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Irrigation Monitoring with Soil Water Sensors

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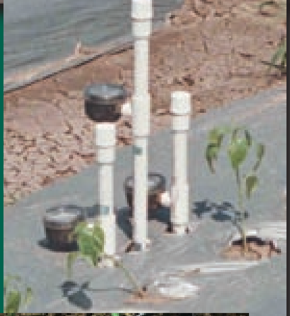

Monitoring soil water content is essential to help growers optimize production, conserve water, reduce environmental impacts and save money. Soil moisture monitoring can improve irrigation decisions, such as how much water to apply and when to apply it. It can also match irrigation water applied with crop water requirements, avoiding over- or under-irrigating the crop. Over-irrigation can increase energy consumption and water cost as well as leaching of fertilizers below the root zone, erosion, and transport of soil and chemical particles to the drainage ditches. Under-irrigation can reduce crop yields.

Basic concepts

Soil water storage capacities are summarized by soil texture in Table 1. They are characterized by soil-specific parameters and are key to efficient irrigation management. These are defined as follows:

Field capacity is the soil water content after a heavy irrigation has finished and when the drainage rate changes from rapid to slow. This point is reached when all the gravitational water has drained (Figure 1). Field capacity is normally attained two to three days after irrigation and reached when the soil water tension is approximately 0.3 bars (30 centibars or 3 m of tension) in clay or loam soils, or approximately 0.1 bar in sandy soils.

Permanent wilting point is the soil water content at which plants cannot recover overnight from excessive drying during the day. This parameter, which may vary with plant species and soil type, has been determined in greenhouse experiments. It is attained at a soil water tension between 10 and 20 bars (102 to 204 m of ten-

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Table 1. Soil moisture content in inches of water per foot of soil.

Soil Texture	Field Capacity	Permanent Wilting Point (15 Bars)	Plant Available Water (in./ft.)
Sand	1.2 (10)*	0.5 (4)	0.7 (6)
Loamy sand	1.9 (16)	0.8 (7)	1.1 (9)
Sandy Loam	2.5 (21)	1.1 (9)	1.4 (12)
Loam	3.2 (27)	1.4 (12)	1.8 (15)
Silt loam	3.6 (30)	1.8 (15)	1.8 (15)
Sandy clay loam	4.3 (36)	2.4 (20)	1.9 (16)
Sandy clay	3.8 (32)	2.2 (18)	1.7 (14)
Clay loam	3.5 (29)	2.2 (18)	1.3 (11)
Silty clay loam	3.4 (28)	1.8 (15)	1.6 (13)
Silty clay	4.8 (40)	2.4 (20)	2.4 (20)
Clay	4.8 (40)	2.6 (22)	2.2 (18)

*Numbers in parentheses are volumetric moisture contents in percent.
Source: Hanson 2000.

sion). A mean value of 15 bars (153 m) is generally used. *Hygroscopic water* is held tightly on the soil particles (below permanent wilting point) and cannot be extracted by plant roots.

Plant available water is retained in the soil between field capacity and the permanent wilting point. This parameter is generally expressed in inches of water per foot of soil depth. It depends on such factors as soil texture, bulk density and soil structure. Table 1 shows approximate values of plant available water for different soil textures. The soil water contained between these limits moves primarily by capillary, or matric, forces (Figure 1).

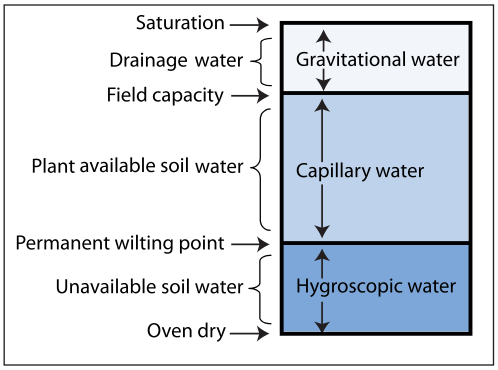

Figure 1. Soil water parameters and classes of water.

Gravimetric water content, which is a direct soil moisture measurement, is the standard method to calibrate other soil water determination techniques. The oven drying technique is probably the most widely used of all gravimetric methods for measuring soil water. A soil sample can be taken with an auger or tube sampler. It is placed in a container and weighed, and is dried in an oven at 105°C until a constant weight is obtained (normally after 24 hours). Then it is weighed again. The gravimetric water content, which is the amount of water in the sample as percent of the dry soil weight, is calculated as follows:

$$\text{Gravimetric water content (\%)} = \frac{\text{Mass of wet soil} - \text{Mass of dry soil} \times 100}{\text{Mass of dry soil}}$$

Bulk density is the expression of mass of dry soil per unit volume of soil. It is related to porosity (void space) and compaction, and it is used to calculate volumetric soil water content from gravimetric water content. This parameter is generally expressed in grams per cubic centimeter of soil accordingly:

$$\text{Bulk density} = \frac{\text{Mass of dry soil}}{\text{Volume of soil}}$$

Volumetric water content is commonly used to express the soil water content. As the following shows, it is obtained by multiplying the bulk density of the soil by the gravimetric water content:

Volumetric water content (%) = (Bulk density of soil/density of water)
x Gravimetric water content (%)

The volumetric water content (%) can be used to calculate irrigation depth. Assume, for example, that the current volumetric water content is 20 percent and the field capacity is 30 percent. 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:

Irrigation depth = (30-20)/100 x 2 ft = 0.1 x 2 ft
= 0.1 x 24 inches = 2.4 inches

If we want to know how much water the soil contains at 20 percent plant available soil moisture, the available water depth can be calculated accordingly:

Water depth = 20% x 2 ft = 20/100 * 24 inches = 4.8 in

Water storage capacity of soils. The soil moisture characteristic curve (Figure 2) describes the relationship between soil water content and the tension at which the water is held in the soil. It is non-linear, and the relationship varies from soil to soil. In a saturated soil, the tension is very near zero; and, as soil dries, tension (suction) increases.

Soil texture influences the characteristic curve. Since sandy soils do not hold as much plant available water, they generally drain more quickly and need to be irrigated more frequently than clay or loam soils.

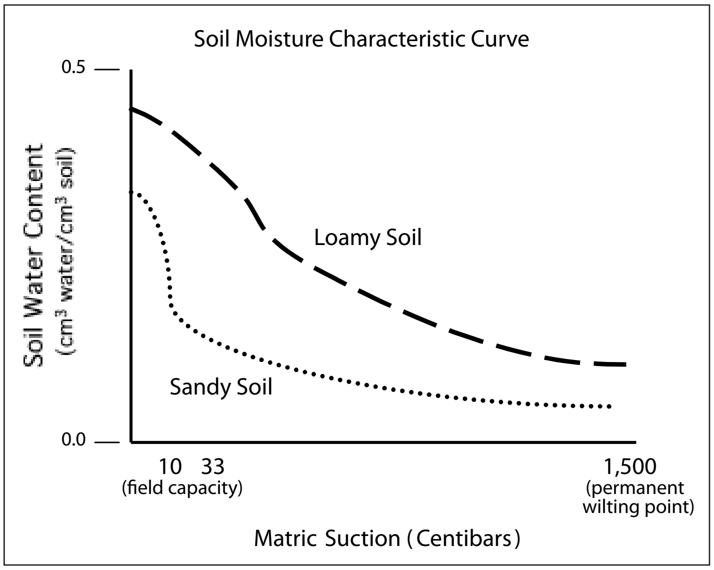

Figure 2. Soil water characteristic curves for typical sandy and clay soils.

Management allowable depletion (MAD). This is the point below which the soil available water should not be depleted to avoid excessive water stress and, therefore, reduction in production. The volume of water between the MAD point and field capacity should be the irrigation depth. The volume of water below this limit is what remains in the soil. The management allowable depletion (or allowable deficit) will depend on the plant species and will vary between growing seasons. It is generally expressed in percent. Recommended MAD levels for many field crops are near 50 percent. For drought-sensitive crops (including many vegetables), MAD may be as low as 25 percent. Table 2 shows the allowable depletion for selected crops.

Another criterion often used to trigger irrigation applications is soil *moisture tension*. This method of irrigation scheduling is most applicable with sprinkler irrigation or microirrigation (drip irrigation) systems that allow for relatively precise irrigation applications. Soil moisture tension can be measured with a sensor such as the Watermark® sensor (granular matrix sensor) or a tensiometer. The trigger-

Table 2. Allowable soil moisture 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

*Root depths can be affected by soil and other conditions. Effective root zone depths are often shallower.
Source: Allen et al., 1998.

ing soil water tension will vary with soil type and the depth at which the sensor is placed. Calibration and site-specific experience optimize the use of soil moisture tension in irrigation scheduling. Some suggested tension values appear in Table 3.

Root depth will determine the soil water available for the plant, and Table 2 shows the expected rooting depths for selected crops. Soil conditions (e.g., compacted layers, shallow water tables, dry soil) can limit root zone depth. In general, vegetables have relatively shallow root systems, and, thus, limited access to soil moisture storage. Crops with lower allowable depletion levels and shallower root depths require more frequent irrigations.

Soil water measurement

Methods used to measure soil water are classified as *direct* and *indirect*. The direct method refers to the gravimetric method in which a soil sample is collected, weighed, oven-dried and weighed again to determine the sample's water content on a mass percent basis. The gravimetric method is the standard against which the indirect methods are calibrated. This section describes several indirect methods for measuring soil moisture.

Granular matrix sensors and gypsum blocks

Gypsum block sensors respond to soil water conditions at the depth they are placed by measuring electrical resistance between two circles of wire mesh that are connected to a porous material.

How it works

Although the electrical resistance is measured in ohms, the handheld meter converts the reading automatically to centibars (1 bar = 100 centibars). Electrical resistance increases as soil water suction increases, or as soil moisture decreases. While the Watermark® sensor (Figure 3) functions similarly to the gypsum block sensor, it differs in that it is more durable in the soil and may be more responsive to changes in soil moisture.

The handheld meter for the Watermark® sensor (Figure 4) indicates soil moisture tension over the range of 0 to 199 centibars. The tension should be interpreted carefully, considering the soil properties. For instance, 10 cb could correspond to field capacity for coarse-textured soils (sand), while 30 cb could correspond to field capacity for finer-textured soils (silt, clay, loams). A rising meter reading indicates depletion of total available water. Therefore, 75 cb could correspond to 90 percent depletion for coarse-textured soils, but only 30 percent for fine-textured soils. Consequently, it is recommended to calibrate the Watermark® sensors to a specific soil. These sensors are slightly affected by temperature and salinity. The sensor in Figure 4 can be adjusted for soil temperature.

Installation and reading

It is important to install several stations of Watermark® sensors in a field to get a good moisture reading accuracy, especially if the field includes several soil types. A station should have sensors placed at multiple depths, depending on the crop grown (and effective root zone depth). This is to evaluate moisture movement and depletion within the root zone over time and with crop water use.

The placement of the sensors will vary slightly according the irrigation technique. In addition, they must be placed in a representative area, such as within the plant row for row crops, in the bed for vegetable crops or in wetted areas under drip irrigation. Depth of placement should also be representative of the effective root zone.

Sensors must be soaked first before installation to improve the sensor response in the first irrigation. They should also be installed wet. To put them into the soil at an appropriate depth, use a ⅞-inch auger to drill a hole in the soil to the desired depth. Push the sensor in with a stick, add water and soil to backfill the hole to bury the sensor, leaving the wire leads accessible on or above the ground. A flag or other marker at each site will make it easier to locate the sensor leads for subsequent readings.

Table 3. 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	40–50
Ripening stage	70–80
Lettuce	40–60
Onion	45–65
Potato	30–50
Tomato	60–150

Source: Hanson et al. 2000.

Figure 3. Watermark® sensor before installation.

Figure 4. Using handheld meter for Watermark® sensor.

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

If sensors are removed, they can be reused for several seasons with care, so clean and dry them before storage. However, once you are ready to install them again, you need to check the sensors first. To do this, soak them in water and 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 gives an instant reading. Regular readings indicate how fast the soil moisture is depleting, and, therefore, indicate when irrigation will be needed. There are some data loggers like the one in Figure 5 that permit the data to be read directly and recorded continuously. They also allow the downloading of data to a portable computer.

Figure 6 shows the movement of soil water at different soil depths (6, 18 and 30 inches) in an orange orchard. In this application, subsurface drip irrigation is triggered when the sensor located at a soil depth of 18 inches reaches approximately 40 cb. An irrigation application (indicated on the graph by a blue triangle) of about 0.7 inches saturates the soil. Note that the soil dries first in the top of the root zone and then later in the deeper portion of the root zone.

Sensors track irrigation and indicate soil moisture trends. Rainfall (indicated on the graph by purple squares) allows the manager to delay irrigation.

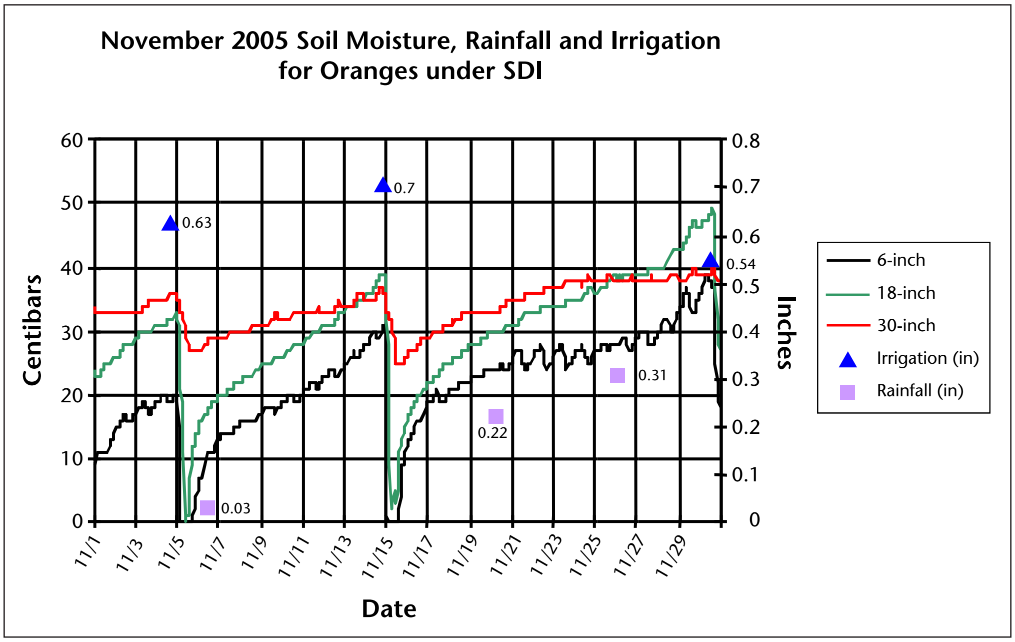

Figure 6. Soil water readings with Watermark® sensors, rainfall and irrigation for oranges under drip irrigation.

Capacitance sensors

These sensors measure changes in the *dielectric constant* of the soil with a capacitor, which consists of two plates of a conductor material separated by a short distance (less than ⅜ of an inch). A voltage is applied at one extreme of the plate, and the material that is between the two plates stores some voltage. A meter reads the voltage conducted between the plates.

When the material between the plates is air, the capacitor measures 1 (the dielectric constant of air). Most materials in soil, such as sand, clay and organic matter, have a dielectric constant from 2 to 4. Water has higher dielectric constant of 78. Hence, higher water contents in a capacitance sensor would be indicated by higher measured dielectric constants. Thus, by measuring the changes in the dielectric constant, the soil water content is measured indirectly.

Some of the available capacitance-based sensors include ECH_2O® probes (Figure 7), EnviroSCAN® and Time-Domain Reflectometry (TDR). (This section only describes ECH_2O® probe sensors.)

Figure 7. ECH_2O probe® and ECH_2O check® meter (dielectric meter).

How it works

These sensors give readings of volumetric soil water content at the depth they are placed (m^3 of water/m^3 of soil). Soil moisture typically ranges from 0 to 0.4 m^3 of water per m^3 of soil. These sensors are already pre-calibrated for a wide range of soil types. However, for high sand content (coarse textures) and soils with high salt contents, the standard calibration will not be accurate. Therefore, some calibrations will have to be done. A value of 0 to 0.1 m^3/m^3 indicates an oven-dried to dry soil (wilting point), and a value of 0.3 to 0.4 m^3/m^3 represents a wet (field capacity) to saturated soil.

The sensors are connected to a data logger (such as a HOBO® data logger or weather station), and a serial cable will allow data downloading to a personal computer. The HOBO® data logger can accept up to four sensors.

Installation and reading

The sensors should be placed at several depths in a representative area of the field in order to evaluate soil water movement and depletion in the root zone. This is monitored over time and with crop water use.

Since sensors measure the water content near their surface, it is important to avoid air gaps and excessive soil compaction around them. This enables readings to be most representative of undisturbed soil.

Probes should be placed at least 3 inches from each other or from other metal surfaces. They can be placed perpendicular or vertical to the soil surface, but it is important to avoid downward water movement along the surface of the probe. To place a probe, make a pre-hole with a 3-inch auger for deeper installations. Then use an ECH_2O probe® auger to insert the probe into the soil at the desired depth (Figure 8). Next you need to cover the probe with soil around it, making sure good contact is made against the probe. The probe cables need to be accessible to be plugged into the data logger through their jacks and will last longer if inserted through a conduit. This protects cables from damage by animals, chemicals and UV rays.

Software is necessary for downloading sensor data from the data logger onto a personal computer (Figure 9). The data logger can be programmed to take readings at different time intervals (e.g., 1 reading every 2 or 24 hours). It is possible to collect soil moisture content data for the whole season for a particular crop.

Figure 8. Using a special auger to install the ECH_2O® probes: a blade of the probes shape is hammered down (top) before inserting and pushing down the probe with another tool (below).

Figure 9. Downloading data from the logger to the personal computer.

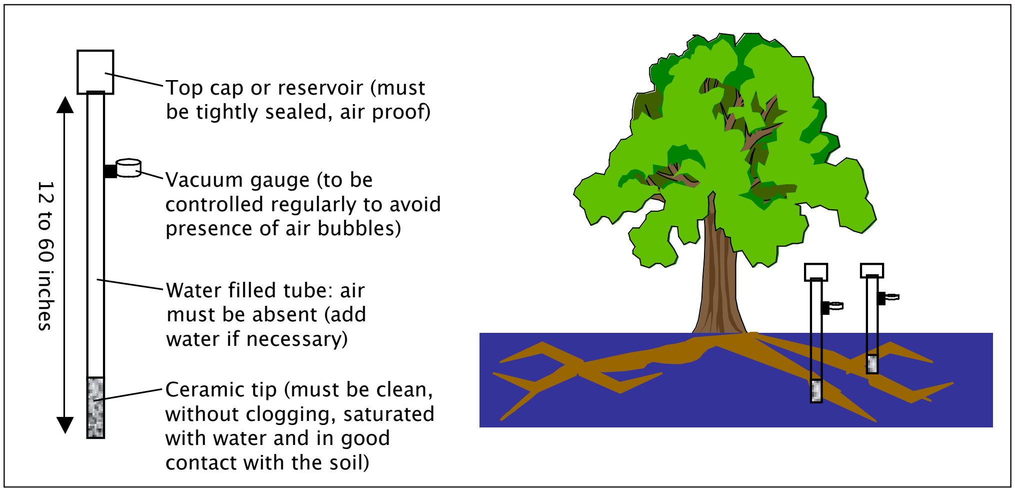

Figure 10. Diagram of a tensionmeter and a station of two tensiometers installed at different soil depths.

Tensiometer

A tensiometer measures the tension of the soil water or soil suction. This instrument consists of a sealed water-filled tube equipped with a vacuum gauge on the upper end and a porous ceramic cup on the lower end (Figures 10 and 11).

Figure 11. Station of three tensiometers installed at different soil depths.

How it works

Water moves from the tensiometer tube through the ceramic cup to the soil in response to soil water suction (when water is evaporated from the soil or when the plant extracts water from the soil.) Water can also move from the soil to the tensiometer during or following irrigation. As the tensiometer loses water, a vacuum is generated in the tube and is registered by the gauge. Most tensiometers have a vacuum gauge graduated from 0 to 100 (centibars, cb, or kilopascals, kPa). A reading of 0 indicates a saturated soil. As the soil dries, the reading on the gauge increases.

The useful limit of the tensiometer is about 80 cb. Above this tension, air enters through the ceramic cup and causes the instrument to fail. Therefore, these instruments are most useful in sandy soils and with drought-sensitive crops because they have narrower soil moisture ranges. During irrigation, water returns to the tensiometer, and the gauge reading approaches 0. After several wetting and drying cycles, some air may be drawn to the tensiometer and collected below the reservoir. Some tensiometers are equipped with small water reservoirs to replace this water and reduce service required.

Installation and reading

Before taking the first step to install the tensiometer, soak the instrument in a bucket of water for 2 or 3 days. Then carry out the following:

- Saturate the ceramic tip with water to eliminate any air bubbles.
- Fill the tube with distilled water, colored and treated with algaecide. Remove air bubbles (from the tube and the vacuum gauge) by tapping the top of the reservoir gently.

- Apply a strong vacuum with the hand vacuum pump until a reading of 80-85 shows on the gauge.
- Seal the cap properly.
- Check the reading you obtain with the ceramic tip immersed in water. (It should read 0 centibar.)
- Install the ceramic cup in the active root zone of the soil. Two tensiometers are needed in each site (Figure 10). For shallow root crops, such as vegetables, install one tensiometer at 6 inches and one at 12 inches deep. Install one tensiometer at 12 inches and another at 24 or 36 inches deep for deeper rooted field crops.
- Use a ⅞-inch auger that has the same diameter as the tube to dig a hole to the desired depth (minus the height of the ceramic tip). Finish the pre-hole with a smaller diameter probe and push the tensiometer into place. Reading accuracy depends on good contact with the soil.
- Backfill and pour water around the tensiometer to improve soil contact, and pack a 3- to 4-inch mound of soil around the tube. It is also possible to backfill with mud from local soil and pour it into the hole before placing the tensiometer.

Neutron probes

Neutron scattering is a time-tested technique for measuring total soil water content by volume. This apparatus estimates the amount of water in a volume of soil by measuring the amount of hydrogen that is present.

How it works

The neutron probe consists of a unit made of a source of fast or high energy neutrons (encapsulated radioactive source) and a detector. This probe unit is lowered in a PVC or aluminum access tube at the desired depth with the help of clips attached to a cable. A control unit, which remains on the surface, is connected to the cable.

Figure 12. Neutron probe used at a citrus orchard.

Fast neutrons, emitted from the source and passing through the access tube into the surrounding soil, gradually lose their energy through collisions with other atomic nuclei. Neutrons collide with hydrogen in soil moisture and slow down. Slow neutrons "bounce" back to a detector, creating an electrical impulse that is counted automatically and gives a number of neutrons per time period. Basically, this number of pulses is linearly related to the total volumetric soil water content. A higher count indicates higher soil water content. While the relationship is linear, it must be calibrated for each particular soil.

For calibration of the neutron probe, a dry and a wet site need to be established for each soil type. Neutron probe readings, gravimetric and bulk density measurements determine a calibration line with these two points. The calibration converts neutron gauge readings to volumetric water contents. Although the method is well accepted as highly accurate, the high equipment cost, licensing requirements and regulatory burden limit its application to research and to areas where extensive sampling is needed.

Advantages and disadvantages of selected soil moisture sensors

Table 4 describes some of the advantages and disadvantages of the gravimetric method, the Watermark® sensors, ECH_2O Sensors, tensiometers and neutron probe.

Table 4. Advantages and disadvantages of selected soil moisture monitoring systems.

	Advantages	Disadvantages
Gravimetric	• Very accurate	• Destructive • Requiring labor • Time consuming
Watermark Sensors	• Good accuracy in medium to fine soils due to their fine-sized particle similar to its inner granular matrix • Affordable (about $20 per sensor, $250 for the meter) • Easy handling (light weight, pocket-size, easy installation and direct reading) • Larger moisture reading range (0 to 200cb, or kPa) • Usable over several seasons with proper care • Continuous measurements at same location	• Slow response to changes in soil water content, rainfall or irrigation (minimum 24 hours) • Lack of accuracy in sandy soils due to their large particles • Requiring intensive labor to collect data regularly (However, it is possible to connect the Watermark® sensors to a data logger; thus, readings are collected automatically and can be downloaded through a program on a personal computer.) • Need for each soil type to be calibrated
Capacitance sensor: ECH2O Sensors (Models EC-20, EC-10, and EC-5)	• Ability to read soil volumetric water content directly • No special maintenance necessary • Highly accurate when sensors are installed properly in good contact with soil • Large range of operating environment (0 to 50°C) and range of measurement (0% to saturated water content) • Continuous measurements at same location	• Expensive technique (requiring PC and $95 for the software or $300 for the meter for manual readings) (The HOBO® data logger costs $200, enabling several sensors to be connected. The EC Ech^2o probes cost $100 (for 1 and 10 units); they are $70 each if 11 or more units are ordered.)
Tensiometers	• Low cost • Direct water potential reading for irrigation scheduling • Continuous measurements at same location	• Requiring periodic service • Operating only to 80 cb soil moisture suction (not useful in drier soil conditions)
Neutron Probe	• Considered among 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	• No reading accuracy for the top 6 inches of soil depth due to the escape of fast neutrons emitted from the neutron probe • Very expensive technique ($3,000 to $4,000) requiring special licensing, regular training for the operator, special handling, shipping and storage procedures • Radiation safety regulatory burden • Need for calibrating neutron probe readings against gravimetric measurements by selecting a wet and a dry spot; and for calibrating to the different soil types and depths

Note: Root depths can be affected by soil and other conditions. Effective root zone depths are often shallower.
Source: Allen et al., 1998.

Conclusions

There are various soil moisture monitoring methods for irrigation scheduling. While each one has advantages and disadvantages, proper installation and calibration can make them effective tools. Soil moisture monitoring complements knowledge of plant water usage, soil moisture storage capacity, and root zone depth and characteristics to improve irrigation management. Optimizing irrigation by timely, adequate – but not excessive — irrigation applications promotes water conservation and profitability.

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