Section 6:

Sensor-Based Scheduling

Brian Lieb and Ken Fisher

Key Points:

- *There are a number of sensor systems now available that provide valuable information on when a field is ready to be irrigated.*
- *Wireless data transmission and improved software interfaces are now making these sensors practical for farm use.*
- *An affordable way to gain experience with sensor-based scheduling is to monitor a field for a season and review the data over the winter to see how your irrigation decisions matched the sensor readings.*

For over 60 years there have been sensors to monitor soil water conditions and provide data to help determine when to irrigate. One of the challenges for the practical use of any of these sensors on a commercial farm is the time it takes to go to the field and record the sensor output. The challenge becomes greater as the number of fields managed per person increase and keeping in mind that at peak water demand some systems may need to be monitored with a frequency of at least every three days. The recent availability of various sensor systems integrated with fairly affordable wireless data transmission capabilities have now made sensor-based scheduling more practical. These new tools are welcome, as Cotton Incorporated's 2008 Natural Resource Survey indicated only about 10% of the cotton producers responding to the survey used weather-based scheduling tools or crop and soil monitoring systems.

Types of Measurements

There are three different physical properties measured by sensors often used to determine when to irrigate:

1. *Soil matric potential* is a measure of how tightly water is bound to the soil – the higher the matric potential the more water stress the plant is under. Sensors that measure matric potential include: tensiometers (Figure 6.1) and electronic sensors, such as the "WaterMark" sensor from Irrometer.

Figure 6.1 – A tensiometer installed in a cotton row.

2. *Volumetric moisture content* is a measure of the volume of water per volume of soil. There are several types of sensors that measure this property including capacitance sensors, time domain reflectometry (TDR) sensors, and neutron probes.

3. *Canopy temperature* is a measure of the temperature of the surface temperature of the leaves. Transpiration cools the leaves; and, as water stress increases, transpiration decreases, so the canopy becomes warmer. Canopy temperature can be measured by carefully placing thermocouples directly on the leaves, but it is most commonly measured with an infrared thermometer (Figure 6.2).

In Section 2, Figure 2.3 illustrates the relationship between matric potential and moisture content. That relationship is very soil specific, and is best determined from soil cores collected with minimal disturbance. Matric potential is a little easier to interpret in terms of an irrigation trigger, as there are soil-specific thresholds already determined for cotton. In soils with more clay content it is generally in the range of 50-centibars, while in sandier soils it can be as low as 30-centibars.

Figure 6.2 – West Texas farmer inspecting an infrared thermometer used to monitor canopy temperature.

Volumetric moisture content requires some site-specific calibration to determine when to irrigate, and is often based on the concept of plant-available water. The water holding capacity of the soil is typically defined as the difference between the water content at field capacity (low tension) and wilting point (high tension). Percent plant available water (PAW) is then defined as:

$$\text{PAW} = \frac{100 \text{ X } [(\text{Measured Soil Moisture}) - (\text{Moisture at wilting point})]}{[(\text{Field capacity}) - (\text{Moisture at wilting point})]}$$

Often a PAW of 50% is used as an irrigation threshold for cotton.

Canopy temperature is a little complicated to interpret into an irrigation management decision, especially in humid regions. When the air is moist (high relative humidity), the amount of evaporative cooling is reduced even for well-watered cotton. Research is still in process to determine the appropriate use of canopy temperature for cotton grown in humid regions. In more arid regions, from west Texas to California, canopy temperature is a good tool for irrigation management. It is either used by accumulating the time canopy temperature is above an optimal temperature (about 82 degrees F for cotton), or based on a crop water stress index that requires an estimate of the canopy temperature of a well-watered crop that can be estimated from weather data.

Types of Sensors

The method a sensor uses to measure soil water content or tension is important for understanding the sensor's performance characteristics in cotton production. The tensiometer uses a porous ceramic tip in direct contact with the soil to directly measure soil tension. Granular matrix sensors measure the change in electrical resistance that occurs as soil water moves in and out of the sensor in response to the surrounding soil moisture, and this electrical resistance measurement is correlated with soil tension. The neutron probe counts the number of neutrons that collide with the hydrogen in water and is usually correlated with volumetric water content. Tensiometers, granular matrix sensors, and neutron scattering have a very long history of use in irrigation scheduling. Over the last twenty years, a new type of sensor has come to the market that measures the soil's dielectric constant or capacitance (ability of a material to store electricity). The amount of water as compared with air in the soil pores is the biggest factor affecting the soil's dielectric constant. One way to determine this electrical property is to measure the change in a radio wave frequency as it passes through the soil, known as Frequency Domain Reflectometry (FDR). Another way is to measure the reflectance pattern of a voltage pulse that is applied to a wire guide placed in the soil, known as Time Domain Reflectometry (TDR). Sensors that measure dielectric constant are usually related to soil volumetric water content.

The tensiometer may have limited usefulness in cotton irrigation scheduling. It is one of our most accurate tools but has a very limited range of measurement (wet readings only) while cotton is fairly drought tolerant and often the soil is allowed to dry to a point where the tensiometer will break tension. An exception would be soils like loamy sands that require frequent watering and hold a majority of their available water in large pores at low tension. All the other sensor types have sufficient range for cotton irrigation, but soil type can still impact sensor performance. The tensiometer and granular matrix sensor need to maintain hydraulic contact with the soil so that water can move in and out of the sensors. In very coarse sands, the hydraulic conductivity becomes very low as the soil dries, and thus water can no longer move in and out of the sensor. This condition can be corrected by adding a porous material around the sensor that creates better contact. Also, clay soils that crack can break hydraulic contact in these sensors. These same cracking clays will cause difficulty with sensors that measure dielectric constant because air gaps next to the sensor will greatly change the measurement. By and large, we have a variety of soil sensors that will work for cotton irrigation scheduling under most conditions.

Costs and Methods of Obtaining Soil Water Data

There are several different strategies for getting soil water/tension readings from the field into your hands. The simplest method we will call "in-field data collection" where sensors are installed in the field with wire leads coming to the surface. In this set-up, a grower or field-hand will enter the field with a hand reader and connect it to the wire leads (tensiometers already have a gauge attached to each sensor). At this point the reading is recorded by hand or logged if the hand reader has a logger. The readings may need to be graphed or formatted to enhance understanding of the results. This approach has a very low equipment cost of around $300 to $1,000 for at least two sensors at a single location and a hand reader. Additional locations will be less expensive because the hand reader can be transported to other sensor locations. Remember to include the time required and cost of sending someone out to read the sensors. This approach is helpful for making irrigation decisions at the time of a reading but usually does not result in a very good record of soil water content or tension. It is difficult to make time for much more than one reading per week, and what often happens in a humid region is that sensors do not get read at all during a rainy period (no need to worry about irrigating) or during a prolonged dry period (already decided that irrigation is necessary). Finally, sensor locations can get lost as the crop grows and no one likes going into a wet cotton field to take readings (head-high corn is worse).

The second approach we will call "edge of field logging" where the sensor leads are either wired to a logger or to a radio transmitter that sends wirelessly the readings to a data logger at the edge of the field where it is easy to access. In this scenario, someone still has to travel to the field to download the readings from the logger and upload the readings to a software program, but no one is required to enter the crop. Some loggers have onboard displays that do not require this download and upload step. The result is a continuous data set that can be easily related to rainfall and irrigation patterns. Of course, this improved convenience and the greater data recording frequency will cost more, around $500 to $2,000 for the first location. In many cases the entire cost needs to be repeated for each new sensor location, but some additional sensor locations can be connected to the original data logger or a wireless receiver/data logger can be portable and thus used at many locations.

A third approach we will call "office computer or smartphone access" where the data logger can be located with the sensors in the field or at the edge of the field and this logger transmits the sensor reading to the internet via long-range radio, cell phone, or satellite. This level of convenience which allows producers to access their sensors almost anywhere carries a marked increase in equipment cost of $1,500 to $5,000 per monitoring site. In addition, there are communication and data hosting fees *that range from $125 to $400 per year.*

Telemetry System	Considerations	Annual Cost
Satellite	Complete coverage Highly dependable	Intermediate to High
Cell Modem	Reliable Requires cell signal	Intermediate
Radio	Requires some technical skill to install Less dependable	Low

Finally, there are "portable sensors and data loggers" in which the sensor is lowered into a PVC access tube at each monitoring location and readings are taken at multiple soil depths inside the access tube. The cost for PVC at each measurement site is small but the cost of the portable units can be considerable, $4,000 to $8,000. The equipment cost per measurement location rapidly decreases as the number of sites increases. Therefore, this approach has most often been used by very large producers or irrigation scheduling consultants. It should be recognized that a portable sensor/logger still requires travel to the field and entry into the crop. However, if a consultant is doing the traveling, you gain another set of eyes watching your crop and weekly delivery of a prepared irrigation scheduling report. If there is a dense enough concentration of irrigators desiring this service, it can be provided at a cost of $1,500 to $2,000 per year per 150-acre field.

Decision Factors

Deciding on an approach depends on several factors. First, consider your management style. How do you make farm operation decisions, who will be reading the sensors and turning the irrigation system on/off, where do you need the information to be and in what time frame? Second, consider your labor resources. Do you have someone available to read the sensors or will someone else need to be hired, what training will be required for someone to perform the desired irrigation scheduling tasks, and how much time will be required to travel to each site to obtain the measurements and process the information? Finally, the costs need to be weighted in regards to the expected returns. Initial equipment costs can be a barrier, but these need to be amortized over the life of the equipment and compared with the expected return in crop value. Also, these approaches can be provided as a service by a vendor, in which case the yearly cost is already determined.

Cost Factors

Commercial service providers tend to gravitate toward the higher cost systems while federal, state and local entities will often help with the lower cost alternatives. Next, the yearly labor and maintenance costs need to be included. With all this information, an informed decision can be made and that decision is not the same for everyone. For instance, a producer with many irrigated acres spread over several counties may opt for office/smart phone access or a consulting service due to the travel time and cost required to visit every site. While a producer with several irrigated fields located close to home may decide to visit "in field data collection" or "edge of field logger" locations once a week on his or her own time.

Locating Sensors

Sensors should be installed in each crop under an irrigation system because different crops will have differing planting dates and water use patterns. The next consideration would be to locate sensors in each major soil type. However, soil types are not often arranged in patterns that allow for an irrigation system to apply differing amounts of water to them. Also, field topography can be important and is often closely related to soil type. A field under a single irrigation system can

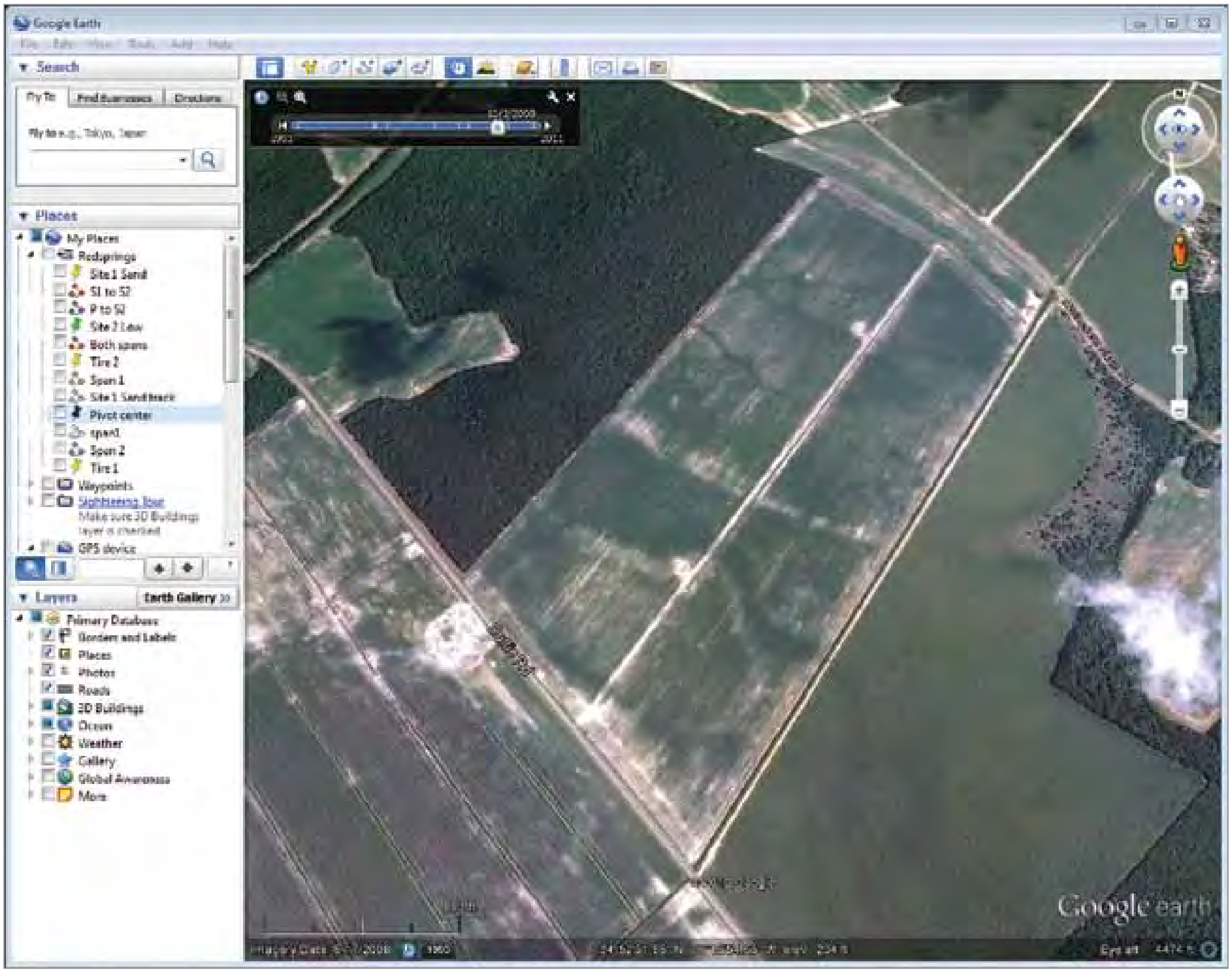

Figure 6.3 – Use of aerial images that are often freely available from programs like Google Earth, pictured above, can be useful to identify inclusions of different soil types that should be avoided for sensor placement.

contain hilltops, side slopes and bottom ground. The side slopes tend to be the driest locations due to runoff of rainfall and erosion of topsoil, while the bottoms are wetter due to sediment deposition and impeded drainage. Hilltops tend to have deep well-drained soils.

Irrigation Scheduling

One approach to dealing with varying soils and topography is to schedule irrigation based on the lowest water holding areas under an irrigation system so that all the soils will have adequate water with the better soil receiving more water than required to optimize yield. This is a good approach where water is not limited or expensive and when the crop does not respond negatively to excess water. Many cotton-growing regions are short of water, and some cotton research has shown loss of yield potential from excess watering. In these situations, the predominant soil type should be chosen for sensor installation instead of the lowest water holding soil.

Types of Irrigation Systems

The type of irrigation system will also affect sensor location. In center pivot irrigation, the pivot point and end gun/corner systems should be avoided because of poor sprinkler uniformity. It may be advisable to place sensors toward the outer pivot spans because this is a region where there is greater potential for runoff. Center pivots apply light, frequent applications of water that don't penetrate very deeply into the soil profile, and the same is often true of short intense summer rain storms. Therefore, one sensor should be located in the top 6 inches because of all the water activity in this zone. At least one more sensor should be placed in the center of the root zone. Surface irrigation applies more water at the head of the field than the bottom because of the longer soaking time. Sensors should be placed in both locations to improve the uniformity of surface irrigation. As for sensor depth and distance from the crop row, these are dependent on the soaking pattern which varies by soil type and length of time irrigation is turned on. One sensor should be placed in the middle of the root zone (depth-wise) and should be within the wetted pattern of the furrow. Other sensors can be placed shallow to detect rainfall and/or deep to detect percolation through the root zone. In drip irrigation, one sensor should be placed between the drip tapes and the edge of the wetting zone to ensure enough water for crop growth. Another sensor should be placed deep below the drip tape to prevent deep percolation from drip irrigation. The last sensor should be placed close to the crop row at the outside edge of the wetting zone to monitor horizontal soaking from drip irrigation and to monitor the water stored in the soil outside the area that can be recharged by drip irrigation.

Access to Sensors

Finally, after considering cropping, soils, topography and irrigation type, a location with good access should be chosen. Sensors should be placed close to a field road but far enough away from the road that this non-cropped area will not affect the readings, at least 20 yards from the road. This obviously helps finding the sensors and entering the field when using an "in-field data collection or portable logger/sensor method," yet easy access can be important for "edge of field data loggers" and wired/wireless systems when maintenance is required. Also, choosing a field road that is on a normal travel route will increase the frequency of obtaining readings.

Sensor Installation

As alluded to in the sensor type section, most sensors need to be installed with good soil contact with the exception of the neutron, where research has shown that small air gaps do not affect the probe's performance. Sensor configuration also affects the means of installation. Sensors that have a cylindrical shape are normally installed with small augers (1 to 2 inches) and create good soil contact by means of a soil slurry or a force-fit into a slightly undersized auger hole. A slurry is created by mixing soil from the auger hole with water to create a thick but flowable mixture. The soil can be first screened to remove stones and soil clods and a paint mixer on a battery-operated drill can also aid in creating a smooth slurry. Some sands will not create a good slurry, but this is not a problem because water can be poured down the bore hole, causing the sand to fill in around the sensor and then quickly drain away. In the force-fit method, some type of hammer and sensor protector may be required or a soil penetration probe on a soil sledge may be used to create a small tight-fitting hole at the bottom of a larger auger hole. Force-fitting preserves the appropriate soil layers next to the sensors but can compact the soil structure while slurries can mix soil layers and crack when dried. Sensors that do not have a cylindrical shape require excavation or larger augers. Once excavated to the desired depth, sensors either have soil hand-packed around them or are inserted into the side wall/bottom of the hole. In this scenario, sensor depth can be limited to about two feet, depending on the length of your arms. Installation help is often available from the service provider when high-cost sensor systems are used. Sometimes government agencies and education institutions will assist in installing lower cost sensor systems.

Compatibility with Field Operations

Some thought should also be given to how compatible a sensor system is with your field operations. You do not want to destroy sensor equipment and not receive the information that you paid for. In no-till cropping, sensors and/or wires can be buried and remain in the field year round. However, even in no-till, transmitters/loggers will probably need to be removed for some field operations, but less removal will be required if equipment is placed in rows that don't have wheel traffic. In conventional cropping or with above-ground sensor systems, sensors, wires and transmitters/loggers will need to be installed after the last tillage operation and removed before harvest. Non-cylindrical sensors will be harder to remove because there may be nothing except wires above ground to grab hold of. In the case of granular matrix sensors, a PVC pipe that extends to the ground surface can be glued to the sensors. Again, placing this equipment in rows that will not have sprayer wheels or N injection coulters on them will increase the time it is in the field and protect it from damage. It is true that wheels can run over wires that are laid on the ground surface. However, a muddy tire can stick to a wire, wrap it around the axle and break the wire. If wheels must pass over wire, this section of wire can be placed an inch below the ground surface. As for wireless systems, consideration must be given to the type and placement of antennas. Satellite and cell phones can transmit through a crop canopy and thus can be placed low enough for spray booms to pass over them. Conversely, short-range radio transmitters operate line of site and must be placed above the canopy with no obstructing terrain or trees. A radio can have a whip antenna that a spray boom can pass over or antenna posts are available that can be lowered and raised before and after spray operations.

Figure 6.4 – A Decagon EM-50g data logger installed in-line with cotton plants.

Connecting Wireless Systems

As a final installation note, you should understand the complexity involved in connecting wireless systems, because you need to know which field and what soil depth you are examining in order to make irrigation decisions. In this regard, some systems are very simple because each sensor/transmitter has a unique address and, when you install batteries to the transmitter and the receiver, that address with soil water data is translated directly to a website and you only need to correctly label the address. Other systems require more attention to detail. You may need to track multiple sensor wires, which connectors they are attached to in the transmitter, uniquely address the connector locations by setting switches or jumpers on the transmitter, and finally be able to identify the address on the software or website. Due to wire breaks and the need to remove transmitters/loggers it is important to identify sensor depth locations by placing different colored electrical tape on sensor wires as they emerge from the ground and at the connection end.

Interpreting Sensor Results

Knowing how to use sensor data to schedule irrigation is the primary objective. Soil tension is often easier to interpret than soil water content because soil type is less of a factor and tension is a measure of how hard it will be for a plant to remove water from any soil. For cotton, 50 to 60 centibars of tension is a good marker of when to start irrigating. Figure 6.5 shows the trends in soil moisture tension when a target of 50 centibars was used as the trigger. Note that due to delays in getting the irrigation system turned on and for water to actually reach that point in the field, the readings did exceed the trigger point and many state-specific recommendations account for such delays (that is, the cotton will not be stressed at 50 centibars, but that is when plans to irrigate should be started). In sandy soil, you want to stay below 50 centibars of tension, while this mark should be viewed differently in high water-holding capacity soils like deep silt loams. During square to first bloom, you want some soil drying to prevent excess vegetative growth, so tension should be allowed to approach 50 to 60 cb and irrigation should not be used to keep tension below this mark. If the rest of the growing season is extremely dry, the 50 to 60 cb tension will be needed to optimize yield. However, if the rest of the growing season is intermittently rainy, cotton yields have been optimized at much higher tension (100 to 120 cb) in good water-holding soils.

In contrast to tension measurements, a reading of 20% soil water content (2.4 inches of water per foot of soil) means different things in different soils. In a silt loam, 20% may mean it is time to irrigate while the sandy soil is at field capacity and there is no need to irrigate. This does not mean you should always choose a soil tension sensor over soil water content because you will have better information from soil water content if you understand the soil that the sensor is in and the sensor is adequately calibrated for that soil. For instance, you may know that 2 more inches of water can be depleted from the soil profile before irrigation is required; and, if the cotton water use rate is around 0.2 in/day, irrigation will be required in 10 days (2.0 divided by 0.2 equals 10). Also if 1 inch of water is depleted below the refill point, you know that one inch of irrigation is required.

Accuracy of Sensor Readings

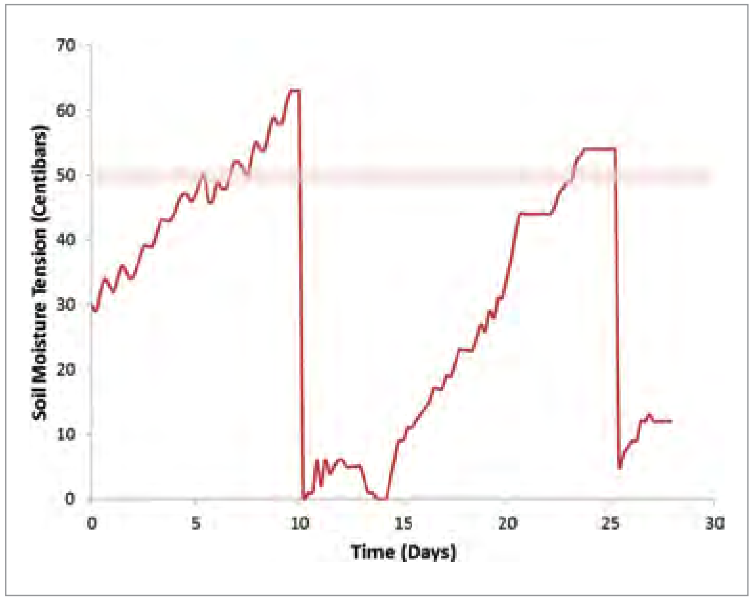

Figure 6.5 – Soil moisture tension versus time for Mississippi cotton in the early squaring growth stage (not a high water use time).

Absolute accuracy of water content from soil sensors is difficult to obtain. It requires a regression analysis between gravimetric samples and sensor readings taken directly from a field, and this procedure may need to be repeated over time to obtain an adequate range of soil moisture. This calibration then has to be linked to important soil conditions in the field such as field capacity, allowable depletion and wilting point. This degree of accuracy can be a selling point for a service provider but will usually not be attempted by a producer. Relative accuracy is a better goal for many producers. For instance, capacitance probes (measure of dielectric constant) will change calibration each time they are installed (even in the same field at nearly the same location) because the background dielectric constant changes with each installation. Therefore, field capacity is usually determined as the point where rapid drainage from application of slurry or a large wetting event stops. Then a manufacturer's calibration for the soil type should be applied to estimate wilting point and allowable depletion. Even though soil water content is not perfectly accurate, estimates of the amount of water that can be removed or added to the soil can still be made. Of course, sensors can be used as markers where the actual numbers have little meaning. Through experience, an upper and lower level can be established and the goal of irrigation is to stay between these two lines.

Finally, you should take a look at the sensor software before making a decision and ask the following questions. Is the software organized so you can easily find sensor field locations and depths? Can you easily add customized management lines, such as crop growth stages and soil field capacity, allowable depletion and/or trigger points? Is it easy to understand what irrigation decisions need to be made, especially if the water resource is shared between several fields? How easy will it be to relay these irrigation decisions to those actually performing the irrigation?

Retrospective Use of Sensors

Ken Fisher

Soil-water sensors offer a view of and information about the below-ground root-zone environment and soil-water resources. These critical components of the agricultural system cannot be readily observed, and must be measured and monitored to better understand and optimize their important and changing conditions.

Soil-water sensor-based scheduling is most often used to schedule irrigations under real-time, on-demand conditions. These conditions assume that water, labor and any other resources are available for irrigation at any time, as needed. Many irrigators, however, do not have such unlimited access to irrigation water, or may not have the needed labor or other resources available at all times. Irrigations may be scheduled on a calendar basis, for example, where water is delivered or available only at fixed time intervals; or, due to labor or logistical constraints, are performed at regular intervals. Soil-water monitoring still has a place, however, and can offer valuable information for a variety of purposes.

While soil-water sensor measurements are usually used for real-time scheduling, the information can also be used in a retrospective, post-harvest analysis of the growing season. Automated monitoring stations installed in the field operate throughout the season, collecting and storing soil-water data passively, while the producer carries out normal production and irrigation activities. At the end of the season, the soil-water data are examined, in conjunction with other production information, to gain insight into how above-ground activities affect below-ground water resources, and vice-versa.

Using Post-Season Soil-Water Data

While a producer's irrigation operations may often be constrained, and significant deviations cannot be made, there is often room to make slight changes. Examination of post-season soil-water information might suggest changes which could be made to irrigation management practices during the following season. For example, examination of soil-water data might indicate that the soil was not drying as quickly as had been assumed. A cotton producer irrigating at ten-day intervals might think about extending the time interval to every two weeks, allowing the crop to better use available soil-water resources, and perhaps reduce the number of irrigations required. Conversely, soil-water measurements might show that insufficient water was being applied, possibly stressing the crop and reducing yield. By applying more water during an irrigation, or irrigating more frequently, more water would be used but, if yield improved, might increase water-use efficiency and overall profit.

Benefits of retrospective soil-water monitoring also extend to other agricultural activities which could impact soil, soil-water, and cultural conditions. Tillage treatments, such as sub-soiling and conservation or minimum tillage, modify soil structure and could affect water infiltration, water-holding capacity, and root growth. Cultural practices such as higher seeding rates or plant densities, or row spacing, can have an effect on soil-water use, and vice versa; soil-water resources can affect crop growth under various conditions. By monitoring soil-water resources and crop-water use, the producer can examine the effects of various cultural practices and better understand their impacts on crop growth, water use, and yield.