



Understanding Soil Water Content and Thresholds for Irrigation Management

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Introduction

The ever-growing population in the world is expected to reach 9 billion by 2050, and there is an urgent need to produce more food, feed and fiber to meet these increasing demands. Irrigated agriculture plays a pivotal role in supplying this demand. In the U.S., only 16 percent of cultivated croplands are irrigated, yet, this small portion produces nearly 50 percent of crop revenues. Simultaneously, the irrigated croplands use a large amount of water to maintain a maximum yield of crops. According to a 2013 Farm and Ranch Irrigation Survey (FRIS) conducted by the National Agricultural Statistics Service of United States Department of Agriculture, Oklahoma had more than 400,000 acres of irrigated land. About half million acre-feet of water was applied in these fields in the survey year. The high water requirement of irrigated agriculture necessitates Oklahoma growers to continue improving irrigation management to maximize water and crop productivity.

Without advanced irrigation management, over- or under-irrigation may occur, leading to several negative environmental and economic impacts. In the case of over-irrigation, growers can lose money due to higher energy costs of pumping additional water without an economic increase in production. In addition, if the irrigation pumps are run more often, the wear and tear will decrease the overall lifespan. Over-irrigation also may increase topsoil erosion and can cause the contamination of downstream resources due to movements of water-soluble chemicals. But most importantly, over-irrigation depletes water resources, which could consequently increase a region's susceptibility to drought. On the other hand, under-irrigation results in reduced yield of crops, which in turn, causes loss of revenue for growers and food security issues for the region.

Several methods can be implemented to achieve efficient and improved irrigation management. Examples include tracking crop water use based on weather data, using crop indicators such as canopy temperature and monitoring soil water status. It is best to use multiple methods (whenever available) to more accurately determine when to irrigate and how much water to apply. This fact sheet will focus on one of the most promising methods in irrigation management: soil water monitoring. In Oklahoma, only 11 percent of farms used soil water monitoring sensors for irrigation scheduling

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(USDA, 2013). Hence, there is a great potential for improving irrigation management by promoting the use of advanced soil water monitoring sensors. To plan for irrigation scheduling, growers need to know how to interpret the numbers reported by these sensors, which requires understanding of the basic soil water concepts and thresholds.

This fact sheet provides agricultural producers with the basic concepts of soil water and the thresholds utilized for proper interpretation of sensor data for efficient irrigation scheduling. With efficient irrigation management practices, producers can manage and conserve water, maximize the yield of crops and improve economic benefits.

Reporting Soil Water Content

The soil water content (SWC) or soil moisture is the amount of water present in the soil. It influences plant growth, soil temperature, transport of chemicals and groundwater recharge. The two most widely used parameters for quantifying SWC or water availability for plants are i) volumetric water content; and ii) soil matric potential.

Volumetric water content (VWC)

The volumetric water content is the ratio of the volume of water to the unit volume of soil. Volumetric water content can be expressed as ratio, percentage or depth of water per depth of soil (assuming a unit surface area), such as inches of water per foot of soil. For example, if the volume of water is 20 percent of the unit volume of soil containing it, the VWC can be reported as 20 percent, 0.20 (ratio) or 2.4 inches per foot of soil (0.20×12 inches per foot).

Soil matric potential (SMP)

Soil matric potential, also called soil suction or soil water tension, represents the forces that bind water molecules to solid particles and to each other in soil pores, thus restricting the movement of water through the soil matrix. Plants must apply a force greater than SMP to be able to extract water from the soil. As the water is removed from the soil, the remaining water is held more strongly, making it harder for the plant to extract water from the soil through its roots. The SMP increases as the water is removed from the root zone of the plant. The SMP is expressed in two major units: kilopascal (kPa) and centibar (cb). One kPa is equal to one cb. Since SMP is a negative pressure (suction), the values

have a negative sign. However, some sensors and sources do not show the negative sign and report the magnitude of SMP without the proper sign.

Relationship between VWC and SMP

Some soil water sensors provide SWC data in VWC format, while others report SMP. In some cases, it may be needed to convert between VWC and SMP. The relationship between these two parameters is not linear, with most of the VWC changes occurring at SMP values of zero to 300 kPa. Beyond 300 kPa, the soil is too dry for the roots of most plants to extract water and VWC changes per unit change in SMP are significantly smaller. A soil water characteristics curve, also known as soil water retention curve, graphically displays the relationship between VWC and SMP for a particular soil type. This curve can be used for converting VWC values to SMP and vice versa. However, some error may be introduced during the conversion, especially if generalized curves are used rather than those developed for the specific soil where sensors are installed. Figure 1 shows the soil water characteristics curves developed by OSU for four soils from central and southwest Oklahoma.

Soil Water Thresholds

Soil water thresholds are specific values of SWC indicating water availability for plant consumption. These thresholds are used to determine when and how much irrigation is needed.

Saturation is the threshold at which all the pores (empty spaces between the solid soil particles) are filled with water. The VWC at this threshold varies from 30 percent in sandy soils to 60 percent in clay soils. The SMP at saturation is less dependent on soil texture and is close to zero, indicating that there is minimal restriction to water movement and plant roots can extract water from the soil with minimum energy.

Field capacity (FC) is the threshold at which water in larger pores has been drained away by the force of gravity. An irrigation application depth that causes SWC to go above FC is not desirable, because the additional water will percolate to deeper layers and will not be available to plant roots. At FC, the water content of the soil is considered to be ideal for crop growth. Thus, FC is usually considered as the upper threshold for irrigation management. Most agricultural soils reach field capacity one to three days after an irrigation or rainfall event. At this threshold, typical VWC varies from 20 percent in sandy soils to 40 percent in clay soils (2.4 to 4.8 inches per foot). Typical value of SMP at field capacity varies from 10 kPa to 33 kPa. When salinity is a concern, increasing SWC to levels above FC may be appropriate to leach salts below the root zone.

Permanent wilting point (PWP) is the threshold where it becomes impossible for plants to extract water at a rate fast enough to keep up with their water demand. At PWP, soil particles hold the water so strongly that it becomes difficult for plant roots to extract it. At this threshold, transpiration (water use by plants) and consequently other processes

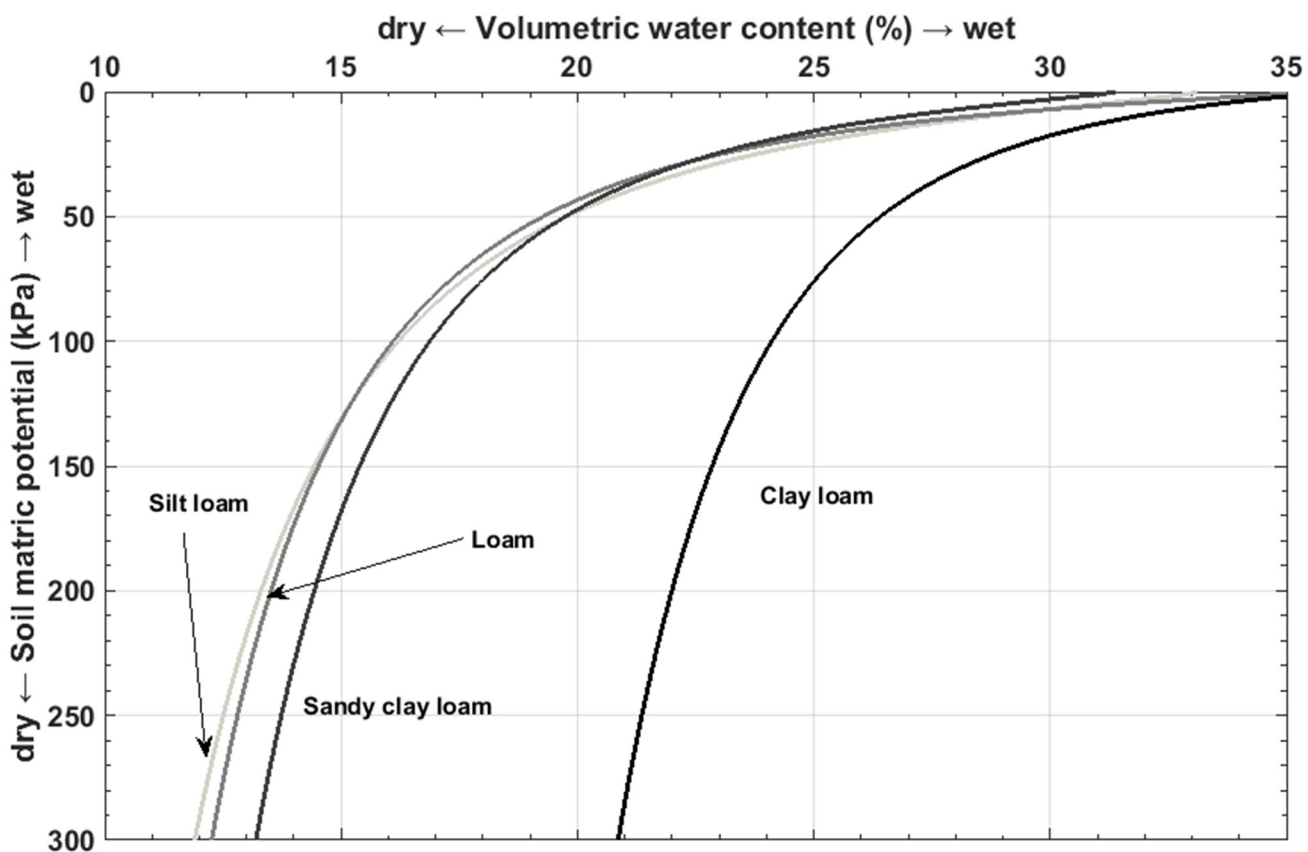


Figure 1. Soil water characteristics curves of four types of Oklahoma soils.

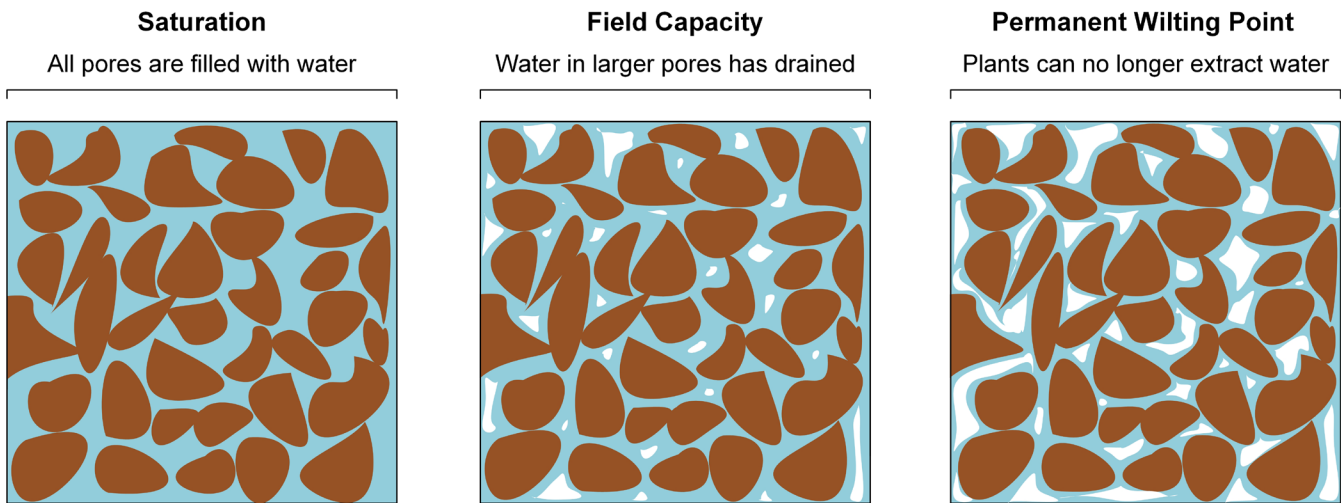


Figure 2. Soil water content at saturation, field capacity and permanent wilting point thresholds.

vital to plant survival come to a near stop. This causes a significant reduction in crop growth and yield of crops. If SWC remains below the PWP for an extended period, the plant will eventually die. Irrigation should be applied well before SWC starts approaching the PWP. The value of PWP varies with the type of plant, soil and climate, ranging from 7 percent in sandy soils to 24 percent in clay soils (0.8 to 2.9 inches per foot) when expressed in VWC. The soil matric potential at this threshold ranges from 500 to 3,000 kPa. The value of 1,500 kPa is usually considered as the average SMP at PWP for most agricultural soils.

Total available water (TAW) is the total amount of water available to plants, estimated as the difference between soil water content at FC and PWP. Above FC, water is available to plants only for a short period of time (one to three days), then lost to drainage. Below PWP, plants cannot apply enough force to extract the remaining water. Thus, SWC outside this range is considered not available to plants. Sandy soils cannot hold a large amount of water and have the lowest amount of TAW, whereas, medium texture soils, such as silt loam and silty clay loam have the largest TAW. Therefore, sandy soils need to be irrigated more often than loam soils. Although plants can extract water in the full TAW range, stress occurs before SWC approaches PWP. Water must be applied at a SWC level above PWP to avoid water stress in plants.

Table 1 shows typical values of FC, PWP and TAW for different types of soils sampled across the U.S., and Table 2 shows these values for agricultural soil samples taken from central and southwest Oklahoma. A comparison between values presented in these two tables shows differences in soil water thresholds for the same soil types. This is because numbers in Table 1 represent U.S. averages and include a large variation due to diversity in soil types. Except for the loam soil, all other soil samples collected from Oklahoma had a smaller TAW compared to national averages. This suggests more frequent irrigations and smaller volumes may be required since sampled soils had a smaller capacity for holding water available to plants.

Management allowable depletion (MAD) is the portion of the total available water (TAW) that can be depleted

Table 1. Typical soil water thresholds for different soil textures sampled across the U.S.

Soil texture	FC (%)	PWP (%)	TAW (%)
Sand	10	4	6
Loamy sand	16	7	9
Sandy loam	21	9	12
Loam	27	12	15
Silt loam	30	15	15
Sandy clay loam	36	16	20
Sandy clay	32	18	14
Clay loam	29	18	11
Silty clay loam	28	15	13
Silty clay	40	20	20
Clay	40	22	18

Source: Ratliff et al. (1983); Hanson et al. (2000)

Table 2. Soil water thresholds for different soil types sampled in central and southwest Oklahoma.

Soil texture	FC (%)	PWP (%)	TAW (%)
Loam	25	13	12
Silt loam	23	10	13
Sandy clay loam	31	20	11
Clay loam	32	22	10

before plants experience water stress and potential growth reduction (consequently yield reduction). Although plants can extract water across the entire range of TAW, the cost is not the same. If TAW is depleted below the MAD limit, plants begin to face water stress. The greater the depletion, the greater the water stress until PWP threshold is reached and a plant's vital processes cease.

Unlike previous thresholds that were mainly a function of soil type, the value of MAD is a function of stress tolerance,

growth stage and water use of the crop. This value is small for sensitive crops, such as some vegetables and is larger for crops that can tolerate higher water stress without affecting their yield. For example, a sensitive crop like lettuce has MAD of 0.30, meaning that it will start experiencing stress once 30 percent of the TAW is depleted. A less sensitive crop, such as cotton has MAD of 0.65, suggesting that stress (and possible yield reduction) will occur at 65 percent removal of TAW. Table 3 shows typical values of MAD and maximum root zone depth for different types of crops. The MAD values represent average crop water use condition of 0.20 inch per day. If the crop water use is higher than 0.20 inch per day, smaller MAD values should be used to avoid stress.

For sensors that report VWC, the MAD values provided in Table 3 are multiplied by TAW and then subtracted from FC to estimate irrigation trigger points. For sensors that report SMP, the irrigation can be triggered at values presented in Table 4 for different types of crops. Irrigation must be applied when SMP values, recorded by soil water sensors and averaged over the root depth reach or exceed limits in Table 4, depending on the climate. The smaller values of SMP are for a dry, warm climate and larger values are for humid, cool climate.

Managing Irrigations Based on Soil Water Content

An optimum irrigation management primarily aims to control the depth and frequency of applied irrigation water to meet crop water requirements, while preventing losses and conserving water resources. An effective approach to achieve this is to manage irrigations based on SWC information. The

Table 3. Management allowable depletions (MAD) and maximum root zone depths for selected crops.

Type of crop	MAD*	Maximum root depth (ft.)**
Cotton	0.65	3.3 – 5.6
Barley and oats	0.55	3.3 – 4.5
Maize	0.50 – 0.55	2.6 – 6.0
Sorghum	0.50 – 0.55	3.3 – 6.6
Rice	0.20	1.6 – 3.3
Beans	0.45	1.6 – 4.3
Soybeans	0.50	2.0 – 4.1
Alfalfa	0.50 – 0.60	3.3 – 9.9
Cool season – Turf grass	0.40	1.6 – 2.2
Warm season – Turf grass	0.50	1.6 – 2.2
Citrus	0.50	2.6 – 5.0
Walnut orchard	0.50	5.6 – 8.0
Carrots	0.35	1.5 – 3.3
Cantaloupes/watermelons	0.40 – 0.45	2.6 – 5.0
Lettuce	0.30	1.0 – 1.6
Onions	0.30	2.0 – 3.0
Potatoes	0.65	1.0 – 2.0
Sweet peppers	0.30	1.6 – 3.2
Cucumbers	0.50	2.0 – 4.0

* MAD values are for crop water use of 0.20 inch/day

** Root depths can vary with soil and other conditions. Effective root depth is usually shallower.

Source: Allen et al. (1998)

Table 4. Recommended SMP values at MAD for selected crops.

Type of Crop	SMP (kPa or cb)
Alfalfa	80 - 150
Cabbage	60 - 70
Cantaloupe	35 - 40
Carrot	55 - 65
Cauliflower	60 - 70
Celery	20 - 30
Citrus	50 - 70
Cotton	100-120
Sweet corn	50 - 80
Small grain	
Vegetative stage	40-50
Ripening	70-80
Lettuce	40 - 60
Onion	45 - 65
Potato	30 - 50
Tomato	60 - 150

Source: Hanson et al. (2000)

three major types of data required for managing irrigations based on this approach are:

1. **SWC:** The soil layer and actual value of SWC at any given time must be known before any decisions on improving irrigation management can be made. Different types of soil water sensors are available in the market, with the ability to provide SWC data in either VWC or SMP units. These sensors are significantly different in cost, accuracy and ease of installation and data retrieval. A factor to consider when collecting SWC information is root depth, which varies with crop type; growth stage; soil type and physical restrictions such as hard-pans (compacted layers) and shallow water tables (Table 3). Crops with shallower rooting depths have reduced access to stored soil water and require more frequent irrigations than crops with deep roots. When installing soil water sensors, it is important to have sensors at several depths across the effective root zone to obtain a complete picture of soil water dynamics. This is because water deficiency at one depth does not necessarily mean the crop is undergoing water stress, as the plant roots can extract water from other soil layers.
2. **FC and PWP:** These thresholds can be obtained from published tables (such as those in this publication) using soil texture information at the site of interest. Soil texture can be identified by sending soil samples to the Soil, Water and Forage Analytical Laboratory at OSU through the local Extension office. The value of FC can also be determined using the soil water reading a day or two after a large irrigation/rainfall event, if sensors were already installed and if the soil had reached saturation. Once FC and PWP are identified, TAW can be calculated (FC – PWP) and used in conjunction with other information to schedule irrigation events. However, the value of FC alone can be very useful in the preliminary assessment of irrigation efficiency through determining water losses from the bottom of the root zone. If the numbers reported

by soil water sensors after irrigation events indicated that SWC was above the FC limit, water is being lost to drainage (deep percolation). The amount of water in excess of FC will not remain at the measurement depth to be extracted by plant roots. Going above the FC limit can be allowed for shallower layers, because the water percolating to lower levels will be still within the root zone. At deeper layers (close to the bottom of root zone), any drainage becomes a loss to plant roots, resulting in waste of water, energy that was used to apply that water and many nutrients carried with water.

- MAD:** The value of this threshold can be obtained from published tables based on the type of crop and its sensitivity to water stress. It can also be modified with time, based on experience and observing the impact of different MAD values on crop yield. If the goal is to avoid even small stresses, then irrigation should be applied as soon as SWC reaches the MAD limit and should be stopped before SWC exceeds FC. In situations where an irrigation decision must be made in advance (for example to request water delivery or to allow the irrigation platform to reach the target area), the time it will take to reach MAD can be predicted based on SWC fluctuations in previous days and forecasted weather conditions. In some cases, it is acceptable (and desired) to allow soil water to drop below MAD. Examples include crops, such as grape that require some level of water stress to reach a specific chemical concentration and develop a richer taste. Another example is during late growing stages, when experiencing some water stress does not affect yield.

Managing irrigations based on the data mentioned above is somewhat different depending on how SWC is reported by soil water sensors (VWC or SMP). The following sections

provide examples of interpreting SWC data collected from two cotton fields in central and southwest Oklahoma, one based on VWC and the other based on SMP.

Managing irrigations based on VWC data

Figure 3 shows hourly fluctuations of VWC monitored by soil water sensors at two depths for a period of 45 days during summer 2016. Irrigation water was applied using a furrow system with cotton planted on the center of the beds. Arrows represent irrigation dates and dashed lines mark soil water thresholds.

The soil texture at this field was sandy clay loam, with FC of 30 percent and PWP of 18 percent. The total available water (TAW) can be calculated as: $TAW = (FC - PWP) = (30 \text{ percent} - 18 \text{ percent}) = 12 \text{ percent}$ or 1.4 inch per foot.

The MAD for cotton was taken from Table 3 as 0.65. This is equal to 8 percent when multiplied by the TAW (12 percent \times 0.65 = 8 percent). In other words, the largest amount of soil water content that can be depleted from the root zone of the crop below field capacity before stress occurs is 8 percent. Therefore, soil water content should not be allowed to drop below 22 percent (30 percent - 8 percent) in the effective root zone if the goal is to avoid any stress. The effective root zone depth is smaller than the maximum root zone and might change, depending on water stress the plant is facing and the crop growth stage. When the upper portion (near the surface) of the root zone is dry, the plants have the ability to extract water from deeper layers with larger water content.

According to Figure 3, four irrigations were applied during the studied period. The first irrigation event, around July 22, took place when the volumetric water content at both 8-inch and 20-inch depths was below MAD, suggesting that cotton was under some stress when irrigation was applied. The irrigation event brought the VWC above FC, meaning that some water percolated below both layers. However, cotton roots go

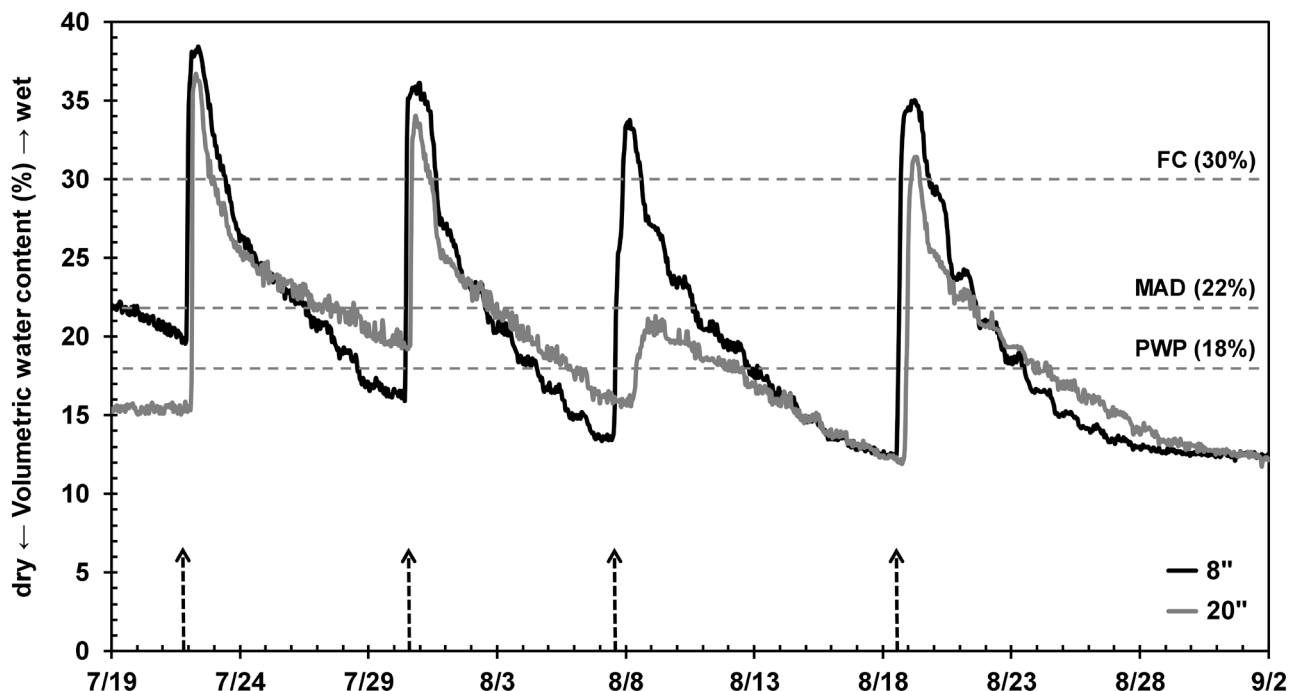


Figure 3. Hourly VWC fluctuations at 8 and 20 inches below soil surface over a 45-day period.

deeper than 20 inches and the drained water may have not necessarily become unavailable to the crop if it remained at lower layers within the root zone. Soon after this irrigation SWC started declining, with a rapid phase during the first two days and then at a slower rate after July 24. On July 26, the 8-inch layer became dryer than then 20-inch layer because it is shallower and prone to larger evaporation and root extraction.

The second irrigation event on July 30 was similar to the first in terms of increase in SWC and the rate of water depletion. The third event on August 7 was somewhat similar, but the 20-inch depth did not respond in the same way. This could be likely due to applying a smaller amount of irrigation water – not enough to saturate the 20-inch soil depth. VWC at this depth had a smaller increase that did not even reach the MAD threshold. Hence, no water was lost to deep percolation below this layer. The fourth irrigation event was similar to the first two events in terms of changes in soil water content.

In general, the SWC data collected at this site indicated irrigation management was fairly efficient, with some deep percolation below 20 inches that may have been retained at lower levels of the root zone. Some water stress may have occurred in between irrigation events as SWC dropped below MAD and even PWP for short periods. However, this does not necessarily suggest a decline in crop yield, since stress periods did not last too long. In addition, the entire root zone should be considered, since plants can take up water from deeper soil, which has a greater water content and compensate for water deficiency at shallower layers. Adding sensors at deeper layers (for example 30 or 40 inches) can help better evaluate the effectiveness of irrigation applications. The data suggest that increasing the amount of water applied in each irrigation would not help with avoiding stress since with current amounts SWC exceeded FC and thus any additional water could be

lost to drainage. In this case, reducing irrigation intervals (if possible) would be more effective in minimizing stress.

Managing Irrigations based on SMP data

Figure 4 demonstrates hourly fluctuations of SMP monitored by soil water sensors at two depths during a period of 45 days in the summer of 2015. Irrigation water was applied to cotton using a sprinkler (center-pivot) system. Arrows represent irrigation/precipitation dates and dashed lines mark soil water thresholds.

The soil type at this field was silt loam, with the FC of 25 percent and PWP of 11 percent. The TAW was 14 percent (24 percent – 11 percent). The MAD for cotton is 0.65. So, the maximum amount of water that can be depleted below FC was 9 percent (14 percent × 0.65). The VWC level for triggering irrigation events is 16 percent (25 percent – 9 percent). Since the soil water sensor used in this case provided SWC estimates in SMP, calculated thresholds were converted from VWC to SMP, using the soil water characteristics curve (Figure 1). The SMP value at FC was 23 kPa and at the MAD was 105 kPa. The estimated MAD is consistent with the range of 100-120 provided in Table 4 as cotton MAD.

Based on the estimated thresholds, irrigations should have been managed to keep the SMP in between 23 and 105 kPa to avoid water loss and stress. According to Figure 4, the SMP at 10 inches remained above FC for most of the study period (after Aug. 4), indicating that water was lost to drainage below 10 inches. However, the drained water was not necessarily lost to the crop since the 24-inch layer was below FC at most times, except a few days at the beginning of the study period. As stated before, irrigation events could have been triggered at SMP of about 105 kPa. However, the SMP at the 10- and 24-inch layers never exceeded 68 and 87 kPa, respectively. The average SMP for these two layers

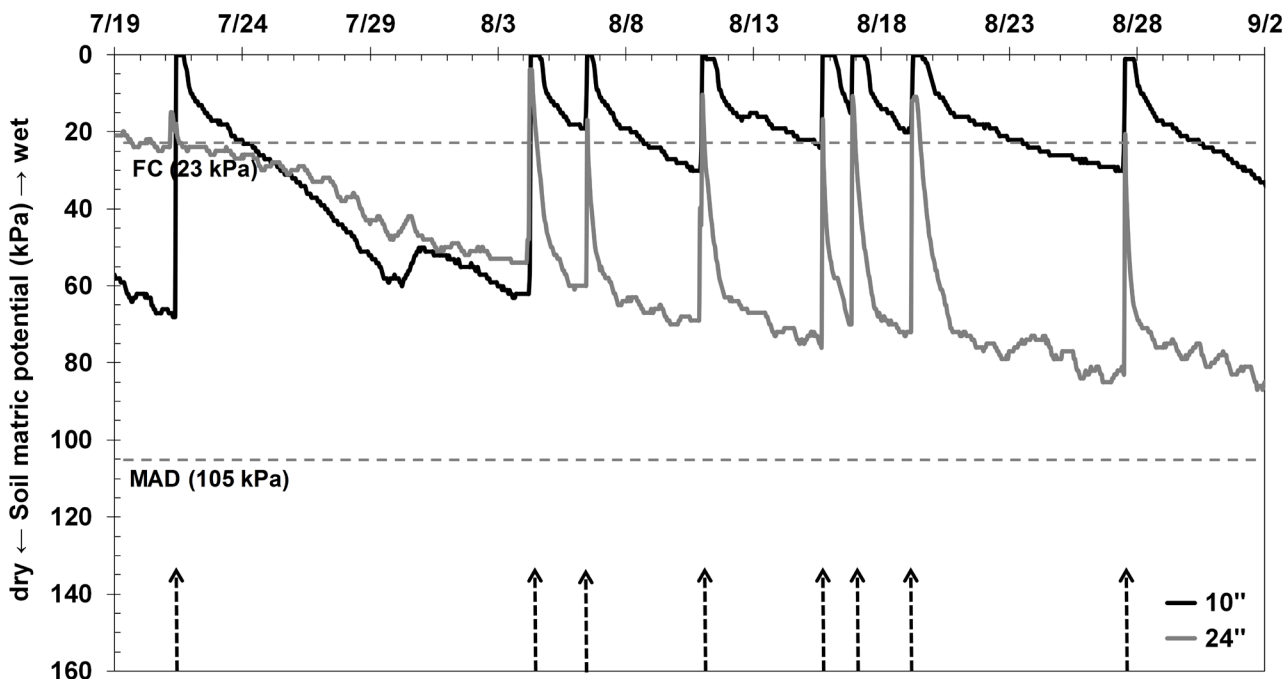


Figure 4. Hourly SMP fluctuations at 10 and 24 inches below the soil surface over a 45-day period.

ranged from zero to 60 kPa. Hence, irrigation intervals could have been longer without affecting crop yield. A lower irrigation frequency (longer intervals) would have resulted in smaller energy use for pumping water, as well as smaller evaporation losses from wet soil and crop surfaces.

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