Assessing Irrigation Scheduling using Mississippi Irrigation Scheduling Tool (Mist) and Soil Moisture Sensors

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Assessing irrigation scheduling using Mississippi Irrigation Scheduling Tool (MIST) and soil moisture sensors

By

Hazel Buka

A Thesis
Submitted to the Faculty of Mississippi State University in Partial Fulfillment of the Requirements for the Degree of Master of Science in Agriculture in the Department of Agricultural and Biological Engineering

Mississippi State, Mississippi

August 2018
Assessing irrigation scheduling using Mississippi Irrigation Scheduling Tool (MIST) and soil moisture sensors

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By using the Soil Conservation Service (SCS) “polynomial” method for corn in the Mississippi Irrigation Scheduling Tool (MIST), the total number of irrigations required during the growing season can be reduced depending on the variety, growing degree days required to reach maturity, and the length of the growing season. Results showed that even though the SCS method called for irrigations earlier in the season, the method did not trigger irrigation events after the crop reached physiological maturity. In addition, although changing the timing of model initiation (planting vs emergence) was not important on the total crop water use, it may have other benefits. Lastly, Watermark 200SS sensors generally did not trigger similar irrigation events, especially around the mid-season, but shallower sensors somewhat matched and showed similar trends with the MIST modeled results and irrigation records. Therefore, using MIST with sensors may be beneficial when making precise irrigation scheduling decisions.
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CHAPTER I
INTRODUCTION

Importance of Irrigation Scheduling

Irrigation scheduling is defined as use of water management strategies and a farmer’s decision process relative to how much, how often and when water is applied at each irrigation event in order to maintain healthy plant growth during the growing season while minimizing yield loss due to water shortages or drought stress (Brouwer et al., 1989; Evans et al., 1996; Fortes et al., 2005; Howell, 1996; Wright, 2002). When scheduling irrigation, knowledge of the soil, soil-water status, crop type, status of crop stress, and potential yield reduction if stressed conditions persist is required (Evans et al., 1996). Additional knowledge of crop water requirements, yield responses to water, the irrigation method constraints, on-farm delivery systems, the limitations of the water supply system, and the financial and economic implications of the irrigation practice are also required (Fortes et al., 2005).

Determining the exact amount and timing to apply water based on the crop’s water needs, soil water storage capacity, and climatic conditions are the primary purpose of irrigation scheduling (Broner, 2005; Kebede et al., 2014). This allows for optimum water supply for crop productivity as soil water content within the root zone is maintained within the range where crop yield and quality are not hampered due to insufficient or excess water (Geremew et al., 2008; Jones, 2004).
Proper irrigation timing helps meet crop water demands, prevents yield losses that may be caused by water stress, maximizes irrigation water use efficiency, and helps maintain groundwater quality by minimizing potential leaching of nitrates and certain pesticides (Fortes et al., 2005; Mun et al., 2015; Wright, 2002). According to Broner (2005) irrigation scheduling allows for rotation of irrigation among various fields, accurate application of water required by the crop thereby reducing energy and labor costs through fewer irrigations. Other advantages include lowering of fertilizer costs by reducing leaching of expensive nutrients below the rooting zone, maximizing net returns by increasing crop yield and quality, reduced soil aeration, and minimized water logging problems (Broner, 2005). There are several different irrigation scheduling methods available, each with different advantages and disadvantages (Broner, 2005; Jones, 2004).

**Irrigation Scheduling Methods**

An irrigation scheduling method depends on the irrigator’s objectives and the available irrigation systems (Jones, 2004). According to Broner (2005), the irrigator’s objective can either be maximization of yield or net returns, and both objectives can be achieved through irrigation scheduling. Measuring and monitoring soil water, crop development, crop water stress, and estimating future crop water needs using a checkbook method is an effective way to achieve irrigation scheduling (Evans et al., 1996; Wright 2002). Several irrigation scheduling methods such as the simple soil-feel, visual crop assessment and scientific methods such as the soil water balance exist and have been used in the past (Fisher et al., 2009), but modern methods utilize plant-, weather- and/or soil-based approaches (Lamm and Rogers, 2015).
One of the common irrigation scheduling methods currently used is the soil-feel and visual observation of the crop’s condition. Although this method is cheaper and a proven scientific method, the downside is that the quality of the measurement is dependent on the experience of the individual performing the task (Martin, 2001; Maughan et al., 2015). Other disadvantages are 1) increased overall chance of yield reduction and 2) decreased crop quality if irrigation is delayed. For most crops, yield losses could be inevitable by the time symptoms are evident (Brouwer et al., 1989).

Soil monitoring is another common method of irrigation scheduling. In agriculture, this approach is common because it optimizes irrigation by keeping the soil water content within a targeted range (Munoz-Carpena, 2004). Soil water measurements such as water content or water potential and soil water balance calculations are commonly used to schedule irrigation (Broner, 2005; Jones, 2004). Jones (2004) indicates that the accuracy of the water balance approach is dependent on evaporation and rainfall estimates, but the approach has been found to be sufficiently robust under a wide range of conditions. The water balance approach is also referred to as a checkbook method, allowing for daily monitoring of a field’s soil water balance in terms of soil water deficit. The checkbook method subtracts water losses such as crop water use and adds water inputs such as usable rainfall and irrigation applications (Lundstrom and Stegman, 1995; Wright, 2002).

The use of soil monitoring devices such as soil moisture sensors is one method that has been encouraged in recent years. Bryant et al. (2017) notes that soil moisture sensors can be used to predict plant water needs in the rooting zone without personal visual observation of the crop. By using sensors, efficient water use can be achieved as
crop water needs are met without applying excess or too little water (Maughan et al., 2015). Soil moisture sensors can show how much water is available in the rooting zone for the crops, which can help farmers know when and how much to irrigate (Kebede et al., 2014). In addition, through use of soil monitoring devices such as soil moisture sensors, the crop’s need for irrigation water can also be predicted via computer-based irrigation scheduling models.

**Computerized Irrigation Schedulers**

Irrigation scheduling by means of computerized irrigation schedulers has been introduced and in use since the 1970’s (Martin, 2001). Fisher et al. (2009) distinguish computer-based models as a method that uses a combination of weather data with the water-balance approach to monitor soil water depletion, while sensor-based systems are those that monitor conditions in the field and give an indication of the soil-water status directly.

Henggeler et al. (2010) report 2008 national adoption rates of irrigation scheduling methods used at US farms obtained through sources of irrigation information survey conducted by the US Department of Agriculture. In 2008, 10.8% of the farms in the U.S used soil moisture or plant monitoring devices, while 21.2% and 9.1% farms scheduled irrigation using computer program, and information from the media reports or press, respectively. Specific to Mississippi, 8.5% farms schedule irrigation by means of soil moisture or plant monitoring devices, with 3.1% farms utilizing computerized irrigation scheduling programs, and 17.9% farms schedule irrigation based on information obtained from media reports or press (Henggeler et al., 2010). Several irrigation scheduling methods are used in Mississippi. Kebede et al. (2014) reports that
47.2% of crop producers in Mississippi use plant-based method, 23.9% practice the soil feel method and 9.6% of the crop producers rely on daily crop ET to schedule irrigations.

Other irrigation scheduling methods implemented in Mississippi are personal calendar schedule (7.9%), trigger irrigation when neighbors irrigate (2.2%), irrigate based on scheduled irrigations by water delivery organization (0.1%), and other methods (3.0%).

Several irrigation schedulers have and continue to be used in the US. Henggeler (2002) and Henggeler et al. (2010) provide a detailed list of some of the software programs available for irrigation scheduling, which include the following: Michiana Irrigation scheduler, KanSched, North Dakota State University’s Computerized Checkbook Method, Arizona Scheduling (AZSched), Cropflex 2000 program, the Woodruff Chart maker, Wateright, and Arkansas Scheduler.

**Existing Irrigation Schedulers in the US**

The Michiana Irrigation Scheduler program (Irris Scheduler) is a computerized irrigation scheduling checkbook model that utilizes weather datasets and can be used for a variety of crops such as corn, soybean, established alfalfa, dry bean, potato and other crops throughout the Michigan and Indiana area (Henggeler, 2002; Kelley, 2016; Purdue Research Foundation, 2017). This irrigation scheduler was developed by Purdue University’s Department of Agronomy and Michigan State University's Department of Crop and Soil Sciences (Henggeler et al., 2010; Purdue Research Foundation, 2017). It is a simple and easy-to-use tool that assists crop producers with irrigation scheduling decisions while also estimating soil nitrogen application (Kelley, 2016; Purdue Research Foundation, 2017). According to the Irris Scheduler website, weather data is retrieved from Weather Underground from the ASOS Airport or Personal Weather Station (PWS),
US National Weather Service Cooperative Observer Program, Iowa Ag Climate Network and Michigan Enviro-weather Network. This scheduler utilizes the 5-day high-low temperature forecast retrieved from the US National Weather Service, and provides an output of weather, soil moisture and evapotranspiration (ET) data (Purdue Research Foundation, 2016; Purdue Research Foundation, 2017).

KanSched program developed by Kansas State University started as a spreadsheet scheduling program known as Kiscorn (Henggeler, 2002). Kiscorn is a simple and easy-to-use irrigation scheduling program for corn on deep silt loam soils in western Kansas (Irrigation at K-State Research and Extension, 2015). Use of this template to schedule irrigation for sandy soils is not encouraged as this may produce inaccurate assumptions. This method tracks the crop water budget and allows three fields to be scheduled with only one template, while also allowing additional fields to be scheduled using additional templates with a different filename. According to Clark et al. (2002), the KanSched computer software program was developed as part of the Mobile Irrigation Lab (MIL) to determine the root zone water level for irrigation scheduling. This program was designed to monitor the soil profile water balance and schedule irrigation events based on ET data. The program requires field inputs such as: soil characteristics, emergence, maximum rooting depths, crop characteristics and crop coefficient and daily inputs such as reference ET, rainfall/irrigation amount and soil water value.

NDSU’s Computerized Irrigation Scheduling by the Checkbook method was developed by North Dakota State University and University of Minnesota to help farmers in North Dakota and Minnesota understand irrigation scheduling and crop water requirements (Henggeler, 2002; Steele et al., 2010). This stand-alone computer program
was developed based on the checkbook crop water use tables that were developed for North Dakota (Steele et al., 2010). The method’s effectiveness largely depends on accuracy, regularity of the in-field observations and measurements collected by the irrigation operator or manager (Wright, 2002). Stegman and Coe (1984) omitted the crop coefficient curves for sugar beet and potatoes from the original list of spring wheat, corn, soybean, and alfalfa, and added sunflower, pinto bean and barley (Steele et al., 2010).

Arizona Irrigation Scheduling (AZSched) is a standalone computerized irrigation scheduling program developed by the University of Arizona to help increase and calculate water use efficiency and crop evapotranspirations (ET$_c$) of twenty eight (28) irrigation crops (Fox et al., 1993; Henggeler, 2002; Henggeler et al., 2010; Martin et al., 2003; The University of Arizona Cooperative Extension, 2003). Like many irrigation schedulers, the assistive program uses a water-balance method to estimate daily crop water use, and Arizona growing degree days to determine crop growth rather than days after planting or emergence (Henggeler et al., 2010). Henggeler (2002) indicated that AZSched clearly displays moisture status of the field before they reach dangerous depletion levels. However, caution and careful transportation of these datasets should be observed when using this program in areas with normal cloud cover different than Arizona conditions.

Cropflex 2000 program was developed by Colorado State University to help manage fertility and irrigation scheduling, and the program allows generic crop data to be used (Henggeler, 2002). According to the US Department of Agriculture Cropflex website, the Cropflex computer software program consists of four components: Irrigation Scheduler, Fertility Scheduler, Yield Prediction Model and Leaching Model. The
Irrigation scheduler recommends timing and amount of irrigation application using a soil/water mass balance to calculate the soil moisture within the crop rooting zone (US Department of Agriculture: Cropflex, n.d.). Henggeler (2002) states that weather data is imported in the CSU, KSU or USDA format, which helps save time as manual input is a slow process and time-consuming. Daily crop water use is estimated using the modified Penman equation, and crop coefficients are generated using polynomial functions (Al-Kaisi and Yin, 2003).

Another existing scheduler are the Woodruff Irrigation charts, a web-based program that was updated from the Woodruff charts that were developed in the 1970s by the University of Missouri. According to the University of Missouri Extension website, Henggeler developed a spreadsheet version of the Woodruff Irrigation chart-maker that allowed charts to be printed in 1998 (University of Missouri Extension, n.d.). According to Henggeler (2002), the tool uses historical weather data, emergence data and weather files to develop an accumulative water use curve that serves as a graphical tool for timing irrigations. In this program, a computer is only required to develop the graph or curve, but once they are printed a computer is no longer necessary. The only input required to predict maturity is the corn Relative Maturity (RM) or the Maturity Group of soybean, and users do not have to input root depth, water holding capacity or Management Allowed Depletion (MAD) in order for the irrigation depth per application to be developed (Henggeler et al., 2010).

Wateright is a web application developed by the Center of Irrigation Technology (CIT) in Fresno, CA (Henggeler et al., 2010). According to the Center for Irrigation Technology website (2017), this program was developed and designed as a multi-function
educational resource for irrigation water management that can be used to schedule site-specific and seasonal agricultural and commercial turf irrigations. Wateright gets real-time weather data on an hourly basis from the California Irrigation Management Information System (CIMIS) weather network and the Washington, Oregon, Idaho and Minnesota weather stations (Henggeler, 2002, Wateright, 2005). The Wateright program has the ability to specify the cover crop, its crop coefficient, and start and end dates and provide estimates based on long term, average weather patterns and average crop coefficient curves (Henggeler, 2002; Henggeler et al., 2010; Wateright, 2005).

Finally, The Arkansas Irrigation scheduler developed by the University of Arkansas has been around since the early 1980s to aid in irrigation management (Tacker, 2006; Henggeler, 2002). It was developed for use in the humid mid-South and has been used for over 20 years by producers in Arkansas and other surrounding states including Mississippi (Henggeler, 2002; Kebede et al., 2014; Vories and Evett, 2014). According to Sui et al. (2015), the Arkansas Irrigation Scheduler is a computer-based water-balance model which estimates daily soil-water deficit as the difference between water incoming (precipitation and irrigation) and outgoing (crop ET) for irrigators in the Lower Mississippi Delta region of the US. Henggeler (2002) adds that the scheduler suggests irrigation deficit based on crop, soil and to some degree irrigation method. According to Tacker (2006), the Arkansas Irrigation scheduler utilizes PCs, are field and crop based, and support pivot systems, furrow, flood and border irrigation.

However, the Arkansas Irrigation scheduler was only used by a very small number of producers in Mississippi and other surrounding humid states. To address that challenge, the Mississippi Irrigation Scheduling Tool (MIST) was then developed to
assist crop producers in humid areas like Mississippi schedule irrigation applications based on actual crop water needs. Although, both the Arkansas Irrigation Scheduler and MIST use the water balance approach and was developed for use in humid areas, the schedulers are different. The major difference being, the Arkansas Irrigation Scheduler require daily input of air temperature and effective precipitation, while MIST automatically extracts all its weather data from online weather data sources (Kebede et al., 2014; Sassenrath and Schmidt, 2012; Sassenrath et al., 2013).

**MIST Development and Use**

States in the Southeastern (SE) region of the United States are known primarily for their climate diversity and extreme weather events (Sherman-Morris et al., 2012). Mississippi receives abundant rainfall throughout the year; however, the major challenge is that the rainfall is not evenly distributed temporally throughout the year to benefit crops, especially during the growing season (Kebede et al., 2014; Sassenrath et al., 2013; Sherman-Morris et al., 2012). Kebede et al. (2014) argues that unlike in arid areas, irrigation scheduling and development of specific crop coefficients is complicated in areas with humid conditions because fluctuating temperature and rainfall results in variable daily evaporative demand. MIST, is a computer-based irrigation scheduling tool that was designed to address these issues and meet the needs of producers in the Mississippi River Valley Alluvial Floodplain (Mun et al., 2015; Sassenrath et al., 2013). Furthermore, no program installation or maintainance is required as the program is accessed through the internet and is currently being updated to an online application for use on several platforms such as smartphones, tablet, desktops, and laptops computers (Kebede et al., 2014; Sassenrath and Schmidt, 2012).
MIST rely heavily on the current weather inputs, soil hydrology and texture information automatically collected from national and regional databases and calculates crop water use based on local weather conditions, soil types and irrigation system capacity, planting date, and crop (Linhoss et al., 2017; Sassenrath and Schmidt, 2012). Precipitation, maximum and minimum temperature, maximum and minimum relative humidity, average wind speed, and solar radiation are the weather inputs required when scheduling irrigation using the model. The model calculates crop water use by multiplying ET calculated using Penman Monteith equation with a crop coefficient (Linhoss et al., 2017) and determines daily soil water balance using a checkbook method to trigger irrigation events (Mun, et al., 2015). Other required parameters include curve number and initial abstraction. A water balance approach is used to trigger irrigation events and determine cumulative soil water balance by summing the previous day’s soil water, subtracting water lost through evaporation, and then adding effective rainfall or irrigation (Sassenrath et al., 2013). Apart from MIST being easy, user friendly and requiring less extensive data collection or manual input, the model has other advantages. One major advantage being the capacity to accurately indicate field-soil moisture, as the Natural Resources Conservation Services (NRCS) runoff equations are utilized to handle field runoff differences.

**Justification and Objectives**

Findings from the uncertainty analysis conducted by Mun et al. (2015) found that the daily water balance predicted by MIST were within an acceptable error of ± 0.5 inch. The same study also concluded that rainfall and irrigation had the most significant impact on the overall uncertainty of the model (Mun et al., 2015). In addition, a sensitivity and
uncertainty analysis conducted by Linhoss et al. (2017) showed that precipitation, crop coefficient, wind, maximum temperature and solar radiation are the most important parameters and inputs of MIST. The same study also found that maximum and minimum humidity were important only when calculating ET$_{os}$, while crop coefficient and precipitation were reported to be the most important parameters when determining what day to initiate an irrigation (Linhoss et al., 2017). For these reasons, the main goal of this study was to improve the corn crop coefficient method used in MIST.

Herein, we examine the corn crop coefficient method being used in the Mississippi Irrigation Scheduling Tool (MIST), a tool developed as one of the ways to manage water resources and improve irrigation scheduling in areas with humid conditions like Mississippi (Sassenrath et al., 2013). Two crop coefficient methods were compared to see which one is more appropriate for the humid conditions in the Mississippi Delta region. MIST model predictions for crop water use and number of irrigations were compared using the Food and Agriculture Organization (FAO) crop coefficient method and the adjusted Soil Conservation Service (SCS) “polynomial” crop coefficient method. Also, the MIST modeled results were compared to the soil tension measurements using soil moisture sensors. The objectives of this study are to 1) improve the crop coefficients used in MIST by examining the SCS “polynomial” crop coefficient” method using a growing season of 120 and 150 days, 2) adjust the length of the growing season using Growing Degree Days (GDDs) to estimate corn emergence and physiological maturity dates, 3) examine the importance of initiating the model at planting vs emergence, and 4) compare MIST modeled results to measured soil moisture data from Watermark soil moisture sensors for the 2014 and 2016 growing seasons.
CHAPTER II
MATERIALS AND METHODS

Site Description
This study was conducted in Jonestown, Coahoma County in the Mississippi (MS) Delta Region. We monitored two fields planted in corn, one irrigated via furrow irrigation (Jonestown Furrow; 34° 20′ 17″ N, 90° 28′ 33″ W) and one irrigated under center pivot irrigation (Jonestown Pivot; 34° 20′ 32″ N, 90° 28′ 31″ W). The furrow and pivot fields cover approximately 22 and 41 hectares, respectively (Figure 1). The fields have an elevation of 52 m. Precipitation for the study area(s) was retrieved from Next Generation Radar (NexRad, 34° 19′ 34″ N, 90° 27′ 29″ W) about 2.12 km from the study site, and all other weather data was downloaded from nearby SCAN Networks. In MIST, an irrigation event for the furrow field was set to 76.2 mm, and an irrigation application for the pivot field was set to 25.4 mm.

Both fields are classified into MS planting zone 3, and the recommended planting dates range from March 21 to July 15 (Mississippi State University Extension, 2018). During the 2014 growing season, Pioneer 1685YHR was planted on May 5th in the furrow field, and Rev 28R10 was planted on March 22nd in the pivot field. During the 2016 growing season, Arigold 6574 was planted on May 25th in the furrow field, and Rev 28R10 was planted on April 7th in the pivot field.
Total annual precipitation received at the study site in 2014 and 2016 was 1,543 mm and 1,413 mm, respectively (Lin, 2016). The mean temperature for the study area was 15.5°C in 2014 and 17.9°C in 2016. Furrow-irrigated and pivot-irrigated fields are both dominated by Bosket Very Fine Sandy Loam and comprised of several soil types. The furrow field is comprised of Bosket very fine sandy loam (30%), Forestdale silty clay loam (24.9%), Forestdale silt loam (13.1%), Dowling clay (11.3%), Dowling soils.

1 Data retrieved from PRISM Climate Group (http://www.prism.oregonstate.edu/explorer/)
(7.7%), Dubbs very fine sandy loam (7.9%), Dundee silt loam (2.9%), Dundee very fine sandy loam (2.0%) and Dundee silty clay loam (0.2%). The pivot-irrigated field is comprised of Bosket very fine sandy loam (31.0%), Dubbs very fine sandy loam (23.5%), Dowling soils (17.8%), Dundee very fine sandy loam (17.7%), Dundee silt loam (7.8%), Dowling clay (2.1%) and Forestdale silty clay (0.1%) (Soil Survey Staff, 2017).

**Crop Coefficient Methods**

**FAO Method**

Kebede et al. (2014) defines crop coefficient as an adjustment factor that depends on crop type and growth stage. Presently in MIST, FAO crop coefficient guidelines are being used. The FAO crop coefficient presents as a series of straight lines joined together describing the phenological periods: initial, crop development, mid-season and late season crop growth stages (Allen et al., 1998). According to Allen et al. (1998), this method requires knowledge of the initial, mid-season and end-season periods, and the crop coefficient value for corn is 0.35 during the initial period and 1.2 for the mid-season period. The guidelines are described in detail by Allen et al. (1998) and Pereira et al., (2014). However, users are encouraged to obtain local information and adjust crop coefficients and length of the development stages to match the appropriate local information obtained. In general, the FAO method suggests 150 days as the length of the growing season with 30 days for the initial stage, 40 days for the development stage, 50 days for the mid-season stage, and 30 days for the late stage for the region of California (Allen et al., 1998). MIST uses these general guidelines. However, the crop coefficients and length of the development stages play such an important role when scheduling irrigation applications. Therefore, they should be adjusted so that they describe true crop
transpiration and estimate crop water requirements by crops in the MS Delta as accurately as possible.

**SCS Method**

The Soil Conservation Service (SCS) method is a statistical regression that estimates crop irrigation requirements based on monthly crop evapotranspiration (ET), monthly rainfall and soil water holding characteristics (SCS, 1970; Smajstrla and Zazueta, 2002). This method suggests four months (120 days) as the length of the growing season for corn and recommends plotting the crop coefficient values as a function of a percentage of the growing season (SCS, 1970). Detailed equations and crop coefficients for various crops can be found in Technical Release No. 21 prepared by the SCS (1970). Since the original SCS method is not digitized, for use in MIST, the SCS method was adjusted to a polynomial curve method.

**SCS Polynomial Method**

The SCS polynomial method was adapted from a study conducted by the former SCS (1970), and the following steps were used to develop corn crop coefficients. This method was then compared to the FAO method used in MIST.

**Step 1: Identify the curvilinear crop coefficients**

The original data curve was determined by entering the crop coefficient points and finding the curve fit using a polynomial equation calculated using the Solver function in Excel. In this study, *Equation 1* was used to identify the curvilinear crop coefficient for corn that will be used to calculate crop water requirements.

\[ Y = A + Bx + Cx^2 + Dx^3 \]  

(1)
where \( Y \) is the value of the crop coefficient at that point, \( x \) is the percent of the growing season and \( A, B, C, \) and \( D \) are variables to achieve the best fit. The Excel’s Solver function was used to determine the values of \( A, B, C, \) and \( D \) that best fit the curve.

**Step 2:** Changing percent of growing season into days

Although the SCS (1970) recommends plotting the crop coefficient values as a function of a percentage of the growing season, the outcome from Step 1 was changed from percent of growing season to days. This was done to allow the length of the growing season to be changed as desired. Changing percent to days was done by dividing the growing season by a factor of 100 (SCS, 1970). The desired growing season included the actual days it took corn to grow from either planting or emergence to reach physiological maturity. In this study, two growing seasons were used to compare the 1) FAO method (150 days) and the 2) SCS polynomial method (120 and 150 days).

Assuming growing seasons of 120 and 150 days, percent of the growing season can be changed by following Example 1: \( \frac{100}{120} = 0.83 \) and Example 2: \( \frac{100}{150} = 0.67 \), respectively. Accumulation of each 0.83 then represents the total growing season of 120 days, and 0.67 represents a total of 150 days. When using large sets of data, the length of the growing season can be added into the inputs, to make the crop coefficient factor self-generate.

**Step 3:** Determining the crop coefficient for the growing season

The crop coefficient was calculated by multiplying the outcome from Step 2 (\( x \)) by the number corresponding to the growing season day that a crop coefficient value needs to be determined. After obtaining the crop coefficient for one day, this step was repeated until the crop coefficients for the whole growing season were determined.
Corn emergence and physiological maturity using GDD

Corn emergence and physiological maturity were calculated using Growing Degree Days (GDD), which is calculated using Equation 2:

\[ GDD = \frac{(T_{max} + T_{min})}{2} - T_{base} \]  

(2)

where \( T_{max} \) is maximum temperature (30°C), \( T_{min} \) is minimum temperature (10°C), and \( T_{base} \) is base temperature set at 10°C. Temperature limits are set because corn does not grow much at 10°C, hence the reason why minimum temperature is limited to 10°C. The maximum temperature is limited to 30°C since crop development does not increase with an increase in temperature beyond 30°C (Hsiao and Fereres, 2012; Nafziger, 2009).

The literature provides a range of GDD required for corn to emerge, but these differ from region to region. Taylor and Elmore (2012) report that corn typically requires 90 to 120 GDDs to emerge, and Nafziger (2009) reports 115 GDDs are needed for emergence. More recently, Elmore and Mueller (2015) report that 125 GDDs are required for corn to emerge. On the other hand, crop maturity is an important factor when choosing the variety to grow and when to terminate irrigation. Corn is considered to have reached physiological maturity when kernel moisture is 30 to 35% (Nafziger, 2009), and this stage is typically identified by the appearance of a black layer on the base of the kernel (Hsiao and Fereres, 2012). An additional application of water after the crop has reached maturity does not have any additional benefit to crop production; therefore, irrigation can be terminated after this stage (Larson and Krutz, 2016; Tacker et al., 2003).
Planting dates and critical water stress growth stages of corn

Corn growth and development is sensitive to cold temperatures, so to ensure even germination and rapid emergence of the seed, corn is usually planted when the soil temperature reaches 10-13 °C (Farnham and Marks, 2001). Taylor and Elmore (2012) indicate that cool soils increase the variability not only of emergence, but also of plant to plant sizes and development stages. Determining the period from planting to emergence is especially important when determining irrigation scheduling. Therefore, a comparison was made between initiating the MIST model at planting date versus initiating the MIST model at emergence date.

The period from March 15 to April 20 is the recommended planting range for corn grown in central Mississippi, according to Wijewardana (2015). Corn planted during this period usually reaches the reproductive stage around June or July, a period where precipitation and Photosynthetic Active Radiation (PAR) are minimal (Reddy et al., 2008). Not only is this period vulnerable to heat and drought stress, it is also a period where water stress can cause detrimental effects to yield.

In addition, corn is more sensitive to water stress during the reproductive stages than the vegetative stages (Nielsen et al., 2009). Wijewardana (2015) notes that sufficient moisture during the reproductive stages is critical because it promotes pollination and grain production. To attain optimum yield, moisture should be present for two to three weeks around tasseling as this is identified as the most critical period (Nielsen et al., 2010).
Soil moisture sensor description

Soil moisture data was collected and compared to the performance of the model. Watermark 200SS soil moisture sensors were used to record soil moisture during the 2014 and 2016 growing seasons for two corn fields in Jonestown, Mississippi. One field was furrow-irrigated, and one was irrigated using a center pivot. Watermark 200SS soil moisture sensors consist of electrodes embedded within a granular matrix and when current is applied, resistance of the current is measured (Irrometer Inc, Riverside, CA). When soil is dry, resistance to the flow of electricity is greater, and this resistance is used to calculate the soil water tension in centibars (cb). Before installation, sensors were soaked in water and left to air dry. This cycle was repeated at least twice and done to remove air pockets and ensure that the sensors were reading properly. Sensors with a reading below 10 cb were selected for field installation. Two sets of Watermark 200SS sensors were installed in each field. Each set was comprised of six sensors installed in six-inch increments from 6 in (15.2 cm) to 36 in (91.4 cm). Each set of sensors was connected to one data logger (model 900), and sets were duplicated to minimize data losses in case there was equipment malfunction between field visits. The sensors were glued to a Polyvinyl Chloride (PVC) pipe, and the sensor wires were run through a notch at the top of the pipe that remained above ground. A cap was placed over the top of the pipe to prevent water from running down the pipe to the sensor. The Watermark 200SS soil moisture sensors were installed when corn plants were four to six inches tall and were removed after the last irrigation event and prior to harvest.

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2 Watermark 200SS are manufactured by Irrometer Inc, Riverside, CA
In both fields, the sensors remained in the field from May 22nd to August 25th in 2014, and from May 11th to August 5th in 2016. Sensors were installed within corn rows and adjacent to each other to ensure that they were close to the crop rooting zone. The sensors were programmed to collect data hourly everyday throughout the growing season. Both sites were checked every two to three weeks, and batteries were replaced as needed. After the end of the season, the downloaded data was synthesized for analysis.

According to the sensor manufacturer, a reading of 0 to 10 cb indicates the soil is saturated. A range of 10 to 30 cb indicates that the soil is adequately wet, while 30 to 60 cb is the usual range for irrigation in most soils. In addition, 60 to 100 cb is the usual range for irrigation in heavy clay soils, and 100 to 200 cb indicates that the soil is becoming dangerously dry (Irrometer, 2018). More specifically, Krutz and Roach (2016) recommend an irrigation trigger of 80 to 100 cb for furrow irrigation and 60 to 80 cb for center pivot irrigation for most Mississippi soils. Although, Ganjegunte and Sheng (2012) concluded that Watermark 200SS sensors tended to over-estimate or under-estimate soil moisture measurements, Krutz and Roach (2015) recommend taking a weighted average of the sensor values throughout the active rooting zone to determine the proper timing of irrigation. Rooting zone is the depth at which roots utilize water throughout the growing season. Using these combined guidelines, sensors with a reading above 30 cb were selected and used to calculate the weighted average of sensor measurements in the rooting zone. For example, when using 36 inches as the rooting zone, four sensor readings would each be multiplied by a factor. For sensors at 6 and 12 inches, the multiplying factor is 17% of 36 inches, and for sensors installed at 24 and 36 inches, the multiplying factor is 33% of the 36-inch soil profile (Krutz and Roach, 2015; Krutz and
Roach, 2016). Finally, all of the readings would be summed to get the weighted average of soil resistance throughout the rooting zone. This example assumes that the plant’s roots are pulling in water through the full 36-inch soil profile. However, if the plant’s rooting zone had only developed through 24 inches, the producer would use different weighting factors. For this reason, different sensors in different rooting zones were used to compare which sensors triggered irrigation when it was needed by the crop.

MIST simulations and measured data from Watermark 200SS soil moisture sensors were compared. Using both the FAO and the SCS polynomial corn crop coefficient methods, the model was initiated at planting and at emergence date. In addition, the measured soil moisture readings were compared to the recommendations of Krutz and Roach (2016) to determine when the weighted average was above the suggested irrigation trigger of 80 cb. Finally, the sensor measured data and actual irrigation records were compared to the MIST model simulations triggered by using both crop coefficient methods. The Solver function in Excel was used for analysis and plotting of the graphs. The FAO method with a growing season of 150 days will henceforth be referred to as FAO 150, while the SCS polynomial method with a growing season of 120 and 150 days will be referred to as SCS 120 and SCS 150, respectively.
CHAPTER III
RESULTS AND DISCUSSION

Comparison of corn crop coefficient methods

A graphical presentation (Figure 2) shows the comparison between the FAO 150, SCS 120 and SCS 150. In MIST, the FAO crop coefficient initial value was 0.38, mid-season peak value was 1.22, and the end of season crop coefficient value was 0.7. The SCS polynomial crop coefficients started with an initial value of 0.33, while the mid-season peak value was 1.06, and the end of season crop coefficient value was 0.83.

Figure 2  Comparison of FAO and SCS polynomial crop coefficient curves.
**Corn emergence and physiological maturity**

Since the emergence dates were not provided by the crop producer, an estimate of when corn emerged was calculated using the GDDs method. To determine corn emergence, a range of 90 to 125 GDDs were used. Table 1 presents estimates of the days it took corn to reach emergence during the 2014 and 2016 growing seasons for the furrow-irrigated and the pivot-irrigated fields.

### Table 1  Days required to reach emergence for corn planted in irrigated fields.

<table>
<thead>
<tr>
<th>Field</th>
<th>Planting Date</th>
<th>Emergence (Days from planting)</th>
<th>Growing Degree Days (GDD)</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>90</td>
<td>95</td>
</tr>
<tr>
<td>Furrow</td>
<td>5/5/14</td>
<td>4</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Pivot</td>
<td>3/22/14</td>
<td>13</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>Furrow</td>
<td>3/25/16</td>
<td>9</td>
<td>10</td>
<td>11</td>
</tr>
<tr>
<td>Pivot</td>
<td>4/7/16</td>
<td>9</td>
<td>9</td>
<td>10</td>
</tr>
</tbody>
</table>

Results presented in Table 1 showed that it took ± one day from the mean for corn to reach the emergence stage when the range of 90 to 125 GDDs were used. During the 2014 growing season, it took an average of five days and fourteen days, respectively, for corn to emerge in the furrow-irrigated and pivot-irrigated fields. However, it took longer for corn to emerge in 2016. It took an average of eleven days in the furrow field and ten days in the pivot field for emergence to occur. Overall, the results also showed that it took more than a week for corn planted in March and April to emerge and less than a week for corn planted in May to emerge. This could be because of cooler temperatures in March and April, whereas the corn planted in May could have benefited from the
exposure to warmer temperatures, thereby shortening the time from planting to emergence.

On the other hand, corn physiological maturity (black layer) estimates were used to determine when to terminate irrigation. One of the planted corn varieties was the Arigold 6574, which required 2,835 GDD to reach black layer. The other varieties that were planted at the study site did not provide their black layer maturity stage GDD requirements. To estimate this stage GDD requirements, physiological maturity for those varieties were set to 2,900 GDD. Physiological maturity estimates presented in Table 2 were used to determine when irrigation should be terminated.

Table 2  Days required for corn to reach physiological maturity for the 2014 and 2016 growing seasons on both irrigated fields.

<table>
<thead>
<tr>
<th>Field</th>
<th>Variety</th>
<th>Planting Date</th>
<th>Physio Days after Planting (DAP)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(m/d)</td>
<td>GDD</td>
</tr>
<tr>
<td>Furrow</td>
<td>P1685YHR</td>
<td>5/05/14</td>
<td>8/22</td>
</tr>
<tr>
<td>Pivot</td>
<td>Rev 28R10</td>
<td>3/22/14</td>
<td>8/06</td>
</tr>
<tr>
<td>Furrow</td>
<td>A6574</td>
<td>3/25/16</td>
<td>7/23</td>
</tr>
<tr>
<td>Pivot</td>
<td>Rev 28R10</td>
<td>4/07/16</td>
<td>7/30</td>
</tr>
</tbody>
</table>

Based on the results in Table 2 for the 2014 growing season, the crop reached the black layer stage on August 22\textsuperscript{nd} in the furrow field and on August 6\textsuperscript{th} in the pivot field. Physiological maturity was reached on July 23\textsuperscript{nd} and July 30\textsuperscript{th} in the furrow and pivot fields, respectively, during the 2016 growing season.

**Total crop water use using FAO and SCS polynomial methods**

Once corn emergence and physiological maturity dates were estimated, total crop water use was calculated by the MIST model to compare the different crop coefficient
methods. Table 3 summarizes total crop water use for furrow-irrigated corn using each crop coefficient method, initiating the model from planting versus emergence for each growing season.

Table 3  Total crop water use required by furrow-irrigated corn during the 2014 and 2016 growing seasons.

<table>
<thead>
<tr>
<th>Method</th>
<th>Growing season (days)</th>
<th>Field / Year</th>
<th>Total Crop Water Use (mm)</th>
<th>From planting</th>
<th>From Emergence</th>
</tr>
</thead>
<tbody>
<tr>
<td>FAO 150</td>
<td>Furrow/2014</td>
<td>437.1</td>
<td>429.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SCS 150</td>
<td>423.4</td>
<td>414.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SCS 120</td>
<td>359.9</td>
<td>352.0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

During the 2014 growing season in furrow-irrigated corn, the SCS 150 called for 13.7 mm less water than the FAO 150 when initiated at planting date and 15.0 mm less water when initiated at emergence. The SCS 120 called for 77.2 mm and 77.8 mm less than the FAO 150 when the model was initiated at planting and emergence date, respectively. In 2016, using the SCS 150 called for 28.0 mm and 25.4 mm less than the FAO 150 when the model was initiated at planting and emergence, respectively. The SCS 120 crop water use was 348.0 mm when initiated at planting date and 353.1 mm when initiated at emergence. This was 106.7 mm and 99.0 mm less than what the FAO 150 called for when the model was initiated at planting and emergence, respectively.

A similar comparison looking at the total crop water use with different crop coefficient methods and different initiation dates for the MIST model was performed for the pivot-irrigated field. These findings are presented in Table 4.
Table 4  Total crop water use required by pivot-irrigated corn during the 2014 and 2016 growing seasons.

<table>
<thead>
<tr>
<th>Method</th>
<th>Growing season (days)</th>
<th>Field /Year</th>
<th>Total Crop Water Use (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>From planting</td>
</tr>
<tr>
<td>FAO</td>
<td>150</td>
<td>Pivot /2014</td>
<td>481.3</td>
</tr>
<tr>
<td>SCS</td>
<td>150</td>
<td></td>
<td>459.2</td>
</tr>
<tr>
<td>SCS</td>
<td>120</td>
<td></td>
<td>385.3</td>
</tr>
<tr>
<td>FAO</td>
<td>150</td>
<td>Pivot /2016</td>
<td>450.1</td>
</tr>
<tr>
<td>SCS</td>
<td>150</td>
<td></td>
<td>424.9</td>
</tr>
<tr>
<td>SCS</td>
<td>120</td>
<td></td>
<td>352.6</td>
</tr>
</tbody>
</table>

Results showed during the 2014 growing season, the SCS 150 called for 22.1 mm less water than the FAO 150 when initiated at planting date and 14.4 mm less water when initiated at emergence date. The SCS 120 called for 96.0 mm and 88.1 mm less water than the FAO 150 when the model was initiated at planting and emergence, respectively. In 2016, the model called for 25.2 mm and 23.6 mm less water at planting and emergence, respectively, when the SCS 150 was applied in comparison to the FAO 150. The SCS 120 called for 97.5 mm and 87.6 mm less water when the model was initiated at planting and emergence, respectively, as compared to the FAO 150.

In both the furrow- and pivot-irrigated corn, overall the SCS method called for less water than the FAO method and could potentially save one or more irrigation events over time. However, changing the model initiation date from planting to emergence did not prove to be important and beneficial as the difference in the amount of water required by corn was below that required for an irrigation event of 25.4 mm for the pivot field and 76.2 mm for the furrow field.
MIST-triggered irrigation events

A comparison was made using FAO 150, SCS 120 and 150 to determine which method called for fewer irrigation events. In 2014, there were no irrigation events triggered by MIST in the furrow-irrigated field. However, in the pivot-irrigated field, irrigation events were triggered, and the findings were presented in Table 5. The table compares the number of irrigation events that were triggered by each method.

Table 5 Number of irrigation events during the 2014 growing season in the pivot-irrigated field.

<table>
<thead>
<tr>
<th>Method /Date (m/d)</th>
<th>FAO 150</th>
<th>SCS 150</th>
<th>SCS 120</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planting</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1st Irrigation</td>
<td>5/17</td>
<td>5/06</td>
<td>5/06</td>
</tr>
<tr>
<td>2nd Irrigation</td>
<td>5/21</td>
<td>5/13</td>
<td>5/11</td>
</tr>
<tr>
<td>3rd Irrigation</td>
<td>5/27</td>
<td>5/23</td>
<td>5/22</td>
</tr>
<tr>
<td>4th Irrigation</td>
<td>6/19</td>
<td>6/20</td>
<td>6/20</td>
</tr>
<tr>
<td>5th Irrigation</td>
<td>7/06</td>
<td>7/07</td>
<td>7/08</td>
</tr>
<tr>
<td>6th Irrigation</td>
<td>7/14</td>
<td>8/06</td>
<td>--³</td>
</tr>
<tr>
<td>7th Irrigation</td>
<td>8/05</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Maturity</td>
<td>8/16/2014</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Irrigations</td>
<td>7</td>
<td>6</td>
<td>5</td>
</tr>
</tbody>
</table>

Results in Table 5 showed that the SCS method called for fewer irrigation events as compared to the FAO method. Although the SCS method called for early irrigations, they were spaced out later towards the end of the season. The SCS 120 method called for a total of five irrigation events (126.6 mm) while the SCS 150 called for six irrigation events (152.4 mm). The FAO 150 method required a total of seven irrigation events (177.8 mm). Although the Rev 28R10 (118 RM) corn variety did not specify the GDD

³ No irrigation triggered
requirement, results showed that maturity was reached on August 6\textsuperscript{th} when using an estimate of 2,900 GDDs. Neither of the SCS methods nor the FAO method triggered any irrigations after the black layer stage was reached.

Similarly, a comparison of irrigation events for the 2016 growing season are presented in Table 6. The table shows the number of irrigation events required by the FAO 150 and the SCS 120 and SCS 150 methods. In the furrow-irrigated field, Arigold 6574 corn variety was planted on March 25\textsuperscript{th}, 2016, and using the company’s guidelines, the variety required 2,835 GDD to reach the black layer stage.

Table 6 Number of irrigation events during the 2016 growing season in the furrow-irrigated field.

<table>
<thead>
<tr>
<th>Method /Date (m/d)</th>
<th>FAO 150</th>
<th>SCS 150</th>
<th>SCS 120</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planting</td>
<td>3/25/2016</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1\textsuperscript{st} Irrigation</td>
<td>6/18</td>
<td>6/22</td>
<td>6/20</td>
</tr>
<tr>
<td>2\textsuperscript{nd} Irrigation</td>
<td>6/23</td>
<td>6/29</td>
<td>6/25</td>
</tr>
<tr>
<td>3\textsuperscript{rd} Irrigation</td>
<td>6/29</td>
<td>7/09</td>
<td>7/03</td>
</tr>
<tr>
<td>4\textsuperscript{th} Irrigation</td>
<td>7/08</td>
<td>7/26</td>
<td>7/22</td>
</tr>
<tr>
<td>5\textsuperscript{th} Irrigation</td>
<td>7/18</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Maturity</td>
<td>7/23/2016</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Irrigations</td>
<td>5</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

Results showed that although the irrigation events were called for on different dates, the first irrigation was triggered within four days for all three methods. The FAO method called for five irrigation events (126.6 mm), while both SCS methods called for four irrigation events (101.6 mm). The maturity stage was reached on July 23\textsuperscript{rd} with an accumulation of 2,840 GDDs. This confirmed that both FAO 150 and SCS 120 methods terminated irrigation before the estimated crop maturity was reached, while SCS 150 terminated irrigation after the estimated black layer stage.
In the pivot-irrigated field, a similar comparison using the FAO and SCS methods was done for the 2016 growing season. Findings are presented in Table 7, which compares the number of irrigation events required using three methods: FAO 150, SCS 120, and SCS 150.

Table 7 Number of irrigation events during the 2016 growing season in pivot-irrigated field.

<table>
<thead>
<tr>
<th>Method /Date (m/d)</th>
<th>Planting</th>
<th>1st Irrigation</th>
<th>2nd Irrigation</th>
<th>3rd Irrigation</th>
<th>4th Irrigation</th>
<th>5th Irrigation</th>
<th>6th Irrigation</th>
<th>7th Irrigation</th>
<th>Maturity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>FAO 150</td>
<td>SCS 150</td>
<td>SCS 120</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4/7/2016</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>6/13</td>
<td>5/22</td>
<td>5/18</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>6/19</td>
<td>6/14</td>
<td>6/14</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>6/24</td>
<td>6/21</td>
<td>6/20</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>6/30</td>
<td>6/27</td>
<td>6/26</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>7/9</td>
<td>7/4</td>
<td>7/3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>7/16</td>
<td>7/13</td>
<td>7/13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>7/26</td>
<td>--</td>
<td>--</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>7/30/2016</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>7</td>
<td>6</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Results showed that, overall, the SCS methods called for irrigation early as compared to the FAO method. The FAO method called for seven irrigation events (177.8 mm), while both SCS methods called for six irrigation events (152.4 mm). Therefore, using a GDDs estimate of 2,900 GDD to reach maturity, the 2016 pivot-irrigated corn reached maturity on July 30th with a total accumulation of 2,928 GDDs. Overall, the SCS methods did not trigger irrigations after July 13th, and the FAO method terminated irrigation after July 26th. Except for the first irrigation, the other triggered irrigations by both methods were slightly similar and had difference of ± five days.
Watermark 200SS soil moisture results

This section presents and discusses Watermark 200SS soil moisture measured results. Soil moisture data was recorded for two sets of adjacent sensors installed on a farm in Jonestown, Mississippi in both a furrow- and a pivot-irrigated field during the 2014 and 2016 growing seasons.

Soil moisture comparisons for 2014 and 2016 in furrow-irrigated field

Soil moisture measurements were recorded by duplicate sets of sensors (Set A and Set B) at depths of 6, 12, 18, 24, 30, and 36 inches from May 22nd to August 25th in 2014 in the furrow-irrigated corn field. The findings from Sensor Set A are presented in Figure 3 and findings from Sensor B are presented in Figure 4. An initial irrigation trigger was set at 80 cb for furrow-irrigated fields, and a sensor reading of 30 cb was used to determine the active rooting zone, and to calculate the weighted average of the sensors.

Results in Figure 3 showed that the roots were pulling water from the 6-inch (June 6th), 12-inch (June 18th), and 18-inch (June 20th) depths, while the remaining sensors were actively pulling water in July. Readings above 30 cb were recorded by the 24-inch sensor on July 1st, 30-inch on July 4th while the 36-inch sensor reading was above 30 cb on July 7th. Overall, no irrigations were triggered at the beginning (May 22nd to June 23rd). A weighted average of 80.4 cb was recorded on June 24th, before dropping below 80 cb from June 25th to July 4th. Results showed that the weighted reading for the sensors was above 80 cb from July 5th to July 13th and stayed below the initial trigger from July 14th until the period when the sensors were taken out of the field.
Figure 3  Soil tension measurements and weighted averages from Watermark Sensor Set A installed at different depths in furrow-irrigated corn field in 2014.

The patterns exhibited by Sensor Set B in Figure 4 were like those observed in Sensor Set A (Figure 3). Using a reading above 30 cb as the initial reading showing active rooting zone, the difference between the two sets is that in Set B the roots did not pull water from the 36-inch rooting zone as shown with the Set B 36-inch sensor not reading above 30 cb throughout the growing season. Similarly, the findings in Figure 4 showed that the roots were actively pulling water from the 6-inch (June 5th), 12-inch (June 18th), and 18-inch (June 21th) sensor depths, while the remaining 24-inch and 30-inch sensors showed that the roots pulled water beginning on July 3rd and July 6th, respectively. Overall, the first weighted readings above 80 cb were reported from June 23rd to June 26th. There was no record of the weighted average above 80 cb until later
from July 5\textsuperscript{th} to July 13\textsuperscript{th}, and the weighted average dropped well below 80 cb on July 14\textsuperscript{th} and remained below the 80cb irrigation trigger until the time when the sensors were taken out of the field.

Figure 4  Soil tension measurements and weighted averages from Watermark Sensor Set B installed at different depths in furrow-irrigated corn field in 2014.

Soil moisture was also measured in the furrow-irrigated field during the 2016 growing season. Duplicate sets of sensors (Set A and Set B) were installed on May 11\textsuperscript{th} and removed from the field on August 5\textsuperscript{th}. Soil tension measurements and weighted averages for Sensor Set A and Sensor Set B are shown in Figure 5 and Figure 6, respectively.
During the growing season of 2016, the 6-inch sensor recorded a reading above 30 cb on May 18. On May 23rd and May 31st, the 12-inch and 18-inch sensor reported a reading above 30 cb. Results in Figure 5 showed that on June 8th, the 24-inch sensor began pulling water from the 24-inch rooting zone. Findings showed that the 30-inch and the 36-inch sensors recorded a reading above 30 cb on June 24th and July 3rd, respectively. Sensor Set A reported readings above 80 cb and triggered irrigations from May 25th to June 10th and again from June 20th to August 5th.

Soil tension findings for Sensor Set B, installed one row next to Sensor Set A in the same furrow-irrigated field, can be seen in Figure 6. The same trend observed in Sensor Set A was also seen in Sensor Set B. The 6-inch sensor in set B reported a reading
above 30 cb on May 16th, and the 12-inch sensor reported a reading above 30 cb on May 22nd. On May 28th, the 18-inch sensor had a reading above 30 cb. On June 6th, the 24-inch sensor had a reading above 30 cb, while the 30-inch and 36-inch sensors reported a reading above 30 cb on June 23rd and June 30th, respectively.

Figure 6  Soil tension measurements and weighted averages from Watermark Sensor Set B installed at different depths in a furrow-irrigated corn field in 2016.

Results showed that using an initial irrigation trigger of 80 cb as the weighted average, Sensor Set B triggered irrigations three times. The first irrigation was triggered from May 25th to June 5th. Another irrigation event was called for from June 8th to June 13th. The weighted sensor average rose above 80 cb again on June 20th and continued to report readings above 80 cb for the remainder of the growing season until the sensors were taken out of the field.
Overall, sensors in Set A installed at depths of 6, 12 and 18 inches were drier than those installed deeper at 24, 30, and 36 inches throughout the growing season. For Sensors Set B, the sensors installed at 6, 12, 18, and 24 inches were drier. The sensors installed at 30 and 36 inches were not as dry as the shallower depths, but once they began to dry and read higher values, they did not appear to re-wet.

Findings from Figures 5 and 6 showed that even though there were similarities among the adjacent sensors throughout the growing season, there were also some discrepancies, particularly with the 6-inch sensor. A comparison between adjacent 6-inch sensors in both sets was done to evaluate if the sensors recorded and triggered similar irrigation events, and if irrigation records and rainfall received corresponds with the dates where there was a decrease in soil tension readings (Figure 7). Although there were no irrigation records available for 2014, irrigation records for 2016 were available.

Results showed that although the sensor readings had a similar trend and a time lag, overall, the 6-inch sensor in Set B was wetter than the 6-inch sensor in Set A. Both sensors triggered the first three irrigations within the same period, but as the season progressed, the sensor in Set A continued to read higher values after mid-July, while the sensor in Set B re-wetted on July 5 (9 cb) and did not rise above 90 cb for the remainder of the growing season.

As shown in Figure 7, actual irrigations applied by the producer did not match with the ones that were triggered by the sensors except the one that occurred on June 30th. Records indicated that actual irrigation applications occurred on May 21st and July 12th. After these applications, the sensor in Set A re-wetted slightly before drying again,
and it continued to record above 160 cb. Meanwhile, the sensor in Set B recorded soil moisture readings of 90 cb and below after the last irrigation and through the remainder of the growing season.

![Graph showing soil moisture readings over time]

**Figure 7** Comparison of adjacent 6-inch sensors in Sets A and B in a furrow-irrigated corn field in 2016.

The reason why the sensor in Set A measured higher soil tension than the sensor in Set B remains unknown. However, it is possible that the sensor had been dry for a longer period causing the seal between the sensor and the soil to break. Sensors in the furrow-irrigated field were installed in an area where the Bosket very fine sandy loam (dubbs) soil type was dominating. This type of soil is classified as a well-drained soil with low runoff, and can transmit water at a rate of 15.2 to 50.8 mm per hour (Soil Survey Staff, 2017). It is possible that one sensor was placed in an area where water was being lost faster than the other, thereby causing the 6-inch sensor measurements to...
fluctuate more due to constant wetting and drying. A coefficient of determination ($R^2$) of 0.27 indicates some association between the sensors. However, this makes precise irrigation scheduling a challenge, especially when one sensor triggers irrigation events while the adjacent sensor reports adequate moisture in the soil profile.

**Soil moisture comparisons for 2014 and 2016 in pivot-irrigated field**

Soil tension measurements were also recorded by two sets of adjacent sensors, Set A and Set B, in a nearby pivot-irrigated corn field during the 2014 and 2016 growing seasons. Soil tension measurements for Sensor Set A and Sensor Set B are shown in Figure 8 and Figure 9, respectively. In fields were older and slower center pivot irrigation systems are used, it is recommended to use an irrigation trigger of 60-80 cb (Krustz and Roach, 2016). For this reason, an initial irrigation trigger was set at 60 cb for the pivot-irrigated field.

Sensors were installed on May 22\textsuperscript{nd}, and results show that the 6-inch sensor had a weighted average above 60 cb from May 22\textsuperscript{nd} to May 29\textsuperscript{th}. Although the sensors were saturated before they were installed in the field, it is possible that the soil was too dry and the sensor had higher readings because it was still adjusting to the soil conditions.
Figure 8. Soil tension measurements and weighted averages from Watermark Sensor Set A installed at different depths in a pivot-irrigated corn field in 2014.

The 6-inch sensor was drier than the other sensors, and its measurements fluctuated throughout the growing season. Both the 12-inch and the 18-inch sensors were actively pulling water and recorded a reading above 30 cb on May 24th. On June 7th the 24-inch reported a reading above 30 cb, while the 30-inch sensor recorded 30 cb on June 8th. Findings showed that the roots began pulling water from the 36-inch rooting zone on June 30th when the 36-inch sensor reported a reading above 30 cb.

Although results showed that the roots were active throughout the 6 to 36-inch rooting zone, the sensors at deeper depths were wetter than the 6-inch sensor. When a reading of 60 cb was used to trigger an irrigation in the pivot-irrigated field, the weighted
average was above 60 cb from May 22\textsuperscript{nd} to May 29\textsuperscript{th} and from July 9\textsuperscript{th} to July 14\textsuperscript{th}. No other irrigations were triggered throughout the 2014 growing season.

Similar data was recorded for Sensor Set B, installed one row next to Set A in the same pivot-irrigated corn field during the 2014 growing season (Figure 9). Unlike the sensors in Set A, the sensors in Set B did not trigger as many irrigations. Results showed the 6-inch sensor in Set A was drier than the adjacent 6-inch sensor in Set B. The 6-inch sensor had a weighted average above 60 cb and triggered its first irrigation from May 25\textsuperscript{th} to May 28\textsuperscript{th}.

![Soil tension measurements and weighted averages from Watermark Sensor Set B installed at different depths in a pivot-irrigated corn field in 2014.](image)

**Figure 9**  
Soil tension measurements and weighted averages from Watermark Sensor Set B installed at different depths in a pivot-irrigated corn field in 2014.
Both the 6- and the 12-inch sensors reported soil tension readings above 30 cb on May 24th. Likewise, the 18-inch sensor recorded a reading above 30 cb on June 9th. Sensor readings showed that the roots were actively pulling water from the 24-, 30-, and 36-inch rooting zone around July 7th. Unlike Set A, the sensors in Set B only had a weighted average above 60 cb from May 25th to May 28th, and another irrigation was triggered on July 16th. The 36-inch sensor in Set A was wetter than the one in Set B. Both adjacent 36-inch sensors showed a similar trend from July 5th to July 25th when the readings were above 30 cb, but after July 25th both sensors dropped to readings below 30 cb and did not trigger any irrigations until the sensors were removed from the field.

Sensors in the pivot-irrigated field were installed in an area where the Bosket very fine sandy loam (Bd) and Dubbs very fine sandy loam (Dd) soil types were dominating. These soils are very similar; they are well drained and classified as soils with low and medium runoff, respectively. The Bosket very fine sandy loam transmits water at a rate of 15.2 to 50.8 mm per hour, while the Dubbs very fine sandy loam transmits water at a rate of 14.5 to 50.3 mm per hour (Soil Survey Staff, 2017). Results in Figures 8 and 9 confirmed that the 6-inch sensor in Set A dried more than the 6-inch sensor in Set B. When irrigation is based primarily on sensor recommendations, sensors that are not taking accurate measurements because they have lost their seal with the soil, or for other reasons, can pose a challenge. It is important for the producer to walk the field and monitor the crop.
A comparison between the 6-inch sensors in Set A and Set B was done to evaluate whether the triggered irrigation matched up with the periods when the soil was dry due to lack of irrigation or rainfall events (Figure 10).

![Graph showing soil tension measurements and rainfall over time]

Figure 10  Comparison of adjacent 6-inch sensor in Sets A and B in a pivot-irrigated corn field in 2014.

While the adjacent 6-inch sensors exhibited the same wetting and drying pattern and had an R² of 0.69, Figure 10 showed the sensor in Set A was drier and triggered more irrigations than the sensor in Set B. There were no irrigation records available for the 2014 growing season. Both sensors showed good performance in responding to high rainfall events that occurred during the monitoring period. The sensor in Set A had a reading of 228 cb on May 26th and 185 cb on May 28th before dropping to 30 cb on May 29th, while the sensor in Set B had a reading of 140 cb on May 28th before it dropped to 4
cb on May 29\textsuperscript{th}. These results correspond with the 25-mm rainfall event that occurred on that day. Likewise, the sensor in Set A responded and re-wetted after a rainfall event that occurred on June 9\textsuperscript{th}, when 40 mm of rainfall was received and sensor readings dropped from 140 cb on June 8\textsuperscript{th} to 4 cb on June 9\textsuperscript{th}. The 6-inch sensor in Set B was reading 33 cb on June 8\textsuperscript{th} and dropped to 4 cb on June 9\textsuperscript{th}.

On June 23\textsuperscript{rd}, the sensor in Set A had a reading of 183 cb, and the sensor in Set B had a reading of 77 cb. The sensor readings for the 6-inch sensors in Set A and Set B dropped to 36 cb and 15 cb, respectively, after a rainfall event of 23-mm on June 24\textsuperscript{th}. Last, both sensors responded to the 24-mm rainfall that was received on July 15\textsuperscript{th}. The 6-inch sensor in Set A dropped from 74 cb on July 13\textsuperscript{th} to 14 cb on July 15\textsuperscript{th}. On the other hand, sensor A dropped from 164 cb on July 13\textsuperscript{th} to 34 cb on July 15\textsuperscript{th}, while sensor B dropped from 74 cb on July 13\textsuperscript{th} to 14 cb on July 15\textsuperscript{th} following the rainfall event.

Overall, the 6-inch sensors installed in the pivot-irrigated field followed a similar pattern of wetting and drying, and the lower readings reported by the sensors matched up with the days when rainfall was received at the study field.

Soil tension measurements were again recorded during the 2016 growing season, with duplicate sets of soil moisture sensors (Set A and Set B) installed in adjacent rows in a pivot-irrigated corn field. The 2016 data for Sensor Set A installed in the pivot-irrigated field are presented in Figure 11.

Results showed that readings above 30 cb were reported on May 14\textsuperscript{th} by the 6-inch, on May 21\textsuperscript{st} by the 12-inch sensor and on June 1\textsuperscript{st} by the 18-inch sensor. It was not until June 10\textsuperscript{th} and June 28\textsuperscript{th} when the 24- and 30-inch sensors, respectively, reported...
readings above 30 cb. Lastly, the 36-inch sensor reported readings above 30 cb on July 2nd. Using 60 cb as the irrigation trigger, sensor readings with a weighted average above 60 cb were reported from May 19th to May 20th, May 23rd to May 26th, June 8th to July 4th, and from July 6th through the end of the growing season.

![Soil tension measurements and weighted averages from Watermark Sensor Set A installed at different depths in a pivot-irrigated corn field in 2016.](image)

Figure 11 Soil tension measurements and weighted averages from Watermark Sensor Set A installed at different depths in a pivot-irrigated corn field in 2016.

The soil tension data for Watermark sensors in Set B are shown in Figure 12. Similar to the adjacent sensors in Set A, the 6-inch and 12-inch sensors reported readings above 30 cb on May 14th and May 21st, respectively. Unlike the 18-inch sensor in Set A, the adjacent sensor in Set B recorded readings above 30 cb on May 25th. On June 7th and June 23rd, the 24- and 30-inch sensors, respectively, reported readings above 30 cb. It was not until July 7th when the 36-inch sensor reported readings above 30 cb. The adjacent
Set B sensors reported a weighted average above 60 cb from May 18th to May 20th, May 22nd to May 26th, and May 30th to July 26th. The last irrigation was triggered on August 3rd, and the sensors continued to report readings with a weighted average above 60 cb until the sensors were removed from the field on August 5th.

![Soil tension measurements and weighted averages from Watermark Sensor Set B installed at different depths in a pivot-irrigated corn field in 2016.](image)

Overall, it is evident that sensors in Set A were drier than the adjacent sensors in Set B. Results showed that the 6- and 12-inch sensors in Sets A and B had similar readings and had readings above 30 cb on May 14th and May 21st, respectively. Figure 11 showed that Set A sensors, the 18- and 24-inch sensors reported readings above 30 cb on May 25th and June 7th, respectively, while the 30- and 36-inch sensors were actively pulling water from June 23rd and July 7th, respectively. However, in the adjacent set B the 18-and the 24-inch sensors were active from June 1st and June 10th, respectively. The 30-
inch had readings above 30 cb on June 28th and the 36-inch sensor was actively pulling water on July 2nd. Although both sets had similar patterns, results show that both sets had readings above 60 cb from May 18th to May 26th the sensors responded differently afterwards. Set A had readings above 60 cb from June 8th to July 4th and also from July 16th to August 5th, while in the adjacent Set B, had readings above 60 cb from May 30th to July 26th and also from August 3rd to August 5th.

Figures 11 and 12 showed that the 24-inch sensors in both sets had a similar pattern at the beginning of the season, but as the season progressed did not report similar readings. The 24-inch sensor readings in Set A fluctuated and recorded two significant drops from 103 cb on July 4th to 24 cb on July 5th, and another drop was recorded on July 26th (123 cb) to July 27th (19 cb). The drops could have been due to the addition of moisture either from irrigation or rainfall, while the adjacent sensor in Set B did not re-wet. A comparison between 24-inch adjacent sensors in Sets A and B installed in a pivot-irrigated corn field during the 2016 growing season is shown in Figure 13.

While the adjacent sensors installed at 24 inches had an $R^2$ of 0.78, the sensors did not record similar conditions after an irrigation (25.4 mm) and a rainfall of 14-mm that were applied and received on June 27th, and another rainfall (8.0 mm) that was received on June 28th. Both sensors had a reading of 103 cb on July 4th, but the 24-inch sensor in Set A dropped to a reading of 24 cb on July 5th, while the sensor at the same depth in Set B did not re-wet. A similar situation occurred on July 27th when the 24-inch sensor in Set A dropped significantly from 123 cb on July 26th to 19 cb following some light rainfall (9 mm) received during that period, while the adjacent sensor in Set B recorded slowly decreasing soil tension measurements with no significant re-wetting.
Results showed that the 24-inch sensor in Set A registered and responded to the moisture that was added into the soil profile, while the same sensor in Set B only slightly responded to the added moisture. The 24-inch sensors had an $R^2$ of 0.78, even though the sensor in Set B was not as responsive as the adjacent sensor in Set A toward the end of the growing season. Using the recommendations of the Set B sensor, one may end up over irrigating, while following the recommendations of the 24-inch sensor in Set A could cause one to assume that there is adequate moisture and no need for an irrigation application. However, when the producer actually applied irrigation on July 12th and July 15th, both sensors were reading above 60 cb.
Comparison of MIST, soil moisture sensor method and actual irrigations

*Furrow-irrigated soil moisture comparisons*

A comparison of the irrigation events simulated by MIST, irrigation events triggered by the Watermark sensors, and the actual irrigations applied by the crop producer, when available, was done. A comparison of the irrigation events predicted by MIST using three crop coefficient methods – FAO 150, SCS 150 and SCS 120 – were used to simulate the number of irrigation events required throughout the growing season if an irrigation of 25.4 mm was applied. Recommendations from Krutz and Roach (2016) were used to the irrigations triggered by the Watermark sensors. A weighted average of 80 cb was used for furrow-irrigated fields. Table 8 below summarizes the findings for the 2014 and 2016 growing season in the furrow-irrigated corn field.

Table 8 Number of irrigation events during the 2014 and 2016 growing seasons in furrow-irrigated field.

<table>
<thead>
<tr>
<th>Year</th>
<th>FAO 150</th>
<th>SCS 150</th>
<th>SCS 120</th>
<th>Sensor A</th>
<th>Sensor B</th>
<th>Actual Irrigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>2014 Furrow</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1st Irrigation</td>
<td>--(^4)</td>
<td>--</td>
<td>--</td>
<td>6/24</td>
<td>6/23 -6/29</td>
<td>no(^5)</td>
</tr>
<tr>
<td>2nd Irrigation</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>7/05 -7/13</td>
<td>7/05 -7/13</td>
<td>no</td>
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<td>2016 Furrow</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3rd Irrigation</td>
<td>6/29</td>
<td>7/9</td>
<td>7/3</td>
<td>--</td>
<td>6/20 -8/05</td>
<td>7/12</td>
</tr>
<tr>
<td>4th Irrigation</td>
<td>7/8</td>
<td>7/26</td>
<td>7/22</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>5th Irrigation</td>
<td>7/18</td>
<td>--</td>
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</tbody>
</table>

During the 2014 growing season, the MIST model did not trigger any irrigations in the furrow-irrigated field, and there were no irrigation records available from the

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\(^4\) No irrigation triggered  
\(^5\) No irrigation records for 2014 growing season
producer. However, Watermark soil moisture sensors in both Set A and Set B reported readings with weighted averages above 80 cb and triggered irrigation events. Sensor A called for an irrigation on June 24th, while Sensor B called for an irrigation from June 23rd to June 29th. Both sensor sets called for a second irrigation within the same period of time from July 5th to July 13th.

Results in Table 8 show that unlike in 2014, there were irrigation events that were triggered by the model, and irrigation records were available during the 2016 growing season. Irrigation records show that there were three irrigations that were applied throughout the season. Sensor Set A called for irrigations from May 25th to June 10th and also from June 21st to August 5th, while the adjacent sensors in Set B called for irrigations from May 25th to June 5th, June 8th to June 13th, and again from June 20th to August 5th. The FAO 150 method called for five irrigations, while the SCS 150 and SCS 120 called for four irrigations. Table 8 confirmed that the sensor readings were somewhat alike and close to those simulated by the model. However, it is difficult to conclude the exact number irrigations triggered by the sensors since the irrigations applied during the growing season were not well reflected by the sensors.

**Pivot-irrigated soil moisture comparisons**

Unlike in the furrow-irrigated field, irrigation events were triggered by both the MIST model and the sensors in 2014 in the pivot-irrigated field. However, there were no irrigation records for 2014, therefore a comparison was only made between the adjacent sensors using recommendations by Krutz and Roach (2016) and the model simulated irrigation results. For the 2016 growing season, a comparison of the irrigation events simulated by MIST, irrigation events triggered by the Watermark sensors, and the actual
irrigations applied by the producer were done. These findings were summarized in Table 9 for the 2014 and 2016 growing seasons for the pivot-irrigated corn field.

Table 9  Number of irrigation events during the 2014 and 2016 growing seasons in the pivot-irrigated field.

<table>
<thead>
<tr>
<th></th>
<th>FAO 150</th>
<th>SCS 150</th>
<th>SCS 120</th>
<th>Sensor A</th>
<th>Sensor B</th>
<th>Actual Irrigation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>2014 Pivot</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt; Irrigation</td>
<td>5/17</td>
<td>5/06</td>
<td>5/06</td>
<td>5/22- 5/28</td>
<td>5/25 -5/28</td>
<td>no&lt;sup&gt;6&lt;/sup&gt;</td>
</tr>
<tr>
<td>2&lt;sup&gt;nd&lt;/sup&gt; Irrigation</td>
<td>5/21</td>
<td>5/13</td>
<td>5/11</td>
<td>7/09- 7/14</td>
<td>7/16</td>
<td>no</td>
</tr>
<tr>
<td>3&lt;sup&gt;rd&lt;/sup&gt; Irrigation</td>
<td>5/27</td>
<td>5/22</td>
<td>5/22</td>
<td>--</td>
<td>--</td>
<td>no</td>
</tr>
<tr>
<td>4&lt;sup&gt;th&lt;/sup&gt; Irrigation</td>
<td>6/19</td>
<td>6/20</td>
<td>6/20</td>
<td>--</td>
<td>--</td>
<td>no</td>
</tr>
<tr>
<td>5&lt;sup&gt;th&lt;/sup&gt; Irrigation</td>
<td>7/06</td>
<td>7/07</td>
<td>7/08</td>
<td>--</td>
<td>--</td>
<td>no</td>
</tr>
<tr>
<td>6&lt;sup&gt;th&lt;/sup&gt; Irrigation</td>
<td>7/14</td>
<td>8/06</td>
<td>--&lt;sup&gt;7&lt;/sup&gt;</td>
<td>--</td>
<td>--</td>
<td>no</td>
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<tr>
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<td>--</td>
<td>--</td>
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<td>no</td>
</tr>
<tr>
<td><strong>2016 Pivot</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3&lt;sup&gt;rd&lt;/sup&gt; Irrigation</td>
<td>6/29</td>
<td>6/21</td>
<td>6/20</td>
<td>6/08- 7/04</td>
<td>5/30 -7/26</td>
<td>7/12</td>
</tr>
<tr>
<td>4&lt;sup&gt;th&lt;/sup&gt; Irrigation</td>
<td>6/30</td>
<td>6/27</td>
<td>6/26</td>
<td>7/06- 8/05</td>
<td>8/03- 8/05</td>
<td>7/15</td>
</tr>
<tr>
<td>5&lt;sup&gt;th&lt;/sup&gt; Irrigation</td>
<td>7/09</td>
<td>7/04</td>
<td>7/03</td>
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<tr>
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<td>7/26</td>
<td>--</td>
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</tr>
</tbody>
</table>

During the 2014 growing season there were no irrigation records available from the producer. Table 9 showed that FAO 150 called for seven irrigations, while the SCS 150 and SCS 120 methods called for six and five irrigations, respectively. Watermark soil moisture sensors in both Set A and Set B reported similar readings. Sensor A called for an irrigation from May 22<sup>nd</sup> to May 28<sup>th</sup>, and again from July 9<sup>th</sup> to July 14<sup>th</sup>, while the

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<sup>6</sup> No irrigation records  
<sup>7</sup> No irrigation triggered  
<sup>8</sup> 20.32 mm rainfall received
adjacent Sensor B called for an irrigation from May 25\textsuperscript{th} to May 28\textsuperscript{th}, and also on July 16\textsuperscript{th}.

Unlike in 2014, during the 2016 growing season the irrigation records were available. Irrigation records show that there were four irrigations that were applied throughout the season and on July 18\textsuperscript{th} a total rainfall of 20.3-mm was received. The FAO 150 method called for seven irrigations, while the SCS methods called for six irrigations, overall. Sensor A called for irrigations from May 19\textsuperscript{th} to May 20\textsuperscript{th}, May 23\textsuperscript{rd} to May 26\textsuperscript{th}, June 8\textsuperscript{th} to July 4\textsuperscript{th}, and again from July 6\textsuperscript{th} to August 5\textsuperscript{th}, while the adjacent sensor B called for irrigations from May 18\textsuperscript{th} to May 20\textsuperscript{th}, May 22\textsuperscript{nd} to May 26\textsuperscript{th}, May 30\textsuperscript{th} to July 26\textsuperscript{th}, and again from August 3\textsuperscript{rd} to August 5\textsuperscript{th}. Although all the methods reported irrigation events that were similar and closely matched, concluding the exact number of irrigations triggered by the sensors remains a challenge.
CHAPTER IV
SUMMARY AND CONCLUSIONS

The objectives of this research were to 1) adjust and examine the Food and Agriculture Organization (FAO) crop coefficient method and the adjusted “SCS polynomial crop coefficient” method adapted and digitized from the former Soil Conservation Service (SCS, 1970) using a growing season of 120 and 150 days, 2) determine corn emergence and physiological maturity using 50 Growing Degree Days (GDD\textsubscript{50}) for use in adjusting the length of the growing season, 3) examine the importance of initiating the model at planting and emergence date, and 4) compare MIST modeled results to measured data from Watermark soil moisture sensors for the 2014 and 2016 growing seasons.

MIST calculates crop water use with the FAO crop coefficient method, which uses a growing season of 150 days as provided by Allen et al. (1998) and Pereira et al. (2014). The SCS polynomial method with a growing season of 150 and 120 days was used to improve the corn crop coefficient being used in MIST. Results showed that the FAO method used crop coefficient values 0.38 for initial season and 1.22 for mid-season, while the SCS polynomial method produced crop coefficient values of 0.33 and 1.06, respectively. Results showed that changing the model initiation date from planting to emergence did not make a difference in terms of the total crop water use as this did not change the number of irrigations. Based on the results, it can be concluded that all the
three crop coefficient methods triggered somewhat similar irrigation applications. However, the SCS polynomial method called for less crop water use overall and fewer irrigation events and was closer to soil moisture measurements than the FAO method.

Although measured data from Watermark 200SS sensors installed in Jonestown fields using both furrow and pivot irrigation systems showed similar patterns, the adjacent sensors did not always trigger similar irrigations. In a study conducted by Ganjegunte & Sheng (2012), it was concluded that Watermark 200SS sensors tended to overestimate or underestimate soil moisture. Similar conclusions could be made for this study, as it was also evident that one set of sensors tended to be drier than the other adjacent set of sensors. It is important to note that because Set A and Set B in the same field did not always agree and trigger similar irrigations, it is possible that one may have overestimated or underestimated soil moisture.

Comparisons between MIST and measured soil moisture readings by sensors showed that most irrigations triggered by the model and the sensors were within the same range. However, because of the missing irrigation records for 2014, it was difficult to separate a decline in soil tension measurements because we could not determine if it was due to an irrigation event that was not recorded or rainfall that was not also reflected by precipitation record from NexRad. Also, the sensors did not pick up some of the known irrigation applications that were made by the producer, and this made it difficult to rely only on one set of sensors, thereby calling into question the sole dependence on granular matrix soil moisture sensors for irrigation scheduling.
Based on these findings, it is recommended that when considering use of soil moisture sensors, it is important to remember that they may not perform as well in the same or especially in different soil types or fields as in this research. One major observation was that the soil moisture sensors at shallower depths matched the model simulations better as compared to the sensors installed at deeper depths. Therefore, one should be prepared to invest in and use multiple sensors in the same field, as this may help clarify issues that may arise when one sensor reports adequate soil moisture while the other sensor reports otherwise. Using both the model and the sensors could improve irrigation efficiency. Finally, when scheduling irrigation applications with both the MIST model and/or Watermark 200SS soil moisture sensors, it is very important to keep a record of all irrigation applications, including when and how much water was applied during the growing season.

Application of these two methods differ in two ways. In field measurements, such as rain gauges for precipitation and soil moisture sensors for field conditions are point measurements which may or may not be representative of the entire field, but are then applied to a very large area. In contrast, MIST uses area calculations, precipitation reflecting an area of 4km, and climate data for large areas. In the model, soil moisture response to soil type is based on calculations from soil maps for the entire field. MIST’s spatial approach should therefore represent the entire field more accurately than a single point value from the in-field measurements.

In addition, MIST is capable of real-time estimations as it is fed automatically as compared to after-the-fact estimations of soil sensors - soil sensors used in this study
were not read in real-time. Furthermore, changes in soil tension will normally lag behind
the addition of water, since it takes a significant period depending on the soil type, for the
water to move down in the soil profile. For example, MIST will reflect a rainfall event
immediately, whereas soil sensors cannot recognize the added water until it reaches the
sensor, with increasing time lags as the depth of the sensors and rooting zone increases.
DISCLAIMER

Mention of a trade name does not constitute an endorsement by Mississippi State University. Details of specific products are provided for information only.
REFERENCES


Henggeler, J. (2002). *Software Programs Currently Available for Irrigation Scheduling*.


