foot of soil.
Source: Hanson 2000.

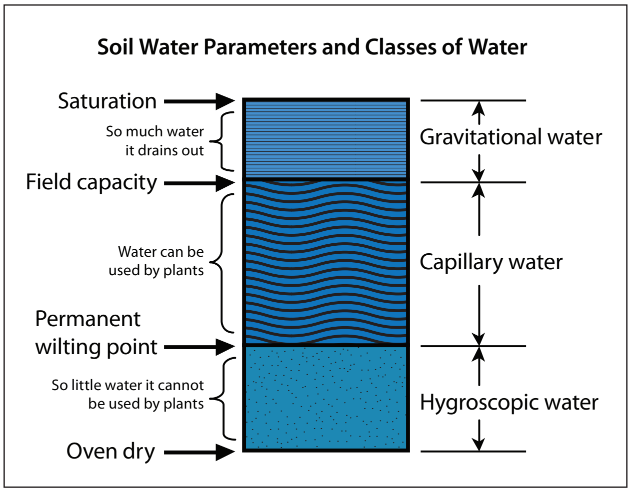

Figure 1. Soil water parameters and classes of water.

Assume, for example, that the current volumetric water content is 0.20 ft/ft and the field capacity is 0.30 ft/ft. If we want to bring the top 2 feet to field capacity, the required irrigation depth to bring the soil to field capacity is calculated as follows:

$$\text{Irrigation depth} = (0.30 - 0.20) \times 2 \text{ feet} = 0.1 \times 2 \text{ feet} = 0.1 \times 24 \text{ inches} = 2.4 \text{ inches}$$

If we want to know how much water the soil contains at 0.20 ft/ft plant available soil water, the available water depth can be calculated accordingly:

$$\text{Water depth} = 0.20 \times 2 \text{ feet} = 0.20 \times 24 \text{ inches} = 4.8 \text{ inches}$$

Water storage capacity of soils

The degree to which water clings to soil is often expressed as soil moisture tension. Soil moisture tension is commonly expressed in units called bars or centibars (1 bar = 100 centibars). Soil that is saturated has a soil moisture tension of about 0.1 centibar, or less; under this condition plants use little energy to draw moisture from soil. As the soil dries out, the tension increases, requiring plants to must use more energy to draw water from the soil.

A soil water characteristic curve (Fig. 2) describes the relationship between soil water content and the tension at which the water is held in the soil. The relationship varies from soil to soil. In saturated soil, the tension is 0; as the soil dries, tension increases.

Sandy soils do not hold as much plant-available water; they generally drain faster and need to be irrigated more often than do clay or loam soils.

Management allowable depletion (MAD) is the percent depletion of the plant available water beyond which the soil water content should not be depleted. Depletion beyond this limit will create excessive water stress on the plant and reduce production.

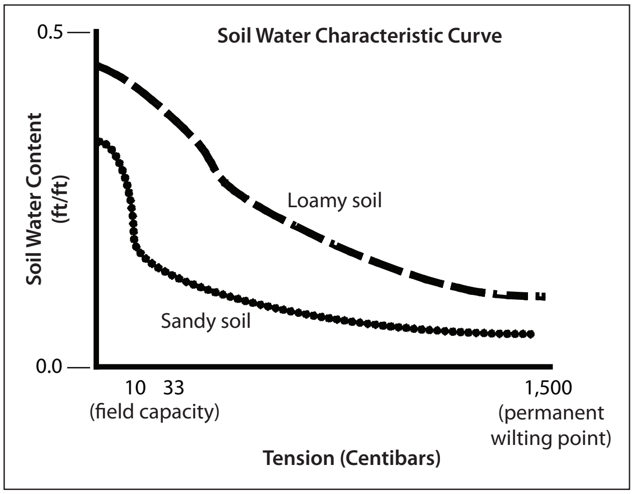

Figure 2. Soil water characteristic curves for typical sandy and clay soils.

The management allowable depletion, or allowable deficit, depends on the plant species and varies between growing seasons. Recommended MAD levels for many field crops are near 50 percent, though it may be as low as 25 percent for some vegetable and other drought-sensitive crops.

Table 2 shows typical values of allowable depletion and root zone depth for selected crops. Soil conditions such as compacted layers, shallow water

Table 2. Allowable soil water depletions (MAD, %) and root depths (ft) for selected crops.

Crop	Allowable depletion (%)	Root depth* (ft.)
Fiber crops		
Cotton	65	3.3–5.6
Cereals		
Barley and oats	55	3.3–4.5
Maize	50–55	2.6–6.0
Sorghum	50–55	3.3–6.6
Rice	20	1.6–3.3
Legumes		
Beans	45	1.6–4.3
Soybeans	50	2.0–4.1
Forages		
Alfalfa	50–60	3.3–9.9
Bermuda	55–60	3.3–4.5
Grazing pastures	60	1.6–3.3
Turf grass		
Cool season	40	1.6–2.2
Warm season	50	1.6–2.2
Sugarcane	65	4.0–6.5
Trees		
Apricots, peaches	50	3.3–6.6
Citrus		
70% canopy	50	4.0–5.0
50% canopy	50	3.6–5.0
20% canopy	50	2.6–3.6
Conifer trees	70	3.3–4.5
Walnut orchard	50	5.6–8.0
Vegetables		
Carrots	35	1.5–3.3
Cantaloupes and watermelons	40–45	2.6–5.0
Lettuce	30	1.0–1.6
Onions	30	2.0–3.0
Potatoes	65	1.0–2.0
Sweet Peppers	30	1.6–3.2
Zucchini and cucumbers	50	2.0–4.0

*Note: Root depths can be affected by soil and other conditions. Effective root zone depths are often shallower.
Source: Allen et al., 1996.

Table 3. Example calculation† using management allowed depletion percentatge to calculate the allowable water content change (θ_{MAD}, $m^3\ m^{-3}$) in three soils with widely different textures.

Soil type	Θ field capacity	–	Θ permanent wilting point	=	Θ plant-available water	×	MAD/100	=	Θ maximum allowable depletion
	ft/ft						fraction		ft/ft
silt loam	0.295	–	0.086	=	0.209	×	0.6	=	0.126
loamy sand	0.103	–	0.066	=	0.037	×	0.6	=	0.022
clay	0.332	–	0.190	=	0.142	×	0.6	=	0.085

† θ_{FC}, θ_{PWP}, and θ_{PAW} are the soil water content at field capacity and the permanent wilting point and the plant-available water.

tables, and dry soil can limit root zone depth. In general, vegetables have relatively shallow root systems; the soil water storage they can access is limited. Crops with lower allowable depletion levels and shallower root depths must be irrigated more often.

Examples of how to determine 60 percent of MAD are shown in Table 3. In loamy sand, the soil water content at field capacity is 0.103 ft/ft and the permanent wilting point is 0.066 ft/ft, resulting in a plant available water content range of 0.037 ft/ft.

If only 60 percent of this water can be used before yield or quality declines, the amount of water that can be safely extracted from the soil is 0.022 ft/ft (θ_{MAD} in Table 3). Subtract θ_{MAD} from θ_{FC} to find that water content at which irrigation should be initiated (0.103–0.022 = 0.081 ft/ft for the loamy sand). The small range of θ_{MAD} severely tests the abilities of most soil water sensors, particularly for the loamy sand soil.

Soil water tension

Another criterion often used to trigger irrigation applications is soil water tension. This method of irrigation scheduling is very well suited to sprinkler irrigation or microirrigation (drip irrigation) systems because they can apply water frequently and precisely. The soil water tension method can also be used with surface irrigation methods as well.

Soil water tension can be measured indirectly with a sensor such as the Watermark granular matrix sensor or with a tensiometer. The soil water tension at which irrigation is required will vary with soil type, the depth at which the sensor is placed, and the crop. Calibration and site-specific experience will help you get the best results from monitoring soil water tension in irrigation scheduling. Table 4 lists suggested soil water tension values for selected crops.

Table 4. Recommended allowable soil moisture tensions for selected crops.

Crop	Tension centibars
Alfalfa	80–150
Cabbage	60–70
Cantaloupe	35–40
Carrot	55–65
Cauliflower	60–70
Celery	20–30
Citrus	50–70
Corn (sweet)	50–80
Deciduous tree	50–80
Grain Vegetative growth stage Ripening stage	 40–50 70–80
Lettuce	40–60
Onion	45–65
Potato	30–50
Tomato	60–150

Source: Hanson et al. 2000.

Soil water measurement

The water content of soil water can be measured directly or indirectly. The direct method uses weight to determine how much water is in a sample of soil. A soil sample is collected, weighed, oven dried, and weighed again to determine the sample's water content either by mass (lb/lb) or by volume (ft/ft). The volume of water in soil as determined by weight is the standard against which the indirect methods are calibrated.

Several indirect methods can also be used to sense soil water content or tension. Studies comparing direct and indirect methods have found that:

- All soil water sensing methods must be calibrated, despite the efforts of manufacturers to provide calibration curves.
- Only the neutron probe and conventional time domain reflectrometry (both expensive and difficult), are accurate enough for scheduling irrigation using the MAD procedure.
- The capacitance methods are sensitive to soil temperature, salinity, clay content and type, and microscale soil structure. This makes them unreliable for MAD irrigation scheduling. They may be used to follow wetting and drying patterns over time and they allow you to detect wetting fronts from irrigation at the depths of sensor installation.

The sensors that respond to soil water tension also require calibration except for the tensiometer, which is a direct method. The case examples here are intended for instruction only and are not a recommendation.

Gypsum blocks and granular matrix sensors

Gypsum block sensors measure the water content of soil at whatever depth they are set. They do this by measuring the electrical resistance between two circles of wire mesh that are embedded in a porous block of gypsum (plaster of Paris, $CaSO_4$). Granular matrix sensors work in essentially the same way, but their block is made of different sized sand particles rather than of gypsum. While sand is inert, gypsum dissolves over time and changes the block's porosity. This change causes the gypsum block's sensors to respond differently to soil water tension.

How it works

Electrical resistance increases as soil water content decreases. Although the electrical resistance is measured in ohms, the handheld meter converts the reading and displays it in centibars (1 bar = 100 centibars). The Watermark sensor (Fig. 3) is a granular matrix sensor. It does contain a small amount of gypsum, but that is to buffer the conductivity of the water in the pores of the sensor against undue influence by soil salinity. It is more durable in the soil than a gypsum block and may be more responsive to changes in soil water suction (tension).

Figure 3. Watermark® sensor before installation.

Figure 4. Using handheld meter for Watermark® sensor.

The handheld meter for the Watermark sensor (Fig. 4) indicates soil water tension over the range of 0 to 199 centibars. The tension should be interpreted carefully, considering the soil properties. Watermark sensors should be calibrated to the soil it will be used in. These sensors are affected by temperature and salinity. The sensor in Figure 4 can be adjusted for soil temperature.

How to install and read a Watermark sensor

To get an accurate water tension reading, install Watermark sensors in several locations within a field, especially if the field includes several soil types. Place them in representative areas, such as within the plant row for row crops, in the bed for vegetable crops or in wetted areas under drip irrigation. Depending on the effective root zone depth of the crop, each station should often have three sensors placed at multiple depths in order to read the effective root zone. This will help evaluate water movement and depletion within the root zone over time and to detect depth of wetting following an irrigation event which may indicate deep percolation losses.

1. Soak the sensors in water and install them wet to improve the sensor response to the first irrigation.
2. Use a ⅞-inch auger to drill a hole in the soil to the desired depth.

3. Push the sensor in with a stick.
4. Add water and soil to backfill the hole, leaving the wire leads accessible above the ground.
5. Place a flag or other marker at each site to make it easier to find the sensor leads for subsequent readings.

Sensors can be reused for several seasons. If you move them, remove the sensors carefully then clean and dry them for relocation or storage. Once you are ready to install them again, ensure that they are reading properly; soak them in water overnight and then make sure that the submerged sensors read between 0 and 5 cb. If they read more than 5 cb, discard them.

Connecting the sensor leads to a Watermark digital meter will give you an instant reading. Regular readings will show how fast the soil water is depleting and help you know when you need to irrigate. There are several data loggers like the one in Figure 5 that read the sensors and record the water level continuously. This information can be downloaded to a portable computer.

Figure 5. Watermark® sensors connected to a 3-port WatchDog® data logger.

Figure 6 tracks the changing soil water tension at different soil depths (6, 18 and 30 inches) in an orange orchard. In this application, subsurface drip irrigation was triggered when the sensor located at a soil depth of 18 inches reached approximately 40 cb. An irrigation application of about 0.7 inches (indicated by a blue triangle) saturated the soil. Note that the soil dried first in the top of the root zone and later in the deeper portion of the root zone.

Sensors such as these that are connected to devices that read and record soil moisture, can track irrigation and indicate soil water trends. Rainfall (indicated by purple squares) allowed the manager to delay irrigation.

Capacitance sensors

This type of sensor measures changes in the *dielectric permittivity* of the soil by using two metal electrodes. There are a wide variety of these types of sensors and they come in many shapes and configurations. The electrodes are inserted or buried in the soil, or are cylindrical rings inside a plastic access tube that is inserted vertically into the soil. Sometimes the electrodes, such as the ECH$_2$O sensors are covered in plastic.

An electronic oscillator circuit energizes the electrodes with high frequency alternating current. The resonant frequency decreases as water content increases. By measuring the changes in the sensor frequency, the soil water content is sensed indirectly. Unfortunately, certain soil properties affect soil's dielectric permittivity, and make capacitance sensors inaccurate. These include: clay content and type, soil temperature, and the bulk electrical conductivity of soil which increases with soil water content, salinity, and temperature. Measuring capacitance is highly sensitive to the conditions immediately next to the electrodes. Consequently, small air gaps or soil structure anomalies next to the sensor can greatly affect the reading. Because of this, these types of sensors are most accurate and repeatable in sandier soils, and

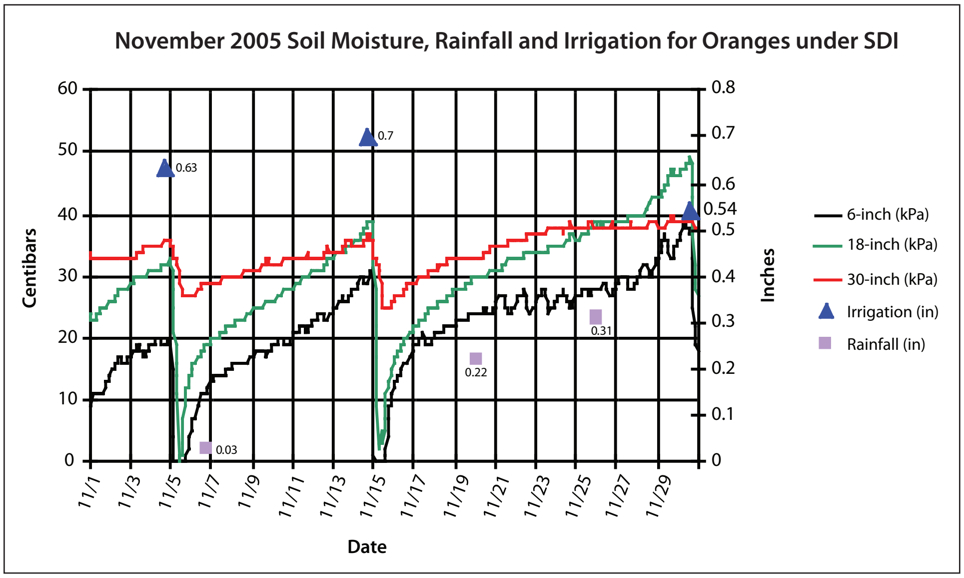

Figure 6. Watermark sensors soil water readings of rainfall and irrigation for oranges under drip irrigation.

soils that won't pull away from the sensor (shrink) as they dry.

Other permittivity sensors

Several dielectric permittivity sensors have been introduced that do not depend on capacitance measurements alone. Two examples are the model CS616 from Campbell Scientific and the HydraProbe from Stevens. Both of these sensors are temperature sensitive and over-predict water content in clayey soil (Fig. 7). Soil-specific calibration will prevent the over prediction, but cannot overcome the temperature sensitivity. Also, these sensors give different water content readings at the same soil water content; there are sensor-to-sensor differences between CS616 sensors and also between HydraProbes.

A sensor that is less temperature sensitive, but still requires soil-specific calibration, is the Acclima. It uses a measurement method that is equivalent to that of the accurate but expensive time domain reflectometry method (Fig. 8). When calibrated for a specific soil, the TDR and Acclima sensors are accurate sensors for irrigation management because they show little sensor-to-sensor variability and little sensitivity to soil salinity and temperature.

How it works

Time domain reflectometry systems are used primarily for research because they are complicated and expensive (>$5,000). However, the Acclima sensor is an affordable consumer alternative for irrigation scheduling. After digging a hole to the

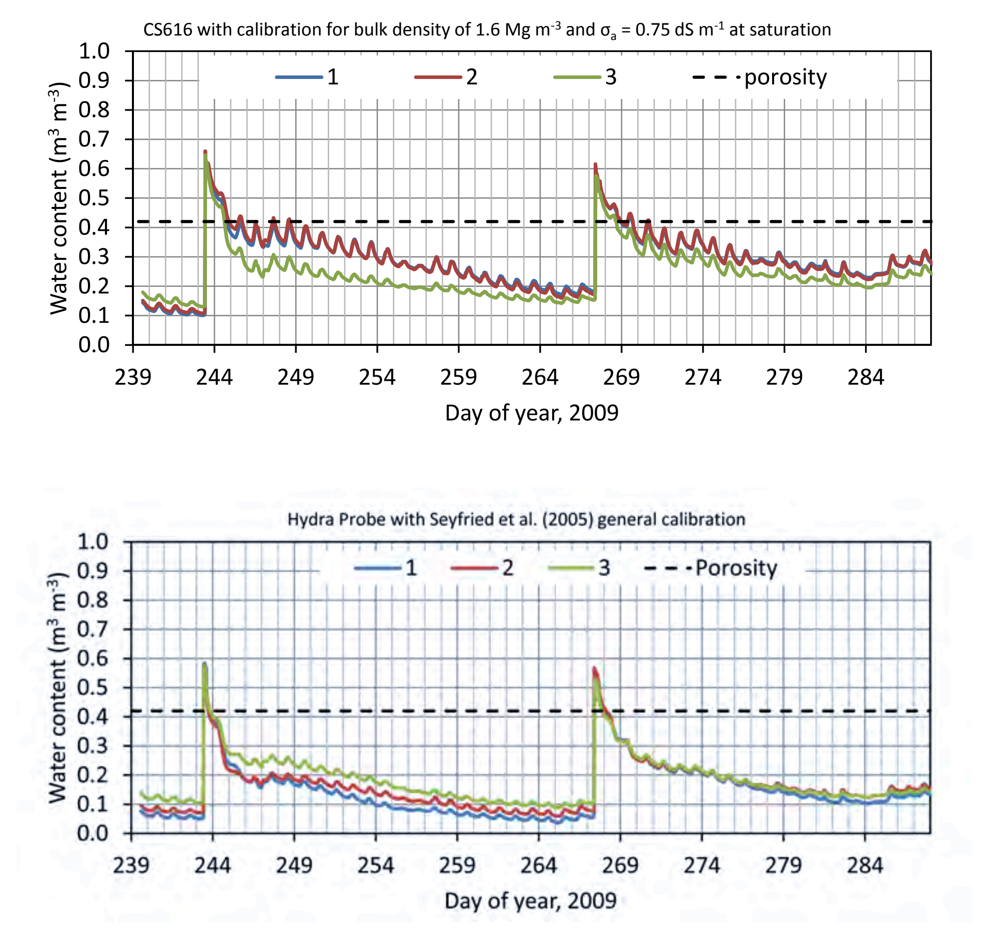

Fig. 7. CS616 water contents from calibration for sandy clay loam with bulk electrical conductivity = 0.75 dS m-1 at saturation (top); and Hydra Probe water contents using Seyfried et al. (2005) general calibration (bottom). All were installed at the same depth in a uniformly wetted soil. This soil cannot become wetter than the 0.42 ft/ft water content marked with the dashed line because that is the porosity of the soil.

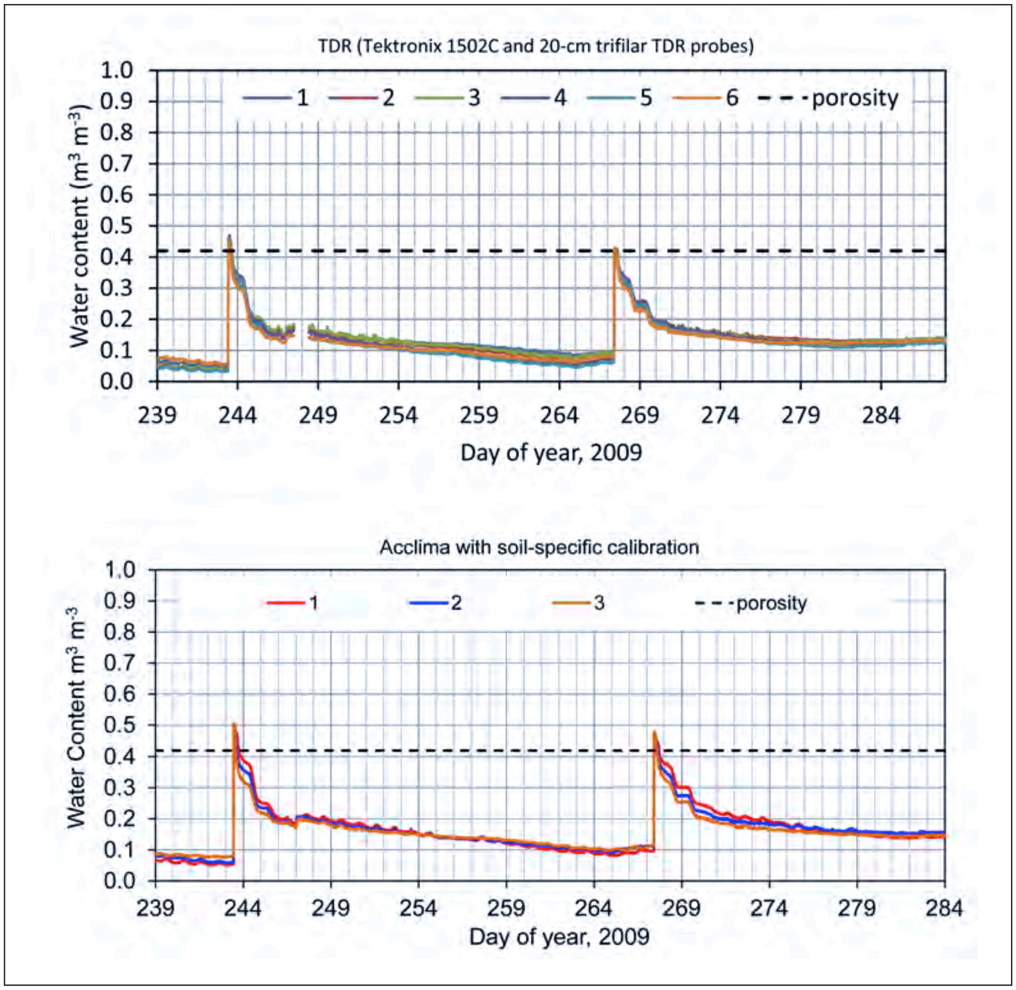

Fig. 8. Conventional time domain reflectometry (TDR) water contents (top); and Acclima sensor water contents (bottom), both using soil-specific calibrations. They were installed at the same depth and in the same soil as the sensors illustrated in Fig. 7. Two irrigations are illustrated.

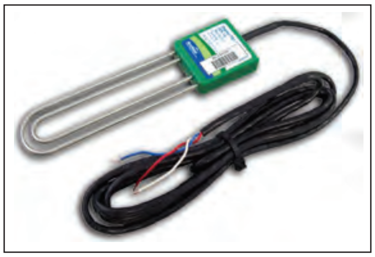

Figure 9. Acclima sensor and cable.

desired depth, the Acclima sensor is buried in the soil and connected by insulated wires to a weather-tight case were data are recorded and stored. Data including the soil temperature can be transmitted by radio to a pivot point or to the edge of a field and viewed.

Tensiometers

A tensiometer measures tension to determine soil water content. This instrument consists of a sealed water-filled tube equipped with a vacuum gauge at the top end and a porous ceramic cup on the bottom (Figs. 10 and 11).

How it works

As soil dries, water will move from the tensiometer tube through the ceramic cup into the soil in response to soil water suction. Water can also move from the soil into the tensiometer during or following irrigation. As the soil dries, the tensiometer loses water, a vacuum forms in the tube and is measured by the gauge. Most tensiometers have a vacuum gauge that registers from 0 to 100 centibars. During irrigation, water returns to the tensiometer, and the gauge reading approaches 0 and indicates the soil is saturated.

The useful limit of the tensiometer is about 80 cb. Above this tension, air sometimes enters through the ceramic cup and causes the instrument to fail (lose suction). Therefore, these instruments are most useful with drought-sensitive crops because they have narrower allowable soil water loss ranges.

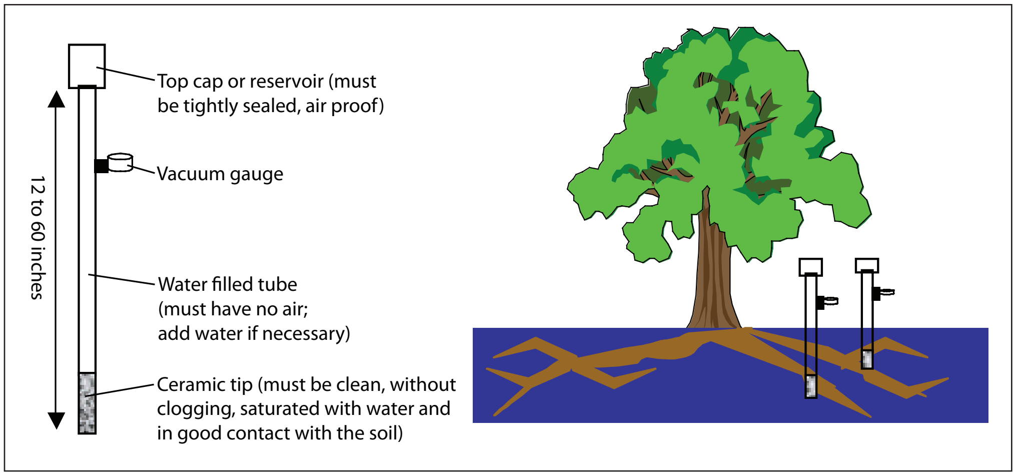

Fig 10. Tensiometer components and two tensiometers installed at different soil depths.

Fig. 11. Station of 3 tensiometers installed at different soil depths.

Tensiometers are useful in intermediate-texture soils and in non-cracking clays. In cracking clays and sandy soils, contact problems often cause measurement errors. After several wetting and drying cycles, some air may be drawn into the tensiometer and collected below the reservoir. Some tensiometers are equipped with small water reservoirs to replace this water and reduce the service required.

How to install and read a tensiometer

1. Soak the instruments in a bucket of water for 2 or 3 days before you plan to install them. This eliminates air trapped in the porous cup.
2. Fill the tube with distilled water you have colored and treated with algaecide. Gently tap the top of the reservoir to remove air bubbles from the tube and the vacuum gauge by tapping the top of the reservoir gently.
3. Apply a strong vacuum with the hand vacuum pump until the gauge reads 80 to 85.
4. Seal the cap properly.
5. Check the reading when the ceramic tip is immersed in water. (It should read 0 centibars.)
6. Install the ceramic cup in the active root zone of the soil. Two tensiometers are recommended at each site (Fig. 10). For shallow-rooted crops, such as vegetables, install one tensiometer 6 inches deep and one 12 inches deep. Install one tensiometer 12 inches deep and another at 24 or 36 inches deep for deeper rooted field crops.
7. Use a ⅞-inch auger that has the same diameter as the tube to dig a hole to the desired depth. To measure the exact depth, subtract the height of the ceramic tip obtain that exact depth. Finish the prehole with a smaller diameter probe, and push the tensiometer into place. To obtain accurate readings, the ceramic tip must have good contact with the soil.
8. Backfill with dirt and pour water around the tensiometer to improve soil contact. Pack a 3- to 4-inch mound of soil around the tube. You can also use a clay slurry to pack the tip of the tensiometer. Use the smallest amount of water possible to make the mud flow just enough to push in the cup.

Neutron probes

Neutron scattering is a time-tested technique for measuring total soil water content by volume. This apparatus estimates the water content of soil by sensing the amount of hydrogen that is present in the soil. Though organic matter in the soil contains hydrogen, only soil water content changes quickly and makes it possible to calibrate the probes to measure water content.

How it works

The neutron probe consists of a unit that includes a source of high-energy neutrons and a detector. The probe is lowered down a plastic, steel or aluminum access tube to the desired depth, where it is held in place by clips attached to its cable. A control and counting unit is connected to the cable above ground.

Fast neutrons are emitted from the source and pass through the access tube into the surround-

Table 5. Advantages and disadvantages of selected soil water monitoring systems.

	Advantages	Disadvantages
Gravimetric	• Very accurate	• Destructive • Requires labor • Time consuming • Results are not immediately available
Watermark sensors	• Good accuracy in medium to fine soils because their fine-sized particles are similar to the sensor's inner granular matrix • Affordable (about $40–50 per sensor, $250 for the meter) • Easy to use (light weight, pocket-sized, easy installation and direct reading) • Greater water measuring range than tensiometer • Reusable for several seasons with proper care (gypsum blocks, must be replaced each year) • Continuous measurements at same location	• Slow response to changes in soil water content, rainfall or irrigation • Lack of accuracy in sandy soils • Problems getting adequate soil contact in clayey and sandy soils • Time consuming to determine what sensor reading is best suited for irrigation • Affected by soil salinity and temperature • Small sample area • Requires intensive labor to collect data regularly (unless you connect the Watermark® sensors to a data logger, collect data automatically, and download to a personal computer.) • Must be calibrated for best accuracy
Capacitance sensors	• Reports volume of soil water content directly • Requires no special maintenance • Measures continuously at same location	• Expensive—requires a computer and $95 for the software or about $300 for the manual meter; The HOBO data logger needed to connect several sensors costs $200. EC ECH2O probes cost $100 for up to 10 units; $70 each for 11 or more. • Affected by soil temperature, salinity, and clay content • Very sensitive to proper installation, which can be difficult • Highly sensitive to the small soil area immediately next to the probe. • Affected by soil salinity and temperature • Requires calibration for each soil type, yet may be inaccurate even with soil-specific calibration
Tensiometers	• Low cost • Direct water tension reading for irrigation scheduling • Continuous measurements at same location	• May require periodic service • Operates only to 80 cb soil water suction; not useful in drier soil conditions
Neutron Probe	• The most accurate methods for measuring soil water content when properly calibrated • Able to measure soil water at different depths several times during the growing season • Samples a relatively large soil volume	• Requires a depth control stand for readings nearer to the surface than 8 inches • Very expensive, about $4500 • Radiation safety regulations require special licensing, regular training for the operator, and special handling, shipping and storage procedures • Needs to be calibrated against gravimetric measurements by selecting a wet and a dry spot; and for calibrating to the different soil types and depths

Figure 12. Neutron probe used at a citrus orchard.

ing soil where they lose their energy to collisions with other atomic nuclei. These neutrons collide with soil water (H_20) and are slowed down by the hydrogen nuclei. Slow neutrons are counted when they bounce back to the detector. This count is linearly related to the total volumetric water content in the soil. A higher count indicates higher soil water content. While the relationship is linear, it must be calibrated for each particular soil.

To calibrate the neutron probe, you need a dry and a wet site for each soil type. Neutron probe readings at each site are correlated with measured soil water contents using the gravimetric method to determine a calibration line with these two end points. The calibration converts the neutron gauge readings to volumetric water contents. Although this method is well accepted as highly accurate, the high equipment cost, licensing requirements and regulatory burden limits its application to research, consultants, or to areas where extensive sampling is needed.

Advantages and disadvantages of selected soil water sensors

Table 5 describes some of the advantages and disadvantages of the gravimetric method, the Watermark sensors, ECH_2O Sensors, tensiometers, and neutron probe.

Conclusions

Several methods are available for monitoring soil moisture. Each has advantages and disadvantages, but when installed and calibrated properly, they all can be effective tools measuring soil water content. Knowing the soil moisture content will enable you to manage irrigation effectively based on plant moisture needs, on soil water storage capacity, and on root zone depth and characteristics. Timely and adequate—but not excessive—irrigation promotes water conservation and profitability.

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