



# Cotton Irrigation Management for Humid Regions



Cotton  
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# Table of Contents

Introduction . . . . .	1
Benefits of Irrigation . . . . .	2
Section 1: Why Irrigate Cotton? . . . . .	2
Irrigation Stabilizes and Boosts Yield. . . . .	3
Removing Risks Associated with Yield Instability. . . . .	3
Why Plants Need Water . . . . .	3
Seasonal Water Requirements Vary by Climate . . . . .	3
Plant Response to Water Stress . . . . .	4
The Relationship Between Water and Yield. . . . .	4
Water Use Efficiency. . . . .	5
Increasing Water Use Efficiency . . . . .	5
Boosting Yield and Reducing Costs . . . . .	5
Optimizing the Use of All Crop Inputs . . . . .	6
Getting the “Most Crop Per Drop”. . . . .	6
Section 2: Why Schedule Irrigation? . . . . .	7
The Risk of Too Much Water. . . . .	7
Proper Irrigation Methods . . . . .	8
Plant Available Water – Staying in the Sweet Spot of Soil Moisture Levels. . . . .	8
Results of Water Loss. . . . .	9
Estimating the Soil’s Ability to Provide Water. . . . .	9
Signs of Water Stress (What Scheduling Should Allow You to Avoid). . . . .	9
Targeted Irrigation Scheduling. . . . .	10
The Art and Science of Irrigation Scheduling. . . . .	11
Section 3: Initiating and Terminating Irrigation for the Season . . . . .	12
When to Initiate the First Irrigation. . . . .	12
Irrigation Near the Time of Emergence . . . . .	13
When to Apply the Last Irrigation . . . . .	13
Section 4: Cotton Water Requirements. . . . .	14
Evapotranspiration . . . . .	14
Measuring Evapotranspiration. . . . .	15
Water Use. . . . .	15
Water Use and Crop Coefficients . . . . .	16
Section 5: Water-Sensitivity of Cotton Growth Stages. . . . .	17
Planting to Emergence . . . . .	17



Emergence to First Square . . . . . 18

First Square to First Flower . . . . . 19

First Flower to Peak Bloom . . . . . 20

Peak Bloom to Open Bolls . . . . . 20

Section 6: Sensor-Based Scheduling . . . . . 21

    Types of Measurements . . . . . 21

    Types of Sensors . . . . . 23

    Costs and Methods of Obtaining Soil Water Data . . . . . 24

    Decision Factors . . . . . 25

    Cost Factors . . . . . 25

    Locating Sensors . . . . . 25

    Irrigation Scheduling . . . . . 26

    Types of Irrigation Systems . . . . . 27

    Access to Sensors . . . . . 27

    Sensor Installation . . . . . 27

    Compatibility with Field Operations . . . . . 28

    Connecting Wireless Systems . . . . . 29

    Interpreting Sensor Results . . . . . 29

    Accuracy of Sensor Readings . . . . . 30

    Retrospective Use of Sensors . . . . . 30

    Using Post-Season Soil-Water Data . . . . . 31

Section 7: Irrigation Scheduling Tools . . . . . 32

    Water Balance Method . . . . . 32

        Soil Water Content . . . . . 32

    Maintaining Soil Water . . . . . 34

    Estimating Crop Water Use . . . . . 34

    The Mississippi Irrigation Scheduling Tool – MIST . . . . . 34

    The MOIST Program (University of Tennessee) . . . . . 35

    Combining Soil Moisture Monitoring with Water Balancing . . . . . 37

Section 8: Management Considerations for Irrigated Cotton . . . . . 38

    Cotton Crop Irrigation Increasing . . . . . 38

    Germination and Seedling Emergence . . . . . 39

    Pre-Squaring Cotton . . . . . 40

    Squaring Cotton . . . . . 40

    Early Bloom Cotton . . . . . 41

    Cutout, Late Bloom and Boll Opening Cotton . . . . . 41

    General Irrigation Management Considerations . . . . . 41

    Irrigation Adds Flexibility to Farming Operations . . . . . 42

    Irrigation and Variety Selection . . . . . 42



Section 9: Irrigation Systems Overview . . . . .	43
Subsurface Drip Irrigation . . . . .	43
Design Criteria . . . . .	44
1. Water Requirements: . . . . .	44
2. Management and Operation Considerations: . . . . .	45
3. Water Quality: . . . . .	45
Filtration Requirements for Subsurface Drip Irrigation . . . . .	45
Chemical Injection for Subsurface Drip Irrigation . . . . .	46
Valves for SDI Systems . . . . .	46
Main and Sub-Main Design. . . . .	47
Drip-Line Design . . . . .	47
Instrumentation and Controls . . . . .	48
Surface Drip Irrigation . . . . .	49
Surface Drip Irrigation Design . . . . .	49
Shallow SubSurface Drip Irrigation (S3DI) . . . . .	50
System Costs and Expenses . . . . .	50
Center Pivots . . . . .	51
Center Pivot Design Considerations . . . . .	52
System Dimensions . . . . .	52
Sprinklers . . . . .	53
Irrigation Water Delivery . . . . .	54
Chemigation . . . . .	54
Control Panels/User Interfaces . . . . .	55
Surface Irrigation (Flood/Furrow) . . . . .	56
Field Geometry . . . . .	56
Water Source . . . . .	56
Irrigation Water Delivery . . . . .	57
The Siphon Tube System . . . . .	57
Pipe Systems . . . . .	58
Poly Pipe Systems . . . . .	58
Irrigation Water Quality . . . . .	59
References and Additional Resources. . . . .	60



# Introduction

Use of irrigation has been increasing across the humid areas of the Cotton Belt for the last 20 years. While there is a large collection of information for irrigation management related to cotton in arid regions, information specific to management under humid conditions is not as well developed. Therefore, the objective of this publication is to provide producers with an overview of the technologies available to schedule irrigation and key concepts related to water management for cotton grown in areas where rainfall provides a significant amount of the water requirements in most years.



*Figure 0.1 – Drop line from a center pivot providing water to a minimal tillage cotton field.*

This document is divided into nine sections that address a variety of topics including: the benefits of irrigation and why water management is important; cotton water requirements in humid areas; growth stages that are sensitive to water stress; and a review of tools for irrigation scheduling. An overview of different methods to deliver water to the field is also provided.

Irrigation water, if managed wisely, is an important tool to optimize productivity of the land and to ensure that no other inputs go to waste. Thus, it is an important tool that can be used in developing a sustainable crop management strategy. Granted, there is great competition from urban and industrial water users, even in the water-rich Mid-South and Southeast, but it is the authors' hope that by using the knowledge presented here every drop of water applied to cotton will be used beneficially.



## Section 1:

# Why Irrigate Cotton?

*Hamid Farahani and Daniel Munk*

### Key Points:

- *Properly managed irrigation provides more consistent yield from year to year*
- *Irrigation protects the crop's yield potential – being short an inch of water at the wrong time can easily result in the loss of 75 pounds of seed and 50 pounds of fiber.*

### Benefits of Irrigation

The majority of U.S. cotton (about 65%) is currently produced under non-irrigated conditions. In the South and the Southeast, non-irrigated cotton systems dominate, while in the arid West nearly all of the crop water requirements are met by irrigation water. With rising production costs and the devastating effect of drought on yield, adopting irrigation to supplement rainfall in the humid areas, and improving irrigation water management in the drier areas, is becoming increasingly essential to stay competitive.



*Figure 1.1 – While rainfall usually supplies what cotton needs in the south, there will be years when irrigation will be the reason there is a crop to harvest.*

Irrigation has economic benefits to the producer by increasing yield per unit land area, and benefits to society by providing a consistent and dependable source of food and fiber. Irrigation offers safeguards against poor crop performance and/or failure due to insufficient and/or untimely rainfall. Safeguarding against rainfall uncertainties is highly desirable in today's competitive markets where substantial investment has been committed at cotton planting time. Irrigation also facilitates agro-chemical management through the use of fertigation and chemigation practices.





## **Irrigation Stabilizes and Boosts Yield**

It is estimated that approximately 70% of the world's fresh water consumption is for irrigation (all crops, not just cotton), and for good reasons. Irrigation can boost yield as well as stabilize yield and quality by ensuring adequate soil water during the entire growing season or at least during critical growth stages in areas where water resources are limited. In the sandy Coastal Plain soils in the Southeast, irrigation has been shown to nearly double the non-irrigated cotton yield from about 750 to near 1,200 to 1,500 lbs. of lint per acre during water limited years. These large differences in yield are mainly because irrigation supplements rainfall, ensuring adequate water in the root zone to meet crop water needs on a consistent basis. The lower non-irrigated yields are mostly due to insufficient soil water during the season, even though yearly rainfall in the humid parts of the Cotton Belt is about 45-55 inches, or almost twice as large as the seasonal cotton water use.

## **Removing Risks Associated with Yield Instability**

The problem is that the occurrence of rainfall is random; one never knows if the right amount will come at the right time in the growing season. Consequently, drought periods could occur at any crop growth stage with varying duration and severity. Because of this, non-irrigated yields can vary widely from year to year. The risks associated with yield instability can be partially removed by irrigation, which leads to a more predictable season-ending yield (and thus return) year after year. This is a significant advantage, allowing for financial planning on the part of the producer.

## **Why Plants Need Water**

Generally speaking, soil water escapes the cotton field by a combined evaporation from the soil and transpiration from the cotton leaves. Soil evaporation and crop transpiration are usually lumped together as "evapotranspiration" or ET. The terms evapotranspiration, crop water use, or crop water requirements are basically the same and are used interchangeably. In the transpiration process, water from the soil is lost to the atmosphere through the many pores on the leaves called stomata (plural for stoma). Stoma is a tiny pore in the outer epidermis of a plant leaf that controls the passing of water vapor and other gases into and out of the plant. During daylight hours, plant leaves receive energy from the sun and need to open their stomata to take in carbon dioxide (CO<sub>2</sub>) to grow and metabolize (a process called photosynthesis). When stomata open to take in CO<sub>2</sub>, water in the leaves transpires, or simply evaporates and escapes the plant. Transpiration cools the plant leaves; allowing the photosynthetic apparatus to produce carbohydrates at optimum levels.

## **Seasonal Water Requirements Vary by Climate**

Like all crops, seasonal water requirements or ET for cotton vary by the climate it grows in. The dryer and hotter the climate is, the more water the plant must transpire to keep cool and produce biomass. While climate (i.e., the level of air temperature, humidity, cloudiness or radiation, and wind speed) determines the demand for water (called evaporative demand), soil water dictates



how much water can be supplied to the plant roots to meet the evaporative demand. As soil water decreases, transpiration falls below evaporative demand because the drying soil is unable to transmit water to the roots fast enough to meet the demand at the leaf surface.

### Plant Response to Water Stress

Under limiting soil water conditions, the reduction in transpiration is caused by a highly complex feedback mechanism in the plant that tells the stomata to close and thus limit further water loss from the leaves. As stomata



close, plant temperature rises and the plant undergoes water stress. Stress may not be visible initially, but plant processes begin to slow down as plant temperature goes up. Soon, visible signs of stress become evident, including leaf darkening and loss of leaf turgor. With stomata at partial opening, the process of photosynthesis or biomass production slows due to lack of CO<sub>2</sub> intake by the plant. Simply stated, water stress causes the plant to grow slower and smaller. The higher the severity and duration of the water stress, the higher the loss of biomass production and thus yield. Also, the sensitivity of the plant to water stress changes with growth stages, and is usually highest during rapid canopy development and effective flowering stages. Cotton is an indeterminate perennial shrub that is somewhat tolerant to drought and soil salinity. Because of its drought adaptations, cotton responds favorably to periods of water stress sufficient to slow vegetative growth; a physiological feature that can be benefited by timely irrigation management.

### The Relationship Between Water and Yield

For the Cotton-Belt, cotton ET increases by about two-fold from the humid East to the arid West. For example, cotton in the desert Southwest requires as high as 40 inches of water per season for long season varieties, about 30 inches in Lubbock, Texas, while as low as 18 inches and mostly between 20 and 25 inches in the humid Southeast (for details, see Section 4: “Cotton Water Requirements”). In the Southeast, the probability of receiving 20 to 25 inches of rainfall evenly distributed during the four-month cotton growing season is quite low, meaning non-irrigated cotton yields rarely achieve their full potential due to inadequate soil water. For example, on average, cotton’s peak daily water use is about 0.25 to 0.3 inch, or about 2 inches per week, during summer near Columbia, South Carolina. The probability of receiving 2 inches of rainfall weekly during August in Columbia is only 30%, implying not only production uncertainty and risk, but also suggesting lost yield potential under non-irrigated farming. While water requirements are higher in the West, so are yields.



## Water Use Efficiency

A useful relationship between yield produced per unit ET or crop water used is water use efficiency (WUE). Modern, high water use efficiency (WUE) cotton varieties tend to provide at least 60 pounds of lint and 90 pounds of seed for every inch of water used. On a global basis, a recent summary of the past 25 years of cotton data (that included some data from the Cotton Belt) lists average WUE

for seed cotton (fiber plus the seed) as 147 pounds per acre-inch or, just considering the fiber, 52 pounds of fiber per acre-inch. On a smaller scale and based on a limited study in south Georgia, the addition of 4 to 6 inches of supplemental irrigation above the seasonal rainfall increased lint yield by 250 to 620 lbs., suggesting 60 to 100 lbs. of lint per inch of irrigation above rainfall.

## Increasing Water Use Efficiency

Generally, water use efficiency (WUE) is computed either as yield (lbs. per acre) per seasonal crop water use (or ET) or as yield per total applied water (seasonal irrigation plus rainfall). The former is more of a biological indicator (basically describes biomass production per transpiration) and there is limited control on the part of the irrigator to alter this efficiency. Since ET is soil evaporation plus crop transpiration, biological WUE can be increased by reducing soil evaporation and increasing crop transpiration. Conservation tillage (i.e., no-till) leaves substantial residue on the surface, which reduces soil evaporation (E) and consequently increases transpiration (T) and thus yield per unit of water input. The latter water use efficiency of yield per unit of applied water is largely influenced by the performance of the irrigation system and the degree of water losses beyond crop transpiration. Irrigators should strive to increase yield per total water applied by employing efficient irrigation water management practices that reduce losses due to deep leaching and runoff, and by improving irrigation system efficiency and application uniformity through system upgrade.

## Boosting Yield and Reducing Costs

Irrigating cotton with the correct amount at the right time can boost yield and reduce input costs. This requires a firm understanding of the critical cotton growth stages and water use. The use of high WUE varieties also helps with securing greater crop per applied water. Increasing WUE and drought tolerance in cotton is highly valuable to U.S. and world agriculture by helping growers to maintain or increase crop production with less water. Currently, traditional crop breeding and advanced gene technology methods are being used by the seed industry to develop cotton varieties with higher WUE and drought tolerance.



## Optimizing the Use of All Crop Inputs

Competition for limited water resources is one of the most critical issues being faced by irrigated agriculture in the United States. Even in the humid Southeast, water consumption in agriculture is quickly becoming a concern, caused by increased demand due to population growth, water quality degradation, and higher frequency and duration of drought. There is no new water and the existing water supply, limited by physical, ecological, and economic constraints, must be managed wisely and more efficiently via conservation, reuse, and increased water use efficiency to meet the increasing demand. This entails reducing over – and untimely-watering and improving system efficiency and application uniformity. Efficient and wise use of irrigation water is essential to remain competitive and maintain profitability and environmental sustainability.

## Getting the “Most Crop Per Drop”

Irrigation delivery methods continue to be refined to make sure producers get the “most crop per drop.” Within the last few years, new technology has also become available that allows individual sections of an irrigated field to be turned on or off. This leads to more water savings. If there is a portion of the field that does not need irrigation (for example, a low spot where rainfall collects) the pivot is programmed to turn off the sprinklers over that area. In spite of all the advances, over – and untimely-irrigation is widespread. In many instances, over-irrigation is used as a management strategy to guard against risks associated with inadequate water management plans. But over-irrigation is also a major contributor to excess leaching of water, nutrients and crop protection chemicals. This is not only costly to the farmer but could also lead to adverse environmental effects. Efficient irrigation starts with a sound irrigation water management, or scheduling. While only about 35% of the cotton acreage in the U.S. is irrigated, for those acres that are irrigated, we must practice wise use of water and ensure that in water-limited regions we get the “most crop per drop,” or simply increased “water productivity.” In areas with abundant rainfall, proper use of supplemental irrigation is needed to reduce waste, avoid under-watering, and ensure “most crop per unit of land,” or simply increased “land productivity.”





## Section 2:

# Why Schedule Irrigation?

*Daniel Munk and Hamid Farahani*

### Key Points:

- *Investments in irrigation scheduling will optimize water use and yield.*
- *Over-application of water wastes energy – about a gallon of diesel is required for every acre-inch of water applied per 100 feet of lift.*

Making informed irrigation management decisions is an essential part of good cotton management practices and often plays a vital role in optimizing productivity and profitability. Improper irrigation scheduling translates to wasting or underutilizing water resources through under – or over-irrigation and more precise irrigation practices involve applying the proper amount of water at the right time. In most years, supplementing rainfall with timely irrigation events will not only assist in supplying water for crop evapotranspiration needs, but also has the role of regulating plant growth, influencing weed and insect pest pressures and can reduce the incidence of disease. Successful growers agree that even in regions where rainfall provides most of the crop water needs during the season, developing a sound irrigation management approach is economical and increases overall resource use efficiency.

### The Risk of Too Much Water

When irrigation water is readily available, there is a tendency for some to over-irrigate cotton to its detriment, thereby reducing the opportunity to maximize profit. While frequent irrigation results in low plant water stress levels and rapid canopy expansion, too much of a good thing can result. Allowing some level of water stress between irrigation or rainfall events is beneficial for cotton and allows the plant to moderate its vegetative growth. Without periodic water stress events during the boll set period, most cotton varieties have the tendency to grow rapidly, thereby shading lower branches that are important in providing photosynthates to nearby bolls. Too much shading too early can compromise lower boll retention and delay crop maturity.





## Proper Irrigation Methods

Over-application of irrigation water on cotton also impacts farm resource utilization by reducing energy and nutrient efficiencies. Applying water that is not required for beneficial use increases pumping costs and creates conditions that can lead to nutrient leaching below the root zone. Figure 2.2 illustrates the relationship between pumping depth and energy requirements to apply an acre-inch of water. Note that approximately one gallon of diesel is needed for every 100 feet that water is raised. The deep percolation of water is responsible for carrying nutrients from the site, potentially contaminating adjacent ground and surface waters. Nitrate nitrogen is often the most common mobile constituent in these leachates; however, other nutrients such as phosphate as well as some pesticides can percolate into the local water table when sound irrigation management methods are ignored.

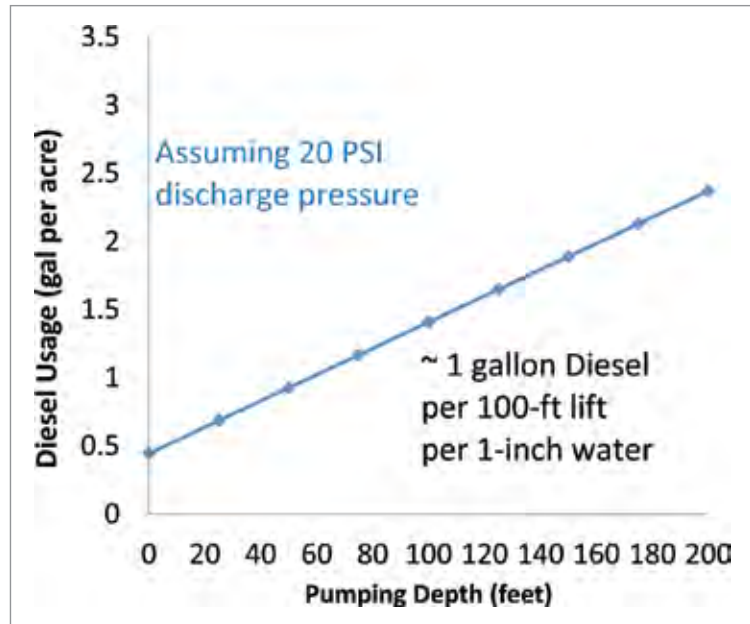


Figure 2.2 – Gallons of Diesel to apply 1 inch of water to one acre

Applying too much water can result in cutting off the root's supply of air that is important for maintaining proper root function. Particularly in areas where confining layers limit downward movement of water or in high clay content soils, anoxic conditions can develop in a relatively short amount of time, limiting cotton's ability to absorb nutrients and water properly. This condition manifests by limiting the optimal expansion of roots by the plant, suppresses optimal nutrient balance and can result in chlorotic plants that have yield limitations.

## Plant Available Water – Staying in the Sweet Spot of Soil Moisture Levels

Central in the practice of irrigation scheduling is the concept of plant available water. Following a significant irrigation or rainfall event, water saturates soil pores and within a day or two drains as a result of gravitational forces taking drainage water deeper into the ground, leaving the soil in a state of high water status or high water potential. Like a fully wet sponge, the soil contains a large amount of water that is readily available to the plant. This water is held by soil colloids and, no longer responding to gravitational forces, is said to be at field capacity and is unique to each soil. In this highly available state, cotton roots are in full contact with soil water and uptake occurs with great ease allowing the plant the capacity to readily take up water, fulfilling the full atmospheric demand for water through evapotranspiration (ET). Because of the ease with which water uptake occurs, the plant's water conducting tissues are also in good water status or high water potential, and plant tissues responsible for growth allow the plant to grow at a high rate.

## Results of Water Loss

However, as readily available water is extracted from the soil, soil water retention forces increase (tension) and the plant root, as well as above ground plant tissues, find it more difficult to transport water and match the rate at which ET proceeds. Under these conditions, both soil and plant water status (potentials) are decreased and eventually get to the point at which plant growth rates are reduced. As the continued extraction of soil water takes place, indicators of water stress increasingly begin to take form. More significant declines in plant growth rate occur, as well as rates of evapotranspiration as plant stomata begin to close and protect the plant from more serious heat stress. If there is a continuation of water loss from the soil and plant without replenishment, the plant ultimately reaches its permanent wilting point and dies. Figure 2.3 illustrates the relationship between soil moisture content and soil moisture tensions for two soil types. Studies have found cotton is nearing soil moisture stress when tension exceeds 30 to 50 centibars in the root zone depending on soil type.

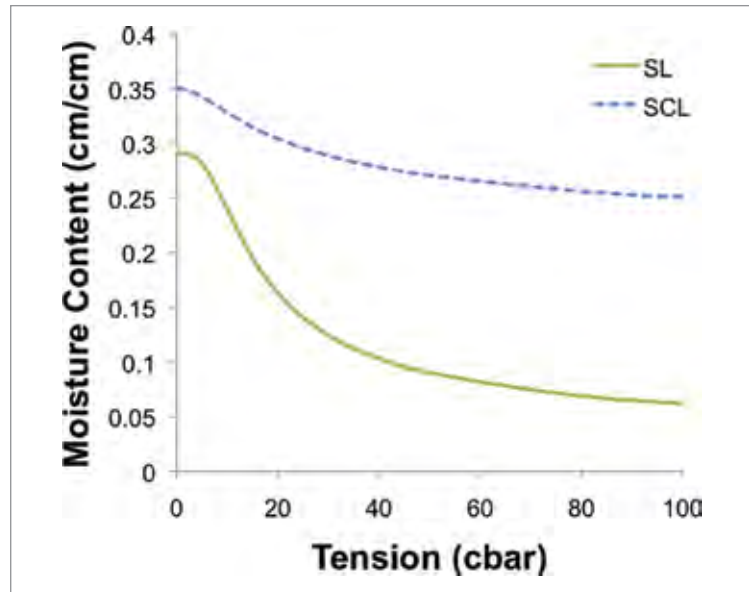


Figure 2.3 – Soil moisture release curves for sandy clay loam (SCL) and sandy loam (SL) soil types.

## Estimating the Soil's Ability to Provide Water

In practice this condition would never be allowed; however, by estimating these quantities, total plant available water can be established as the difference between the water content held at field capacity and the water content of the soil at permanent wilting point. Once we define or approximate plant available water for a given soil or field, we can now better estimate the individual soil's ability to provide water to the crop and better plan the timing of irrigation events. There is also a relationship between plant available water and plant water stress and, once understood, will go far to assist the grower in properly establishing the scheduling of irrigation events.

## Signs of Water Stress (What Scheduling Should Allow You to Avoid)

Even in regions where spring and summer rainfall is considerable, the cotton plant can experience water stress to the point where productivity and quality are reduced. This is especially true during extended periods of drought and in soils that have limited plant available water. Although the soil acts as an ideal medium to store water and nutrients, the amount of plant available soil water is reduced daily following a rainfall or irrigation event. As the duration of water deficit increases, so too



*Figure 2.4 – Do not let wilted leaves be the sign you need to irrigate – yield has been lost at that point.*

does the intensity of the stress and the eventual need for irrigation. Water stress can build to the point where physical and physiological changes can influence crop performance.

Indicators of heightened water stress levels in cotton include the reduced size of newly formed leaves, shortened main stem internodes, reddening of the leaf petioles and the reduced growth rate of the entire plant. And while cotton often benefits from some level of growth-limiting stress, more severe water deficits can depress the yield and quality expectations. As cotton water stress levels are elevated, more severe reductions in vegetative growth occur and the leaf stomata begin to close. Photosynthesis slows, ultimately leading to significant reductions in amount and type of carbohydrates produced by the plant. Particularly during the early and middle boll set periods, more severe water stress depresses fiber quality primarily by reducing the length and strength of cotton fiber and can simultaneously lower seed cotton yield.

## **Targeted Irrigation Scheduling**

Research studies have consistently shown that in humid regions, irrigation can dramatically increase cotton yields, in some cases doubling yield and improving overall quality depending on the extent and duration of the water deficit. Targeted irrigation scheduling allows the cotton producer to more precisely manage the plant by controlling the amount and duration of the water stress that, in turn, impact overall crop performance. Proper scheduling of water recognizes that climate and soil water availability primarily determine the rate at which water stress accumulates in cotton. Understanding how these two interact to affect crop water status is key to good water management practices.

Irrigation scheduling is the science of determining when to irrigate, how much to apply, where to apply, and for what purpose. The purpose may be to maximize land productivity (yield per unit land),





water productivity (yield per unit water used), net profit, and/or quality and marketability. Different scheduling strategies are usually needed depending on the producer goals in mind. For instance, achieving maximum yield via maximum irrigation may not necessarily lead to the highest water productivity or net profit. In fact, research in the dry environments shows that the highest crop water productivity may coincide with irrigation amounts at levels below the full crop water requirements.

When water availability is limited, the traditional practice of maximum irrigation for maximum land productivity may no longer be wise. In such conditions, irrigation must be optimized, and may prove more profitable, by attempts to get the most crop per drop rather than the most crop per unit land. This may require practices such as deficit irrigation on all the land rather than full irrigation on part of the land.

### **The Art and Science of Irrigation Scheduling**

The primary goal of irrigation is to ensure that sufficiently high crop water use rates are sustained during the season that allow non-limiting soil water conditions for optimum plant growth and development. However, establishing sound irrigation practices also provides that ample stress will build between irrigation events that keeps vegetative growth manageable and in line with the field and variety management strategy. Managed stress also promotes late season boll maturation, boll opening and improved defoliation. That strategy includes incorporating the knowledge of cultivar performance, plant growth regulator approach, and how the soil retains water and nutrients, keeping in mind that these strategies can change during the season depending on climate, pest and nutrient conditions. Given these complexities that influence irrigation management decisions, it is no wonder that many successful growers regard irrigation scheduling as both an art and a science.

## Section 3:

# Initiating and Terminating Irrigation for the Season

*Earl Vories and Ed Barnes*

### Key Points:

- *Early irrigation can improve stand establishment.*
- *Delaying the first irrigation can be costly.*
- *Ending the irrigation season too early can reduce yield, but extending it too long can increase pest management cost and delay harvest.*

### When to Initiate the First Irrigation

Historically, cotton irrigation research started in the arid west where the question about when to start irrigating was never asked, as cotton did not start to grow until water was applied. In the Mid-South and Southeast, there is often residual soil moisture to get the crop started. In general, producers prefer to delay irrigation as long as possible so all of the early season field operations can be completed such as weed control and nitrogen side dressing. This is particularly true in furrow-irrigated fields relying on pipes to deliver the water to the furrow. Also, there is the perception among many farmers that early season moisture stress encourages root development, and while true in some cases (see primed acclimation in Section 5: “Most Water-Sensitive Cotton Growth Stages”), too much stress can limit yield potential.



*Figure 3.1 – There is no doubt that putting out poly pipe early in the season creates problems accessing the field, but there are years where significant yield loss will occur if delayed.*



## **Irrigation Near the Time of Emergence**

Poor moisture conditions near the time of emergence can result in poor and spotty stands. This may result in the need to replant or create management problems for the rest of the season as sporadic stands can result in: a) increased weed pressure; b) inconsistent crop height; and c) differences in crop maturity making termination decisions difficult. Therefore, if soil moisture limitations threaten a good stand, irrigate. Note that water use is very low at this point in the crop's development, so a large volume of water is not needed. This may make application with a furrow or flood system impractical.

In the first 30 days after emergence, cotton water demands are low and this is one of the least water-sensitive time periods for the crop; however, the crop is much more sensitive to water stress after this point (see Sections 4 & 5). This sensitivity and its economic impact of delaying early season irrigation was captured in studies in the Mid-South where a full-season, well-watered control was compared to two treatments: 1) the first irrigation was skipped and irrigation began when the well-watered control received its second irrigation; and 2) the first two irrigation events were skipped and irrigation initiated where the third irrigation was applied to the well-watered control. The average results over three years showed a consistent trend for lower yield for each delay in the first irrigation. And when the costs of irrigation were considered, delaying irrigation also led to lower net revenues. Therefore, following irrigation recommendations based on field sensors (Section 6) or scheduling programs (Section 7) is important.

## **When to Apply the Last Irrigation**

The perennial nature of cotton makes it difficult to make end-of-season decisions about when to stop applying water. Stop too soon and there is a risk the final fruit set will not fill out and yield loss will occur. On the other hand, applying irrigation too late can result in delayed harvest, increased pest management cost, and no yield increase, not to mention the costs of the irrigation itself. The COTMAN program has proven useful for making end-of-season decisions, and a study was carried out in the Mid-South to see if the COTMAN approach could be applied to irrigation termination. In that study, a clear relationship between time after five nodes above white flow (NAWF5) and time of the last irrigation could only be established for fields north of 34° N latitude. In those fields it was determined that an irrigation applied after 18 days past NAWF5 would not increase yield enough to be profitable.



## Section 4:

# Cotton Water Requirements

*Ken Fisher and Theophilus Udeigwe*

### Key Points:

- *Water requirements for cotton vary during the season.*
- *At mid-season, cotton water demands are the highest – about 0.28 inch per day.*

### Evapotranspiration

In the humid Mid-South U.S., cotton irrigation is a challenge because of the variations in rainfall, temperature, and cloudiness during the growing season. Cotton crop characteristics, as well as the prevailing environmental conditions, are critical in determining cotton water use. Its use increases gradually from the initial stage (dominated by water loss from evaporative surfaces) to developmental stage, and finally peaking at the mid-season stage. This peak water-use stage coincides with a stage of full canopy and maximum boll load of the cotton plant which is normally in August (a month typically characterized by high air temperature and solar radiation) in the Mid-South U.S.

Cotton uses water throughout its lifecycle through the combined processes of evaporation and transpiration, often referred to as evapotranspiration (ET). Water use, or ET, includes the amount of water transpired by the growing plant and evaporated from the soil in which it grows. ET is therefore a function of weather variables (mainly solar radiation, wind, air temperature, and humidity), as well as soil characteristics, crop characteristics, and cultural practices.



Reference evapotranspiration ( $ET_o$ ) is the combined processes of evaporation and transpiration measured over a reference surface (typically a grass surface). Crop evapotranspiration ( $ET_c$ ) represents the amount of water lost through the process of evaporation (from soil surface) and transpiration (from plant tissues) from a crop, grown in a large field, under a given climatic condition. The amount of water used to balance this loss is often referred to as the crop water use.  $ET_c$  is estimated by first calculating reference  $ET_o$ , which quantifies the evaporative demand of the



environment.  $ET_0$  is then adjusted by a crop-specific crop coefficient function,  $K_c$ , which accounts for specific crop and growth-stage conditions. As the crop changes throughout the growing season, the crop coefficient adjusts to account for differences in plant growth and water use.

## Measuring Evapotranspiration

The best way to measure  $ET_c$  when determining a crop coefficient is with a lysimeter that measures the weight of water loss or gain during the day (Figure 4.1). The variability among environmental and cultural factors across regions requires the determination of local  $ET_0$ ,  $ET_c$ , and crop coefficients,  $K_c$  for a given crop for irrigation scheduling.



Figure 4.1 – Cotton growing in a weighing lysimeter in Northeast Louisiana.

## Water Use

Typical cotton water use at important stages (initial, developmental and mid-season) of a cotton plant is presented in Table 4.1. Data were collected from a cotton planted with Stoneville 5458 B2RF grown on a Sharkey clay soil in Northeast Louisiana. At the initial stage of the crop (approximately 0-25 days past planting), daily crop water use ( $ET_c$ ) ranged from 0.03 – 0.20 inch/day with an average of 0.09 inch/day or 0.63 inch/week. Average water use was 0.22 inch/day (approximately 1.5 inch/week) at the crop developmental stage and 0.28 inch/day (approximately 2.0 inches/week) at midseason. The corresponding average  $K_c$  values are 0.48, 1.02 and 1.44 for initial, developmental and midseason stages, respectively (Table 4.1).

<b>Cotton Growth Stage</b>	<b>Length of Stage (days)<sup>b</sup></b>	<b>Daily <math>ET_c</math> (inch)</b>	<b>Avg. Daily <math>ET_c</math> (inch)</b>	<b>Avg. <math>K_c</math></b>
Initial	25	0.03 – 0.20	0.09	0.48
Crop Developmental	35	0.09 – 0.36	0.22	1.02
Midseason	50	0.18 – 0.44	0.30	1.44

<sup>b</sup> Days are approximate

Table 4.1: Cotton growth stages and corresponding daily  $ET_c$  and  $K_c$  values



Crop water use in Stoneville, Mississippi was similar but the  $K_c$  values there were lower. Water use ranged from about 0.05 inch/day early in the season to a peak of 0.28 inch/day, and then decreased after boll opening to 0.12 inch/day. Crop coefficient values ranged from 0.4 during the initial period to 1.2 during midseason, and then decreased to 0.6 at the end of the season. Average daily water use and crop coefficient functions are shown in Figure 4.2.

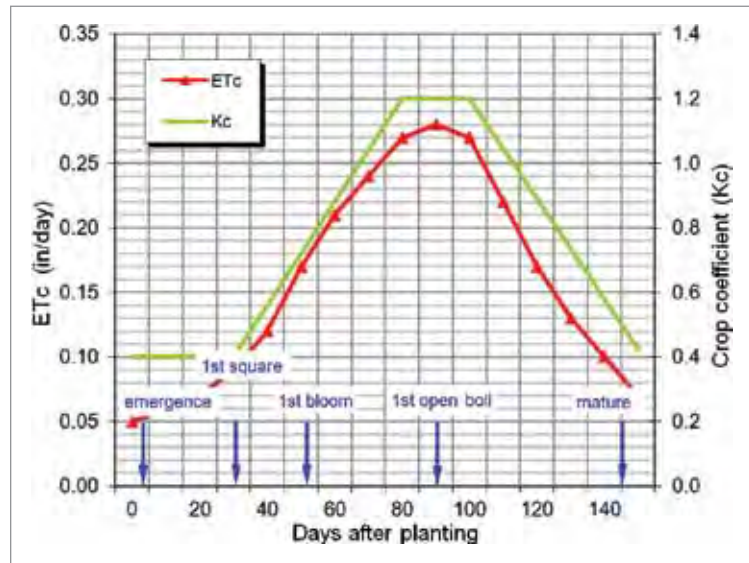


Figure 4.2 – Water use and crop coefficient function for cotton in Stoneville, Mississippi.

## Water Use and Crop Coefficients

A typical 24-hour variation in the mass of a weighing lysimeter planted with cotton crop in Louisiana is illustrated in Figure 4.3. Figure 4.4 represents a water use (crop evapotranspiration) curve showing the seasonal water use characteristics of cotton at essential growth stages. Daily water use is expressed as a function of days past planting. Water use was observed to increase steadily from planting to first open boll and tended to decline slightly afterward. This suggests the need of maintaining well-watered field conditions until the first open boll. At about 60% boll opening, water use tends to substantially decline (Figure 4.3).

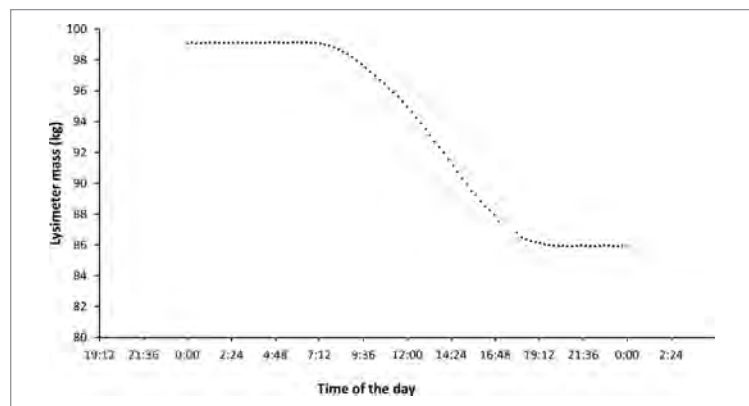


Figure 4.3: A typical 24-hour changes in the mass of a weighing lysimeter planted with cotton in Northeast Louisiana.

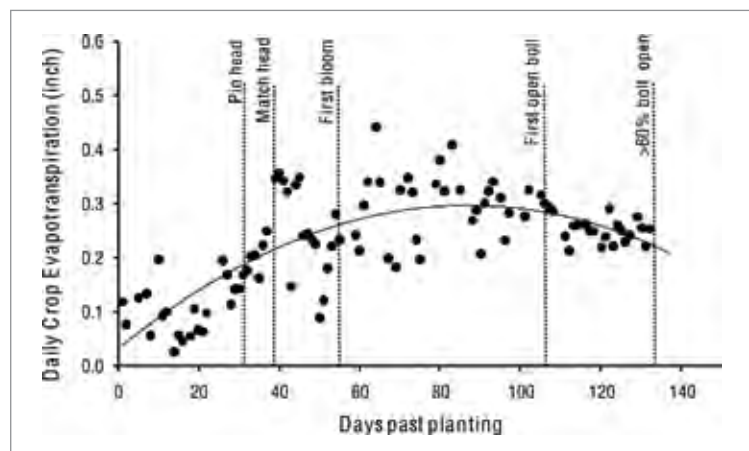


Figure 4.4 – Measured crop water use ( $ET_c$ ) from a cotton field in Louisiana over the growing season.



## Section 5:

# Water-Sensitivity of Cotton Growth Stages

*Phil Bauer, Wilson Faircloth, Diane Rowland, Glen Ritchie*

### Key Points:

- *The sensitivity of cotton to water stress varies by growth stage.*
- *First square to first bloom is a critical time for avoiding severe water-deficit stress.*
- *It is also important at planting to establish a good plant stand.*



All irrigations during a season are not equal in terms of providing economic return on the money spent to irrigate. This section provides a brief description of the effect of water stress on cotton during the different growth stages of the plant and the relative benefit of irrigating to relieve stress.

Irrigation alleviates the detrimental impact of soil water deficit stress on two diverse physiological processes in plants that occur when they cannot get enough water. The most sensitive physiological process in plants to water deficit stress is cell growth. From root tips expanding through the soil to fibers elongating on seedcoats, the ability of individual cells within a plant to expand is largely determined by the availability of soil water. Along with reducing growth, soil water deficit stress triggers hormonal changes in reproductive growth that results in the shedding of fruiting structures (squares and bolls). Irrigation management should be aimed at reducing stress at critical times so the plants are provided the greatest ability to initiate, retain, and mature bolls.

### Planting to Emergence

*Water use by cotton – low.* Water is critical for germination and irrigating at this stage is primarily for stand establishment. If the seedbed is dry and irrigation is needed to establish a stand, it is preferable to irrigate before planting. Pre-irrigation reduces the possibility of seedling disease compared to irrigating shortly after planting. In addition, irrigating after planting will cool the soil and may reduce seedling



growth rates. Once the seeds germinate, sufficient moisture must be in close proximity of the seedling until sufficient roots are developed to increase the area of water uptake. Establishment of the root system is quite fast, with taproots growing up to 2.4 inches per day after they emerge from the seed.

## Emergence to First Square

*Water use by cotton – from <0.1 to 0.1 inches of water per day.*

Early season water deficit after stand establishment is often not an issue if there is adequate water for emergence and early seedling development. Water demand at this time is low and young cotton plants partition significant resources to the roots. Unless soil water deficit is extremely severe, irrigation at this time contributes relatively little to yield.

In fact, a mild water deficit early in the season can stimulate root production, especially encouraging deeper root systems. Primed Acclimation (PA) is an irrigation concept that uses intentional mild drought stress during early vegetative development to induce physiological changes in the plant that make it more drought tolerant during mid-season, when detrimental effects of water stress are maximal. As the name implies, a time of mild, controlled water deficit acclimates plants to water scarce conditions; thereby beginning (or priming) a cascade of plant responses that increases water-use efficiency. Some of these changes include increased root growth, decreased water-use, changes in fruiting patterns,

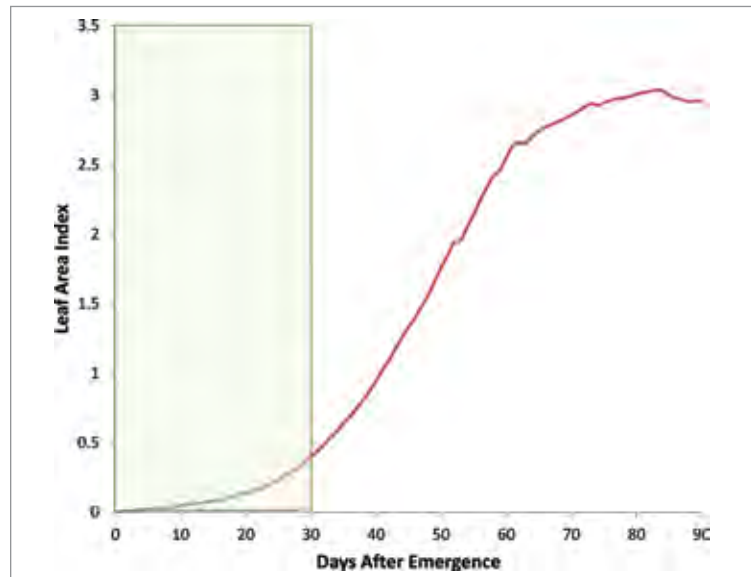


Figure 5.1 – Leaf area index (a measure of number of leaves present / plant size) versus days after emergence. Prior to first square, water stress typically has little impact on cotton yield or fiber quality.

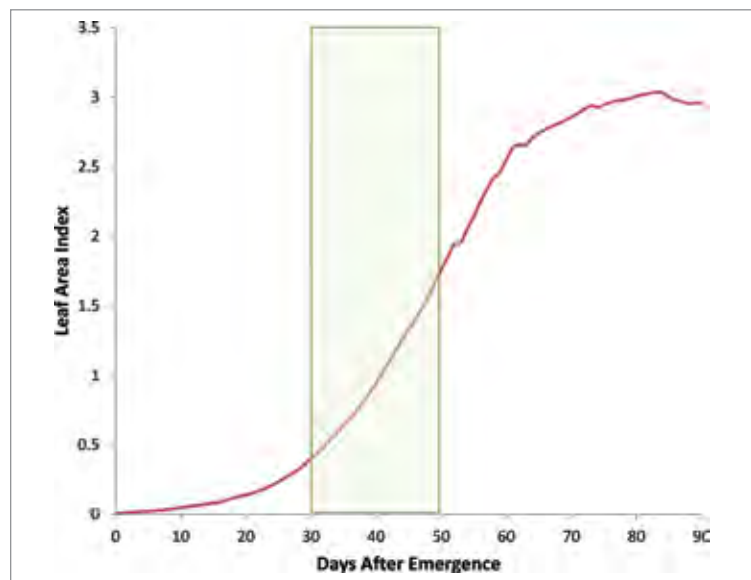


Figure 5.2 – Water stress during first square to first bloom can reduce the total number of potential fruiting sites for the season.





and elicited molecular/enzymatic responses. PA can maintain yield with significant water reduction. For cotton, the PA period lasts about 35 days, starting at full stand establishment (~14 days after planting) to late squaring/first bloom. During this time period, water may be reduced by as much as 30% with no yield loss in some southern production regions. An additional benefit to properly applied PA is a reduction in plant growth regulator needed later in the growing season and a more uniform maturity.

Note that figures 5.1 to 5.4 illustrate the general time period the growth stages occur relative to the number of days after emergence. The red line in the charts represents the leaf area index – a measure of how many leaves are present on the plant. For most cotton planted on 38 to 40 inch row spacing, the gaps between plant rows usually closes as the leaf area index approaches 3.

## First Square to First Flower

*Water use by cotton – increases from 0.1 to 0.2 inches of water per day as plants grow.* The approximate 21 days from first square to first bloom is a critical time for avoiding severe water-deficit stress. During this period, cotton vegetative growth is very rapid and the number of potential fruiting sites for the crop is determined, especially in short season environments. This is also the period when plants are most rapidly taking up phosphorus and potassium from the soil because of rapid root growth. There is evidence from field-based imaging and measurements of cotton root systems that the maximum depth of the rooting system can be achieved relatively quickly and often exceeds 36 inches in depth. Maximum depths may be reached within 40 to 60 days after planting. Severe water deficit stress during this period is especially damaging to the cotton crop in short-season environments.

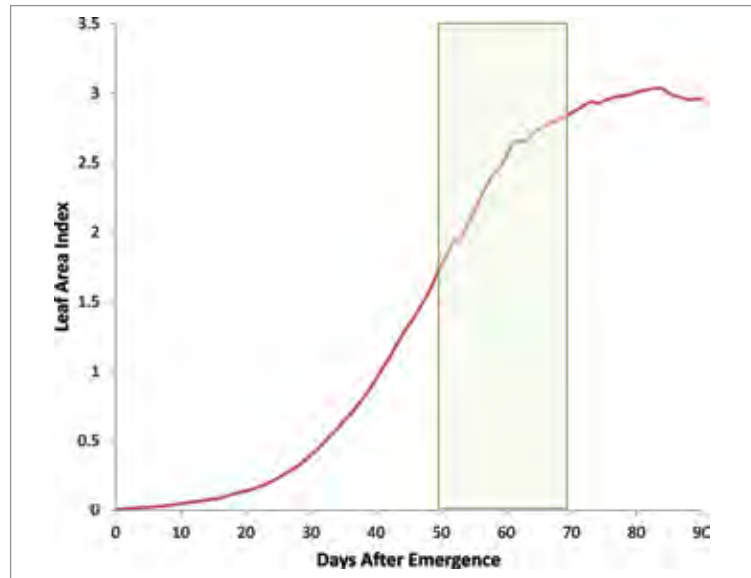


Figure 5.3 – Water stress impacts growth, boll retention, and fiber properties during this time period.

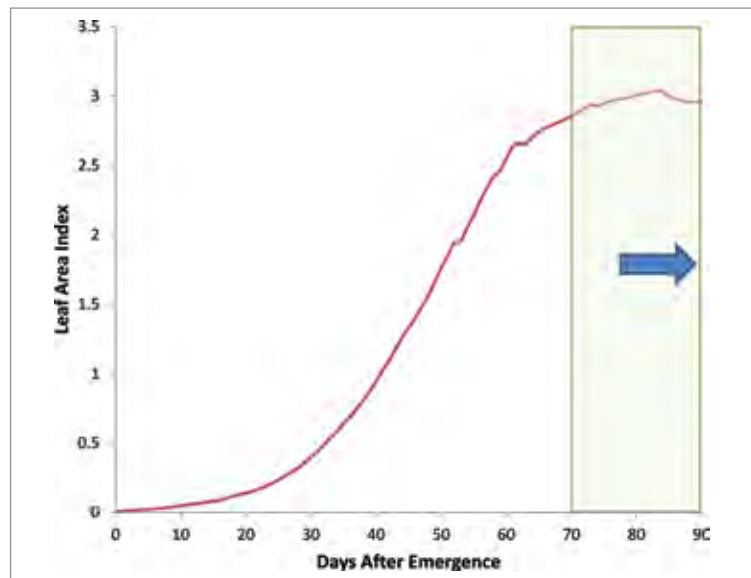


Figure 5.4 – Water stress has less impact than squaring and early bloom after peak bloom has occurred.



### **First Flower to Peak Bloom**

*Water use by cotton – increases from 0.2 to 0.28 inches of water per day as plants grow. Water deficit stress early in this growth stage reduces plant growth which reduces the number of fruiting sites that are initiated. In addition, severe water deficit stress can also reduce boll number through shedding of young bolls and results in substantial yield loss. During early bloom, squares are generally not lost due to water deficit stress, so if square shedding is observed, other causes should be investigated. Water deficit stress at this time also impacts yield by reducing the size of surviving bolls. Severe stress reduces fiber quality through shorter staple and higher micronaire. At this growth stage, maximum rooting depth is achieved but lateral roots continue to grow throughout the rooting profile so that the final size of the root system may not be reached until 90 days after planting.*

### **Peak Bloom to Open Bolls**

*Water use by cotton – decreases from 0.28 inches of water per day as plants age. Water deficit stress during this growth stage is less critical than during squaring and early flowering. Water stress during this period can result in square and young boll shedding. However, these losses of late fruit have less impact on yield than loss of early season bolls. Fiber quality parameters affected by stress at this time are fiber length and micronaire, particularly in the young bolls.*

After bolls start opening, plants should be allowed to become water stressed to allow for better harvest conditions. Stress at this time hastens boll opening, makes defoliation easier, and reduces regrowth.

## Section 6:

# Sensor-Based Scheduling

Brian Lieb and Ken Fisher

### Key Points:

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

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

### Types of Measurements

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

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



Figure 6.1 – A tensiometer installed in a cotton row.

2. *Volumetric moisture content* is a measure of the volume of water per volume of soil. There are several types of sensors that measure this property including capacitance sensors, time domain reflectometry (TDR) sensors, and neutron probes.
3. *Canopy temperature* is a measure of the temperature of the surface temperature of the leaves. Transpiration cools the leaves; and, as water stress increases, transpiration decreases, so the canopy becomes warmer. Canopy temperature can be measured by carefully placing thermocouples directly on the leaves, but it is most commonly measured with an infrared thermometer (Figure 6.2).

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



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

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

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

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

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

## Types of Sensors

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



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



## Costs and Methods of Obtaining Soil Water Data

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

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

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

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



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

### **Decision Factors**

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

### **Cost Factors**

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

### **Locating Sensors**

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

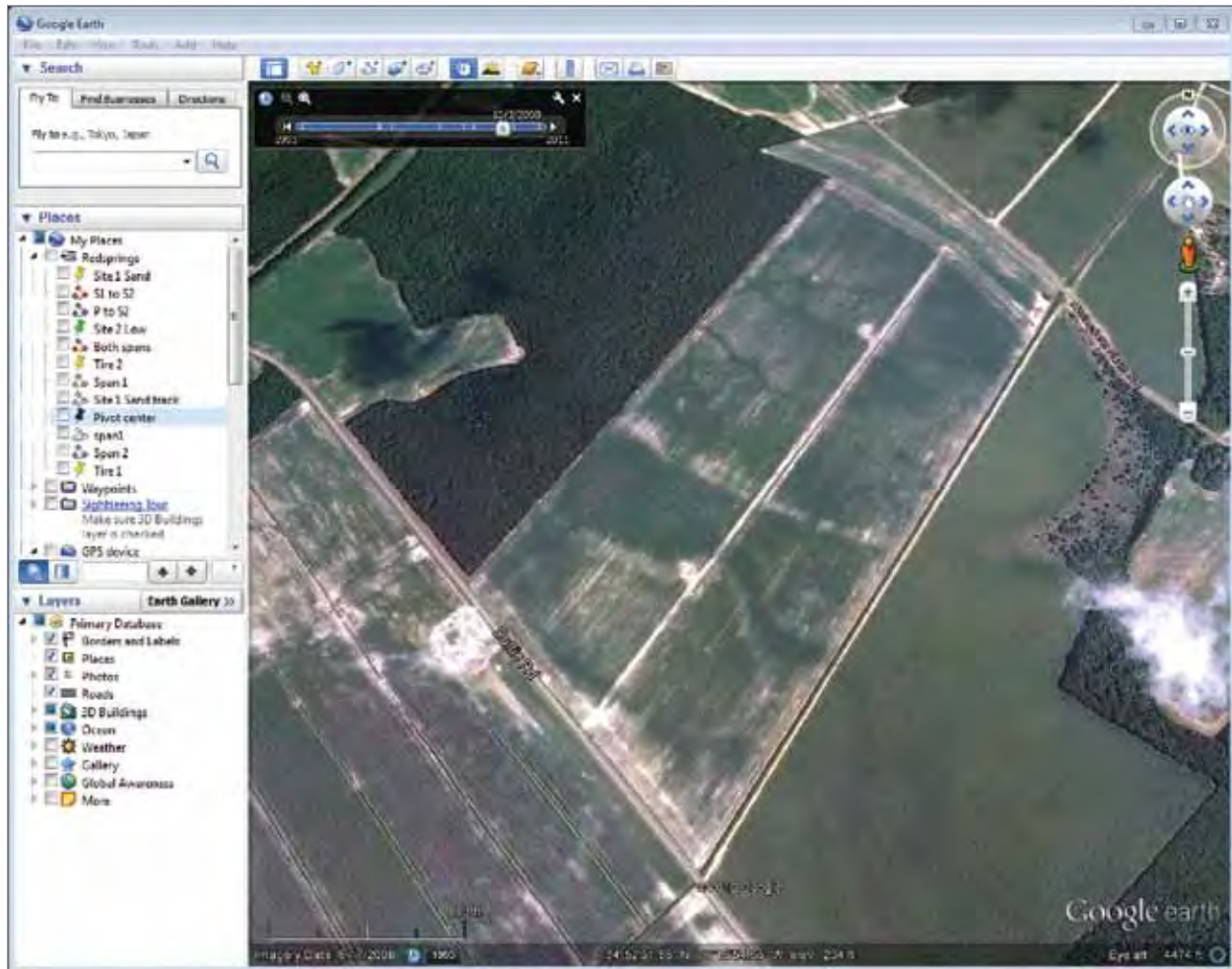


Figure 6.3 – Use of aerial images that are often freely available from programs like Google Earth, pictured above, can be useful to identify inclusions of different soil types that should be avoided for sensor placement.

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

## Irrigation Scheduling

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





## Types of Irrigation Systems

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

## Access to Sensors

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

## Sensor Installation

As alluded to in the sensor type section, most sensors need to be installed with good soil contact with the exception of the neutron, where research has shown that small air gaps do not affect the probe's performance. Sensor configuration also affects the means of installation. Sensors that have a cylindrical shape are normally installed with small augers (1 to 2 inches) and create good soil contact by means of a soil slurry or a force-fit into a slightly undersized auger hole. A slurry is created by mixing soil from the auger hole with water to create a thick but flowable mixture. The soil can be first screened to remove stones and soil clods and a paint mixer on a battery-operated drill can also aid in creating a smooth slurry. Some sands will not create a good slurry, but this is not a problem because water can be poured down the bore hole, causing the sand to fill in around the sensor and then quickly drain away. In the force-fit method, some type of hammer and sensor

protector may be required or a soil penetration probe on a soil sledge may be used to create a small tight-fitting hole at the bottom of a larger auger hole. Force-fitting preserves the appropriate soil layers next to the sensors but can compact the soil structure while slurries can mix soil layers and crack when dried. Sensors that do not have a cylindrical shape require excavation or larger augers. Once excavated to the desired depth, sensors either have soil hand-packed around them or are inserted into the side wall/bottom of the hole. In this scenario, sensor depth can be limited to about two feet, depending on the length of your arms. Installation help is often available from the service provider when high-cost sensor systems are used. Sometimes government agencies and education institutions will assist in installing lower cost sensor systems.

## Compatibility with Field Operations

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



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



## Connecting Wireless Systems

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

## Interpreting Sensor Results

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

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

## Accuracy of Sensor Readings

Absolute accuracy of water content from soil sensors is difficult to obtain. It requires a regression analysis between gravimetric samples and sensor readings taken directly from a field, and this procedure may need to be repeated over time to obtain an adequate range of soil moisture. This calibration then has to be linked to important soil conditions in the field such as field capacity, allowable depletion and wilting point. This degree of accuracy can be a selling point for a service

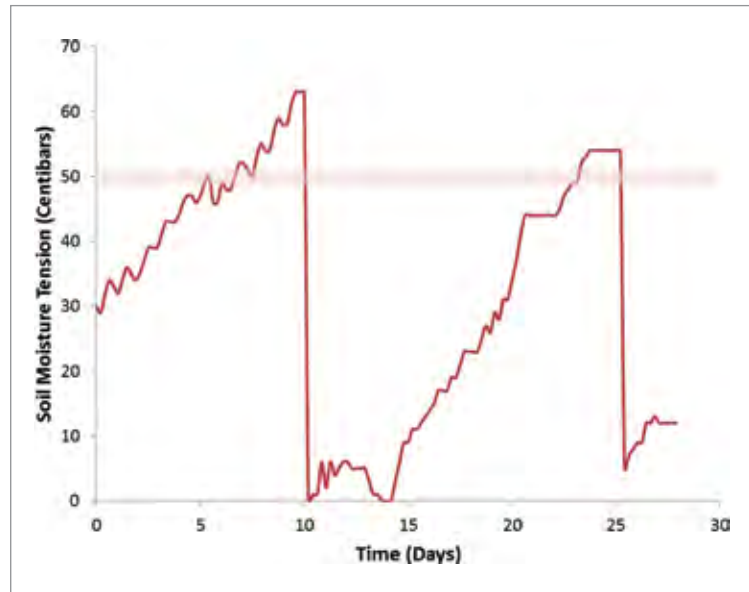
provider but will usually not be attempted by a producer. Relative accuracy is a better goal for many producers. For instance, capacitance probes (measure of dielectric constant) will change calibration each time they are installed (even in the same field at nearly the same location) because the background dielectric constant changes with each installation. Therefore, field capacity is usually determined as the point where rapid drainage from application of slurry or a large wetting event stops. Then a manufacturer's calibration for the soil type should be applied to estimate wilting point and allowable depletion. Even though soil water content is not perfectly accurate, estimates of the amount of water that can be removed or added to the soil can still be made. Of course, sensors can be used as markers where the actual numbers have little meaning. Through experience, an upper and lower level can be established and the goal of irrigation is to stay between these two lines.

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

## Retrospective Use of Sensors

*Ken Fisher*

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



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



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

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

### **Using Post-Season Soil-Water Data**

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

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



## Section 7:

# Irrigation Scheduling Tools

### Key Points:

- *Many states have free scheduling tools.*
- *Often these tools are linked to live weather data.*

There are many freely available irrigation scheduling tools that predict when to irrigate based on weather and crop conditions.

The weather data is used to calculate an amount of water that would be evaporated by a reference crop such as grass, and then a crop coefficient is used to scale that reference value to a specific crop. Crop coefficients for western conditions have been obtained from lysimeters in Arizona and Texas. Current studies are using lysimeter studies in Louisiana, Mississippi and South Carolina to determine cotton crop coefficients for more humid conditions. Most of these programs are based on the water balance method described in the next section.

### Water Balance Method

*Gretchen Sassenrath and Amy Schmidt*

Scheduling irrigation using a water balance, or checkbook method, is based on the available water in the soil. Like a checkbook, inputs are credited to the total soil water, and withdrawals are debited from the soil water. The net daily water balance is then:

$$\text{Soil Water (today)} = \text{Soil Water (yesterday)} - \text{withdrawals} + \text{inputs}$$

The inputs to the soil water are rainfall and irrigation. Withdrawals include transpiration through the plant, evaporation from the soil surface, and deep percolation into lower soil layers. During the growing season, evaporation and transpiration, commonly termed “evapotranspiration” and abbreviated “ET,” are the most important processes by which water is removed from the soil (Figure 7.1). Deep percolation accounts for only very minor withdrawals during the growing season, and so is assumed to be negligible.

### Soil Water Content

The water balance equation requires knowledge of the available water in the soil. Determination of subsequent soil water level is dependent on the initial soil water content. Soil water is dependent

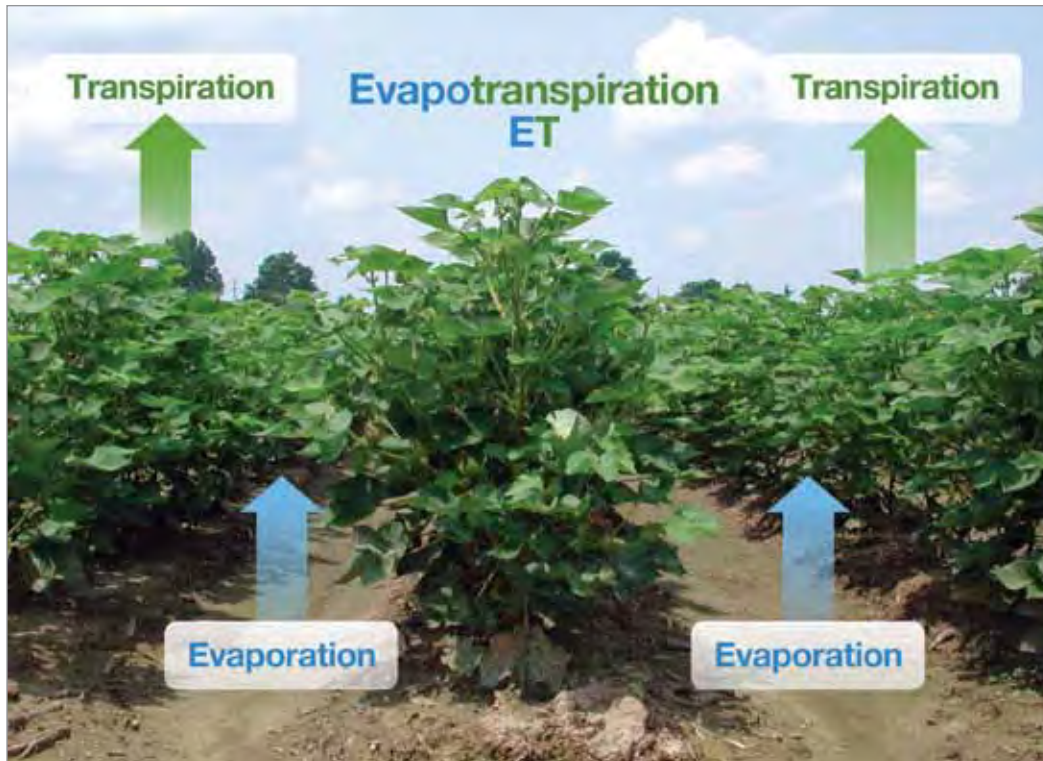


Figure 7.1 – Loss of water from a crop field during the growing season results primarily from evaporation from the soil surface, and transpiration through the plant leaves. These processes are termed “evapotranspiration” and commonly abbreviated “ET.”

on the texture of the soil. Sandy soil has larger particles and pores that hold the water less tightly, reducing the soil available to plants. Conversely, clay soils have many, very small pores. The clay particles bind the soil water more tightly. While clay soils hold more water than sandy soils, less of the water is available to the plant because of the tight binding. Loamy soils have good pore space to hold moisture and do not bind the soil water tightly enough to prevent plants from extracting the water. These soils have more water available to the plant (Figure 7.2).

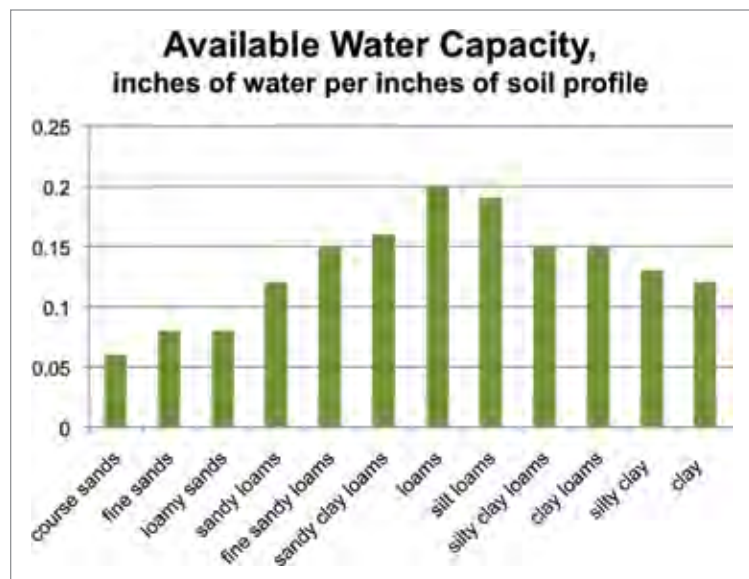


Figure 7.2 – The water in the soil that is available to the plant changes with soil texture. Sandy soils and clay soils have less plant-available water than do loamy soils.

The extent of soil drying is also dependent on soil texture. After a soaking rain, soil is saturated, meaning that all the pores between soil particles are filled with water. The saturated soil dries because



water percolates to lower depths and evaporates from the soil surface. Two to three days after saturation, soil is said to be at “field capacity.” At this water content, the soil pores have a mix of air and water. The soil will continue to dry until it reaches a point termed the “permanent wilting capacity.” At this level, the water remaining in the soil is no longer available to the plant, and the plants will wilt.

## **Maintaining Soil Water**

Irrigation scheduling is a method of maintaining soil water available to the plants in the range between field capacity and permanent wilting point. In the water balance approach, the initial soil moisture is estimated based on soil texture. The water in the soil is then tracked using the daily changes in water use and water inputs.

The inputs to the crop system can be accurately measured. Rainfall is measured using individual rain gauges in the field, or tipping bucket rain gauges on a weather station. Irrigation can be measured directly or estimated from the total amount of water applied over a given area. The outputs from the system are more difficult to measure exactly and are usually estimated.

## **Estimating Crop Water Use**

Crop water use can be estimated in several ways. A standard method that has been developed estimates a reference evapotranspiration from weather parameters (Allen, et al., 1998). The reference ET is then converted to the crop ET using crop-specific coefficients. Alternatively, methods have been developed that estimate ET from curves developed from years of field measurements. These empirical methods can be quite accurate, but are specific for the location from which the data was collected.

## **The Mississippi Irrigation Scheduling Tool – MIST**

The Mississippi Irrigation Scheduling Tool relies on the most current scientific knowledge of crop water use to assist producers in making irrigation decisions. The system is designed to be easy to use and access. Rather than requiring the user to take readings in the field and input data, MIST automatically collects information from national and regional databases and continuously calculates crop water use. Information on soil hydrology and texture are downloaded from the Natural Resource and Conservation System, based on the spatial location of the fields. Field information can be input by the user, or downloaded automatically from information collected by FSA. Weather information is updated automatically from weather stations located throughout the state and maintained by the Delta Research and Extension Weather Center. Spatially accurate rainfall information is automatically downloaded from the National Weather Center gridded rainfall data, or can be input by the user if they so choose. To handle differences in field runoff, MIST uses the NRCS runoff equations. This gives a more accurate indication of within-field soil moisture following a rain event. No soil or plant measurements are required to run the scheduler. Automatically downloading information from these databases allows growers to use MIST, without requiring extensive data collection or input to the model.





With MIST, there are no programs to install or maintain. The program is accessed through the internet, and is available on several platforms, including smart phones, tablet computers, laptops, and desktop computers. This allows the user to determine crop water needs from any location, and instantly tell when a crop needs water. Using a daily time-step for calculations and weather updates allows a more accurate determination of soil available water. Use of a daily time step also allows calculations to determine future crop water needs over the next several days, allowing growers to better manage their water resources.

The user selects a minimum water deficit, based on their irrigation system capacity. MIST indicates when an irrigation is needed based on the soil type, weather conditions, and capacity of the irrigation system. A final output of water used is available at the end of the season, and can be used for reporting to NRCS and water management districts to document water conservation.

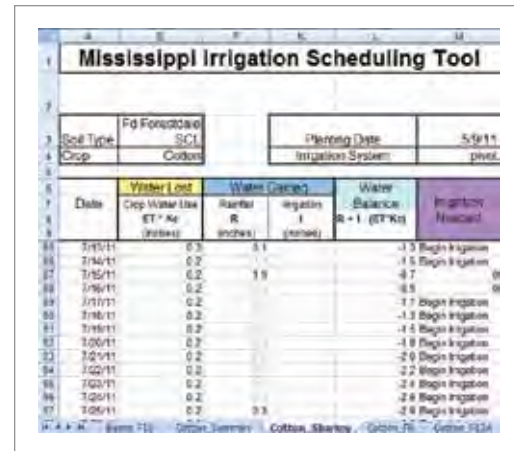


Figure 7.3 – Screen capture of the Mississippi Irrigation Scheduling Tool, MIST. MIST uses a water balance approach to estimate when irrigation is required. The need for irrigation is indicated when the soil moisture falls below a level set by the user, based on their soil and irrigation system. Crop water use is calculated using the Modified Penman-Monteith equation and crop coefficients developed for Mid-South growing conditions.

## The MOIST Program (University of Tennessee)

Brian Leib

Most water-balance, irrigation-scheduling programs function in a similar manner, but the means of data input and the representation of the output can be very different. The Management Of Irrigation Systems in Tennessee (MOIST) program from the University of Tennessee requires weekly input of rainfall and irrigation instead of daily data. This is easier for producers to maintain and thus keep track of the needed rainfall and irrigation amounts. The approach works fine for the more drought-tolerant row crops that are grown in the good water-holding soils of West Tennessee; however, weekly input may not be adequate for water-sensitive crops grown in low water-holding soils like sands.

MOIST also provides a graphical output in addition to a table format as shown at the bottom of Figure 7.4. The red diamonds represent weekly crop water use in inches and the pattern of increasing water use as the crop canopy expands and temperature/solar radiation increases is easily identified. During the dry period shown in mid July, cotton water use was calculated at 1.7 inches per week. The solid blue dots represent weekly rainfall and, up until the beginning of July, rainfall exceeded or nearly equaled crop water use, resulting in very little soil water depletion shown by the dashed black line. During this time, rainfall maintained soil water with only a 1.5 inch depletion of water below field capacity for this soil.

The soil represented here is a deep silt loam that can store 4.3 inches of readily available water as shown by the solid brown line labeled allowable depletion. It is not until mid – and late-July that



irrigation is required due to the lack of rain and the high cotton water use rates. Two inches of irrigation were applied at this time to maintain the soil water depletion at 1.5 inches. Irrigation plus rainfall is represented by the open blue squares. For center pivot irrigation in good water-holding soils, 1.5 inches of soil water depletion is a good target because center pivots are designed to keep up with crop water use and not to catch up or replenish the soil profile. Drip and furrow irrigation systems could allow depletion closer to the maximum allowable depletion because they may be designed to apply more water in a single irrigation event. At the present depletion of 1.5 inches, there is still enough soil storage capacity to capture a sizeable rainfall event and enough buffer to sustain the crop if the center pivot is not able to apply water for an extended period. The pink stars represent the predicted soil water depletion if no irrigation or rainfall occurs in the next one week and two weeks, respectively.

MOIST also provides a forecast type of output (upper portion of Figure 7.4) so that center pivot irrigators can have a plan of action once they update data into the program. In this example, the producer plans to apply 0.5 inches per revolution. If he wants to maintain his soil water depletion at around 1.5 inches, he would make 3 revolutions in the upcoming week if no rainfall occurs and 2 revolutions if 0.5 inches of rainfall occurred according to the columns on the left side of the page. If he wants to increase the amount of soil water in the profile by 0.5 inches, he would have to operate continuously for the whole week if there was no rainfall and make 3 revolutions if 0.5 inches of rain occurred according to the column on the right side of the page. The amount of gain or loss in soil water can be adjusted according to the producer's management goals, but this forecast also shows that it is difficult to increase soil water with a center pivot system during the middle of a growing season. This forecast type of output allows a producer to schedule irrigation without having to go back to the MOIST program every time a rainfall or irrigation event occurs.

Water balance programs are great irrigation scheduling tools because they predict water use on a whole field basis and are not particular to one small location in a field when a crop is adequately watered. A

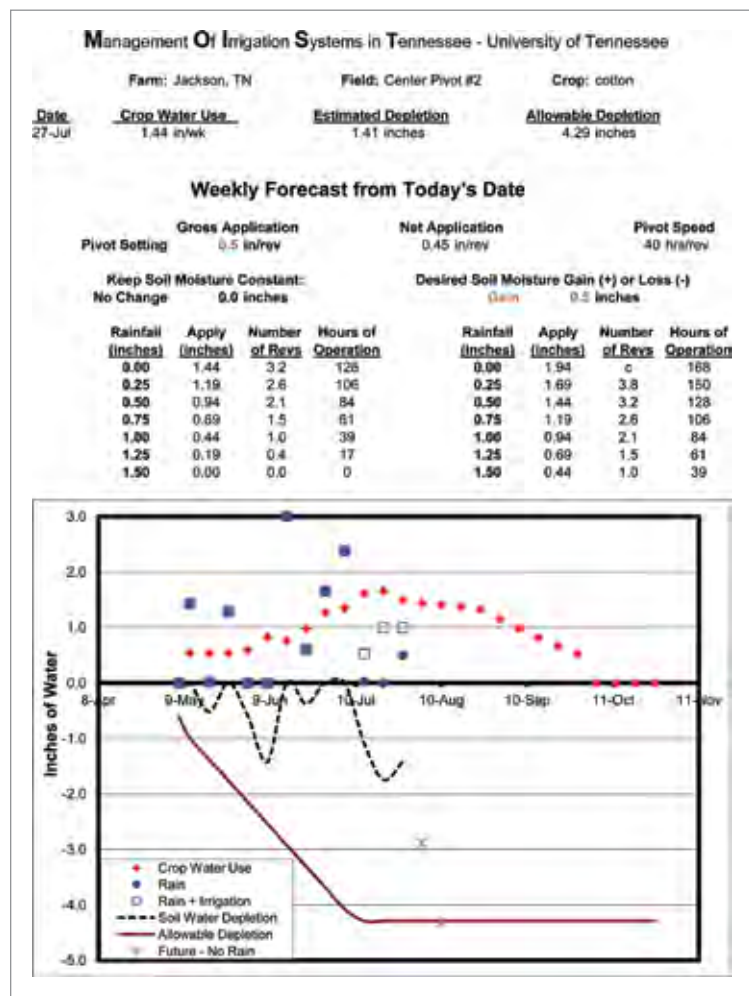


Figure 7.4 – Output from the MOIST program.



producer should always feel confident that they know how much water is needed to replace the water being used by their crop when using a water balance approach. However, there are some limitations that one should be aware of. For instance, most water balance programs assume that excess water in a soil quickly drains to field capacity and this is not true of all soils. Also there can be run-off from intense rainfall events and if the entire rainfall amount is entered into the program, a water balance approach will not automatically recognize that the entire rainfall amount did not enter the soil profile.

### **Combining Soil Moisture Monitoring with Water Balancing**

Combining soil moisture monitoring with a water balance approach can avoid these pitfalls. For instance, early in the growing season when scheduling irrigation on a poorly drained soil, a water balance approach may indicate a need for irrigation while a soil water sensor may show plenty of available water. Conversely, after an intense rainfall event, a water balance may indicate that no irrigation is required because it does not automatically recognize how much of the rainfall ran off, while a soil water sensor may indicate drier than expected conditions leading to earlier irrigation after a rainfall event. It may appear that soil water sensors alone are the answer to these limitations, but one must remember that sensors only measure in a very small location in a field and may not always represent the field as a whole. Therefore, we recommend a combination approach of a water balance and soil sensors.



## Section 8:

# Management Considerations for Irrigated Cotton

*Guy Collins and Kater Hake*

### Key Points:

- *Irrigation generally increases management intensity.*
- *It also provides the ability to deliver fertilizers and activate herbicides.*

Irrigation brings a set of management challenges and opportunities. In general, irrigated fields require more intensive management, not only due to the need to schedule irrigation, but also due to the ability to manage water stress in the field. Early season irrigation can reduce soil crusting and improve plant stands. Also, as discussed in Section 5, careful control of water stress early in the season can reduce the need for plant growth regulators later in the season. It should be noted that, in general, irrigation will increase yield potential, so fertilizer requirements will also tend to increase, particularly nitrogen.

An advantage of irrigation not commonly considered is the ability to activate herbicides after application. With herbicide-resistant weeds, timely activation of residual herbicides can be guaranteed with pivot irrigation systems. This can also apply to fertilizer applications, especially side-dressed nitrogen. With the proper equipment, irrigation can also be used to deliver fertilizers and some crop production products.

### Cotton Crop Irrigation Increasing

Acreage of irrigated row crop land has consistently increased during the last 20 years in the Mid-South and Southeast where rainfall typically exceeds evapotranspiration each month of the year, although episodic hot and dry periods frequently occur. This increase has occurred despite the significant costs of irrigation (approximately \$600 to \$800 per acre to purchase and install a 125-acre pivot) and the challenge of irrigating irregularly shaped and sloped fields. Thus, land owners and growers must already recognize the economic benefit from irrigation in row crops and the stability it brings to modern farming enterprises. Regardless of whether the driver for this irrigation expansion is \$6/bushel corn or \$14/bushel soybeans, maximizing irrigation benefit to cotton in the Mid-South and Southeast requires a careful consideration of the benefits and detriments of supplemental irrigation. Unlike in California and Arizona, where rain is unlikely during the growing season and full irrigation is the norm, in the Mid-South and Southeast rainfall **MUST** be



considered in making irrigation decisions and is strictly supplemental to rainfall. The following chart identifies the uses and risks of irrigation during the growing season and is expanded upon in each of the following paragraphs.

<b>Crop Stage</b>	<b>Crop Sensitivity to Water Deficit Stress</b>	<b>Benefits of Irrigation</b>	<b>Detriments of Irrigation</b>
<b>Emergence</b>	Moderate	Activate herbicides Hydrate germinating plants Cool surface soil	Seedling disease if cool Create soil crusts Herbicide injury
<b>Pre-Squaring</b>	Slight	Few unless extreme drought	Shallow root system
<b>Squaring</b>	Moderate	Avoid subsoil water loss Build plant size Brings fertilizers into solution	Soil saturation Excessive vegetation
<b>Early Bloom</b>	High	Retain bolls New fruit and leaves Compensate for nematodes Compensate for compaction Compensate for herb. injury High fiber quality	Few
<b>Late Bloom</b>	Moderate	Retain bolls Healthy leaves High fiber quality	Few
<b>Cutout</b>	Slight	Healthy leaves	Delay maturity
<b>Opening</b>	None	Few	Boll rot, Delayed harvest

## Germination and Seedling Emergence



Seedbed moisture is essential for germination and emergence. Pivot sprinkler irrigation can enhance these processes by providing moisture for root and hypocotyl expansion, by softening surface crusts and by cooling the surface of sandy soils during periods of extreme heat. Frequent and small (one-quarter to one-half inch) irrigations are appropriate when the weather is hot but should be avoided when the weather cools and are not usually necessary after full seedling emergence. Irrigating emerging and seedling cotton during cool weather promotes seedling disease. Pivot sprinkler



irrigation is also highly useful in activating pre-emergence herbicides. Typically, 0.2 to 0.75 inch is sufficient to move pre-emergent herbicides into the soil where they are protected against photo degradation and are activated to control germinating weeds. Unfortunately, frequent rain or irrigation can also move herbicides into cotton's root zone, causing phytotoxicity.

Row watering planted but not emerged cotton fields is difficult unless water control, bed shape and field slope allow subbing into the planted zone with overtopping the beds.

### Pre-Squaring Cotton



Irrigation is rarely needed in Mid-South and Southeast cotton during the pre-squaring period, although irrigation could alleviate stress during severe hot and dry periods. During the pre-squaring period roots are expanding into new soil at over twice the rate that shoots are expanding, and in most fields are able to provide sufficient water to support maximum seedling growth of the small leaf area. Frequent irrigation prior to bloom may limit the rooting depth by restricting soil oxygen or by promoting shallow root. Roots proliferate in soil favorable for growth (i.e., warm, moist, friable, non-toxic, and containing sufficient oxygen and nutrients). If these conditions are maintained near the soil surface then root expansion in the subsoil will be limited and the plant will be vulnerable to periodic drought during the bloom phase.

### Squaring Cotton



During the squaring period, the root volume and most of the harvestable fruiting sites are created. Plant stress during this period can limit both of these and place an upper limit on yield, especially for earlier maturing varieties that tend to set a larger proportion of fruit on lower nodes, and are thereby less likely to recover from stress. Severe water-deficit stress, to the point of plant wilting, should be avoided during this time period. In sandy or low-water infiltration fields with limited irrigation capacity (less than ~5 gpm per acre), care should also be given to avoid depleting subsoil moisture reserves that will be needed during the bloom period. Varietals and season length differences should also be considered in water management of squaring cotton. Water deficit stress during the squaring period is more injurious to the yield of early maturing and more determinate varieties in long growing seasons. Excess water, and lack of soil oxygen, is a more likely problem during squaring than water deficit stress, since the limited plant size and cooler temperature restricts water use. If surface soils remain saturated for an extended period of time, plant growth is curtailed and fruit may be shed.



## Early Bloom Cotton



During this period, daily water use, daily fertilizer use, and sensitivity to water-deficit stress all increase. Retention of small bolls (less than  $\frac{3}{4}$  inch) is the most sensitive crop stage to water-deficit stress such that the key yield-enhancing benefit of irrigation is to avoid water-deficit stress during bloom. A secondary benefit is the quick activation and/or delivery of nitrogen fertilizer to under-fertilized cotton fields. Although sprinkling during the morning hours will cause some pollen rupture reducing seed set, boll size, and boll retention when water contacts open blooms prior to midday, this detrimental impact has been shown to be slight compared to the benefit of maintaining a healthy photosynthetic capability and sustaining new leaves, new squares and new bolls. Where shallow soils, acid soils, nematodes or compaction limit root function, maintaining ample soil water during early bloom is essential for high yields.

## Cutout, Late Bloom and Boll Opening Cotton



Once cotton has reached cutout or the last effective bloom date, water deficit stress can usually be increased gradually such that new vegetative growth is curtailed but healthy turgid (non-wilting) leaves are maintained until over half of the bolls are mature. Irrigation interval and soil moisture deficit should be increased during this period to minimize the cooling associated with evaporation and to prevent waterlogging under rainy conditions. Avoiding irrigation when bolls start to open will lessen canopy humidity and resultant boll rot or hard lock. A dry surface and subsoil also facilitates soil surface drainage which minimizes harvest delays and soil compaction from field traffic after heavy rains.

## General Irrigation Management Considerations

Irrigation brings a set of management challenges and opportunities. In general, irrigated fields require more intensive management, not only due to the need to schedule irrigation, but also due to the ability to better manage inputs and water-deficit stress in the field. Just as non-uniform soil types in a field present management challenges, a non-uniform irrigation system also presents challenges. Growers can do little about the former, but non-uniform irrigation can and should be avoided when designing and operating both sprinkler and row-water irrigation systems. Despite the management challenges that irrigation creates, substantial opportunities to stabilize yield and fiber quality through their proper application to cotton at various stages will raise the overall profitability and management skills of cotton farmers.



## **Irrigation Adds Flexibility to Farming Operations**

Cotton growers now manage anywhere from a few hundred to a few thousand acres. Due to equipment limitations, a grower cannot plant all acres at a single time, much less plant significant acreage immediately after a rain. Irrigation is critical when planting into limited soil moisture during hot, dry weather. Having irrigation capacity on some fields allows for a larger proportion of dryland acres to be planted soon after a rainfall event, while the irrigated acres can be planted at any time. For late-planted or double-cropped cotton (generally cotton planted behind wheat), immediate emergence and rapid seedling growth is critical and days lost while waiting on a rain will invariably reduce yield. Additionally, irrigation enables producers to develop and retain the earliest set bolls which boost yield in a compressed season often observed in later-planted cotton.

## **Irrigation and Variety Selection**

Another management consideration for irrigating cotton includes variety selection and positioning. Modern cotton varieties vary widely with regard to maturity, boll distribution, drought tolerance, need for growth regulation, and yield response to irrigation. Although most, if not all, cotton varieties respond positively to supplemental irrigation when encountering dry weather, some varieties respond differently to increased irrigation rates or to deficit irrigation. Research has shown that some varieties (primarily later-maturing varieties or ones with drought-tolerant characteristics) show little to no yield penalty associated with deficit irrigation unless extreme high temperatures and prolonged drought occurs. In contrast, other varieties (typically earlier maturing varieties that set a higher proportion of bolls on lower nodes) are touted to respond to greater amounts of applied water. With the variation between cotton varieties in their yield response and growth characteristics to water, growers can position varieties into appropriate fields and environments. Later-maturing varieties or those that are less injured by water-deficit stress are ideally positioned into fields with reduced irrigation capacity (large pivots, restricted application amounts, severe runoff, low water-holding capacity soils) while varieties that set bolls lower on the plant can be positioned into fields with greater irrigation capacity.



## Section 9:

# Irrigation Systems Overview

### Key Points:

- *There are many ways to deliver irrigation water to the field.*
- *The best system is field specific.*

There are several options for delivering irrigation water. The three major categories of irrigation systems are:

1. *Sprinkler irrigation systems – where center pivots are the type most commonly used for cotton production;*
2. *Surface irrigation – applying the water down the furrow from siphon tubes or poly-pipe as well as flooding an irrigation basin;*
3. *Drip irrigation – surface or subsurface.*

Each of these systems is described in more detail in the following sections. Many factors determine which is best for a particular field including soil type, field slope, field geometry, and water source (well capacity or surface water).

### Subsurface Drip Irrigation

*Ahmad Khalillian*

Subsurface drip irrigation (SDI) is proving to be an economical method of water application to agronomic row crops such as corn, peanuts and cotton. A subsurface drip irrigation system offers many advantages compared to other irrigation systems. There is less annual labor and an increased life expectancy; a dry soil surface reduces the occurrences of soil-borne diseases and helps to control weed infestations. The dry soil in furrow enhances trafficability and reduces soil compaction. There is a more efficient use of water and nutrients, and there is a significant improvement in yield and quality components.



*Figure 9.1 – Drip tube installed between the rows of cotton.*



SDI is normally defined as a “permanent” system, that is, the drip lines are not taken up every year. SDI systems must be carefully designed and installed so that they operate with proper efficiency and so that fertilizers and chemicals can be applied in a uniform and efficient manner.

Before the design of an SDI system is done, it must be determined that the intended site is suitable for SDI. These considerations include adequate water supply, acceptable water quality, and appropriate topography. Another consideration is management, which is important to all drip irrigation systems and especially important to SDI systems in which drip lines are below ground – out of sight.

The design of an SDI system is similar to the design of other drip irrigation systems, with additional consideration given to system flushing and traffic. In humid regions, topography and field layout will normally demand extra attention.

## Design Criteria

### **1. Water Requirements:**

The SDI system must be designed to deliver the required flow rate, and the water supply must be adequate to deliver the amount of water required over the growing season. The SDI system may be intended to irrigate more than one crop (rotation), in which case the crop with the highest water demand should be satisfied. The amount of water required will depend on many factors, including climate, crop, and soils.

*Climate:* In humid areas, the water requirement is normally lower than more arid regions due to reduced vapor pressure gradient, or driving force, for evapotranspiration. Other factors, such as temperature, sunshine and wind influence evapotranspiration. With an SDI system, evaporation from irrigation is reduced to a negligible amount in most cases, since the soil surface is not normally wetted.

*Crop:* The most important aspect of crop water use for SDI design is the “peak” water requirement or the amount of water that a crop uses during its highest water use period. While rain may be factored in to reduce the irrigation requirement for a season, it should not be factored in when calculating a peak use rate. This is because, even in humid regions, the probability of receiving appreciable rain in a few-day period with high dependability is low. The design flow rate calculated for crop water needs must be matched to the manufacturer-specified drip line flow rates at the recommended pressure.

*Soils:* The soil type into which an SDI system will be installed can impact system design. Soil characteristics such as texture, structure and layering can affect soil hydraulic characteristics such as infiltration rate and hydraulic conductivity. Drip lines will need to be more closely spaced in a sandy soil since the lateral spread of water from the drip lines will be less pronounced than in a finer textured soil. Slow emitter emission rates may be required on heavy textured soils, such as clay, so that the emission rate does not exceed the hydraulic conductivity of the soil. In general, drip line depths should be shallower in coarser textured soils and deeper in finer textured soils.

## 2. Management and Operation Considerations:

An essential step in the design of an SDI system is to consider how the use of the area will vary. It is not enough to design only for next year's crop. A well-designed system should be in operation for at least 10 to 15 years, so some attempt must be made to plan for the future. Important questions that should be asked include: a) Will the same crop be grown each year or will there be a rotation of multiple crops? b) Will the entire field be planted to one crop or will it be divided into smaller areas of different crops? c) Will the different crops in a rotation employ different cropping systems? d) Is subsoiling a part of the production system? In addition, there will be system maintenance operations (e.g., acid injection, iron settling, flushing, etc.) not required or less extensive than for other types of irrigation systems. Ignoring the maintenance to save time will most likely lead to a significantly shorter life for the system.



*Valves controlling water delivery to different drip irrigation sections*

## 3. Water Quality:

When designing an irrigation system, water quality concerns may include two sources of design criteria, one for the system and one for the crop. Water quality criteria for crops normally focus on leaching requirements or application concerns (foliar burning, etc.). In humid regions, where salts do not build up in the root zone, a leaching requirement is not required. Also, since SDI systems don't wet the plant, problems resulting from the contact of irrigation water with the plant are not an issue. As a result, water quality criteria for the design of SDI systems in humid areas focuses on irrigation system concerns. Emitter clogging is the primary concern with SDI systems as with all drip systems. Water quality will dictate filtration requirements, chemical injection requirements and management of SDI systems to prevent emitter clogging.

### Filtration Requirements for Subsurface Drip Irrigation

Filtration is critical in SDI systems. Since the emitters are buried, determining the location of clogged emitters is very difficult. For optimum performance, only clean (free of particulate matter) water should be pumped through drip irrigation systems. The size and type of filter required will depend on the water source and the kinds (if any) of fertilizer and chemical stock solutions to be injected. Filtration systems are placed at the headworks of the SDI system.

1. *Media Filters:* Media filters are superior for filtering surface water due to their large filter area and capacity. They can be quickly back-flushed for cleaning which can be automated. At least two media filters are needed, since during the back-flushing operation; clean water from one filter is used to remove contaminants from the other filter.

2. *Screen Filters:* Screen filters are used as secondary filters with surface water systems or as primary filters with well or municipal water sources. Screen filters vary in both shape and size. They may vary in size from 1 inch (for one acre or less) to 10 inches in diameter. Mesh sizes range from 40 to 200. Although some screen filters have automatic back-flush capabilities, most need to be manually flushed.

3. *Disk Filters:* Disk filters are used as secondary filters with surface water systems or as primary filters with well or municipal water sources. These filters contain a series of grooved plastic disks that may have an equivalent screen size ranging from 40 – 200 mesh. Disk filters have the advantage of having more surface area than screen filters and are therefore better suited for higher flow rates and are also easier to clean.



*System used to install surface drip tape.*

## **Chemical Injection for Subsurface Drip Irrigation**

Chemigation refers to the application of a chemical into an irrigation system. It includes the application of chlorine, acids, fertilizers and pesticides. Because drip emitters are small, they clog easily. Along with filtration, the capability to inject chlorine and acid are important features in an SDI system, especially in humid regions for removing algae. Other benefits of chemigation are uniform and timely application of fertilizer, reduced soil compaction due to reduced traffic, and reduced labor requirements, exposure to chemicals, and environmental contamination.

The design of a chemical injection system involves the selection of the injector, both type and capacity (size). If the injection system is to be used for fertigation, the injection unit should be sized for this since injection rates for fertilizers are usually much higher than injection rates for chemicals such as liquid chlorine or acid. Two basic types of injection pumps, the Venturi injector and the metering pump, are commonly used for injecting fertilizer and other chemicals into drip irrigation systems.

## **Valves for SDI Systems**

As with any drip irrigation system, proper selection and placement of valves is critical in an SDI system. Water flow rate and pressure throughout the SDI system should be precisely controlled to ensure efficient and timely water application. Valves play key roles in controlling pressure, flow and distribution under different conditions to optimize performance, facilitate management, and reduce maintenance requirements in SDI systems. Valves used in a complete SDI system include check valves, shut-off valves, pressure relief valves, electronic remote control valves, pressure regulators, and air/vacuum pressure regulators.

## Main and Sub-Main Design

In normal irrigation design, pipe size should be specified based on economic, friction loss, and water hammer considerations. In SDI system design, pipe size may also be dictated by flushing concerns. Main and sub-mains are normally “telescoped” or reduced in size as water is discharged along the line to sub-mains or drip-line laterals, and required pipe capacity is reduced.

Lateral length will determine the zoning and therefore the layout and design of sub-mains. New developments in drip-line production allow designers to extend lateral lengths to distances that were previously considered hydraulically impossible. Larger diameter drip-lines and lower flow rate emitters combine to allow lateral lengths of up to 1,320 feet in some cases. While these distances are now possible, they may not be advisable when drip-line flushing is considered. Care should be taken to properly size sub-mains where field shape varies. In these instances, each drip-line lateral may have a different length and a different total flow rate for that lateral. Sub-mains should be designed based on actual flow rates of the laterals and not on an “average” flow rate per lateral for irregularly shaped fields.

## Drip-Line Design

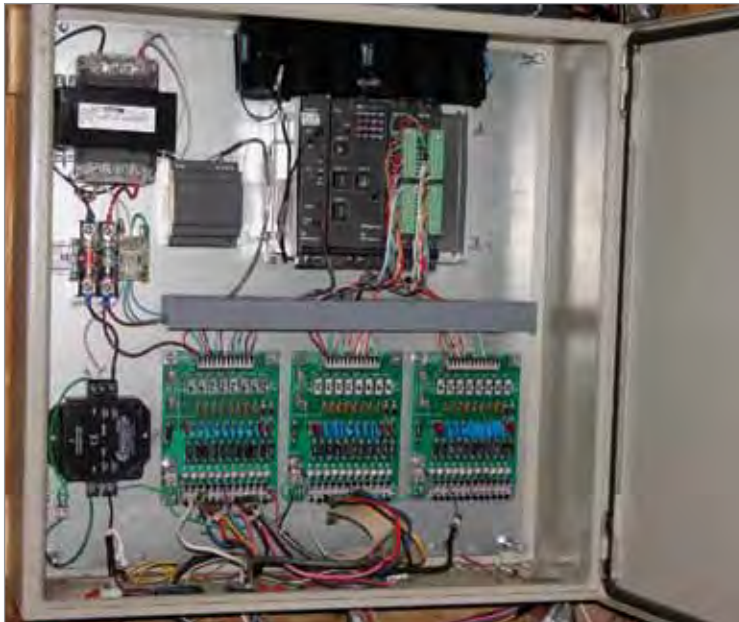
With any irrigation system, the design process starts at the plant and works “upstream.” Hydraulically speaking, this means that the first step of the design process in an SDI system is drip-line design. The design of drip-line for SDI systems consists of drip-line selection, and specification of drip-line depth and spacing. Drip-line selection will depend upon plant spacing, soil characteristics, and drip-line durability and hydraulic characteristics. A minimum drip tape wall thickness of 15mil is normally specified. Discharge rates are normally expressed in gpm per 100 feet. Another consideration in drip-line selection is clogging potential. In general, higher flow rate emitters tend to clog less due to larger flow passages.



Drip-line depth should be specified in any SDI system design. Drip-line depth will depend on soil characteristics, rooting depth, and cultivation practices. In general, SDI systems are too deep to aid in germination, but in medium to heavy textured soils with a higher potential of horizontal and upward movement due to capillarity, it may be a consideration. Drip-lines should be installed below tillage depth. If deep tillage is required (at or deeper than the drip-line), it must avoid the drip-lines. Generally, the deeper the drip line, the less the system will promote weed germination. In Coastal Plain soils (with hardpan problems) optimum depth of drip-lines are between 13 to 15 inches for row crops. Without significant hardpan issues, 10 to 12 inches is a sufficient depth.

Drip-line spacing, like depth, depends on soil characteristics as well as the crops to be grown. In general, coarser-textured soils will require narrower drip-line spacing than a finer-textured soil, since lateral water movement is less in coarse soils. In rotations that include a row crop, drip-line spacing is most often a multiple of row spacing.

## Instrumentation and Controls



Automation of irrigation has increased in the past couple of decades. Automation can pay for itself by reducing labor requirements and by enabling more precise irrigation. Since SDI is a relatively permanent system, it lends itself to automation. Basic instrumentation starts with meters that help monitor system performance and that help diagnose potential problems. Pressure gauges are also vital in an SDI system to monitor pressure and to help diagnose problems. Low pressure and/or increased flow rates during normal operation may indicate a leak.

Irrigation control can be achieved by two general types of systems: open control loop systems and closed control loop systems. Open loop systems do not incorporate feedback and amounts and timing of irrigation are pre-determined by the operator. This type of system is usually a simple irrigation controller operated with a clock. In general, these controllers initiate irrigations at preset times and control the duration of irrigation by activating solenoid control valves that serve zones. The controllers vary in the number of valves that can be controlled, the number of valves that can be simultaneously held open, the number of separate irrigation programs available, and the number of start times available for each program. These controllers are not normally set to operate with feedback, although most offer a rain switch that terminates irrigation during precipitation events.

Since humid areas, by definition, have appreciable rainfall, soil moisture may change unpredictably, and therefore make it difficult to schedule irrigations. As such, a closed looped system offers many advantages. Automation of irrigation using feedback can prevent leaching of chemicals, and reduce pumping costs, by only allowing irrigation when the crop needs it. Many different systems for automating irrigation scheduling are available. These systems can be divided broadly into two groups: systems that infer crop-water stress using soil-water content information and those that estimate crop evapotranspiration (ET<sub>c</sub>) or crop-water use.

## Surface Drip Irrigation

*Ken Stone and Ron Sorensen*



*Figure 9.2 – Surface drip tape under a cotton plant.*

shaped fields to maximize the irrigated acreage. Disadvantages of surface drip irrigation include the initial cost of the system, specialized equipment to install and remove tubing, and the annual system component replacement. Without proper care, some irrigation system components can be damaged with machinery. Additionally, rodents and insects can create additional maintenance problems by chewing holes in the plastic tubing.

For many years, surface drip irrigation has been used to irrigate high-value vegetable crops. In recent years, surface drip of row crops has been increasing throughout the United States. Surface drip irrigation can precisely deliver water and nutrients to the crop root zone. Surface drip irrigation systems save water by only wetting a small area of the overall soil surface, thus reducing evaporation. Additional advantages for surface drip irrigation include low application rates, precise water placement, and low operating pressures. Drip irrigation can also be used in irregularly

## Surface Drip Irrigation Design

A typical surface drip irrigation system would consist of a pumping plant, pressure regulation, a filtration system, and a distribution system divided into zones delivering water to the drip tubing. A major consideration in design of surface drip irrigation systems is in the drip tubing lateral spacing. Typical lateral spacing for row crop production is for either 1) every row or 2) alternative row middles (see Figure 9.3). In previous research with traditional row crops grown in the humid southeast and other more semi-arid regions of the U.S., no significant yield differences were observed between the two lateral spacings. An advantage of alternative row spacing is the reduction in tubing cost and the ease of tubing removal.

For row crop operations, the drip irrigation emitters are usually imbedded into the drip tubing. The emitter spacing on the drip tubing varies but are typically spaced from 12 to 24 inches apart. Emitter spacing is determined by one or any combination of field length, field/zone size, or water capacity.

In high-value crops, surface drip laterals are typically replaced with each crop. In some row crop production systems, annual tape replacement may be cost-prohibitive while other cropping systems may be quite cost-effective. Some researchers and manufacturers have developed

methods to retrieve the drip tape after crop harvest and methods to repair damaged tape. If the cropping system is using strip tillage and GPS systems for planting operations, the tubing may be used for several years before retrieval and replacement are needed.

## Shallow SubSurface Drip Irrigation (S3DI)

More recently, some researchers have started using shallow subsurface drip irrigation (S3DI). The S3DI is basically surface drip irrigation buried 2-4 inches into the soil in alternate row middles. This is much shallower than sub-subsurface drip irrigation (SDI), but can reduce the damage from rodents and insects.

## System Costs and Expenses

Cost for surface drip and S3DI are similar and much less expensive than deeply buried subsurface drip systems. For instance, both surface and S3DI systems can be installed for about \$250 to \$350/acre infield expenses. This cost includes manual filtration, pressure regulation, tubing, fittings,

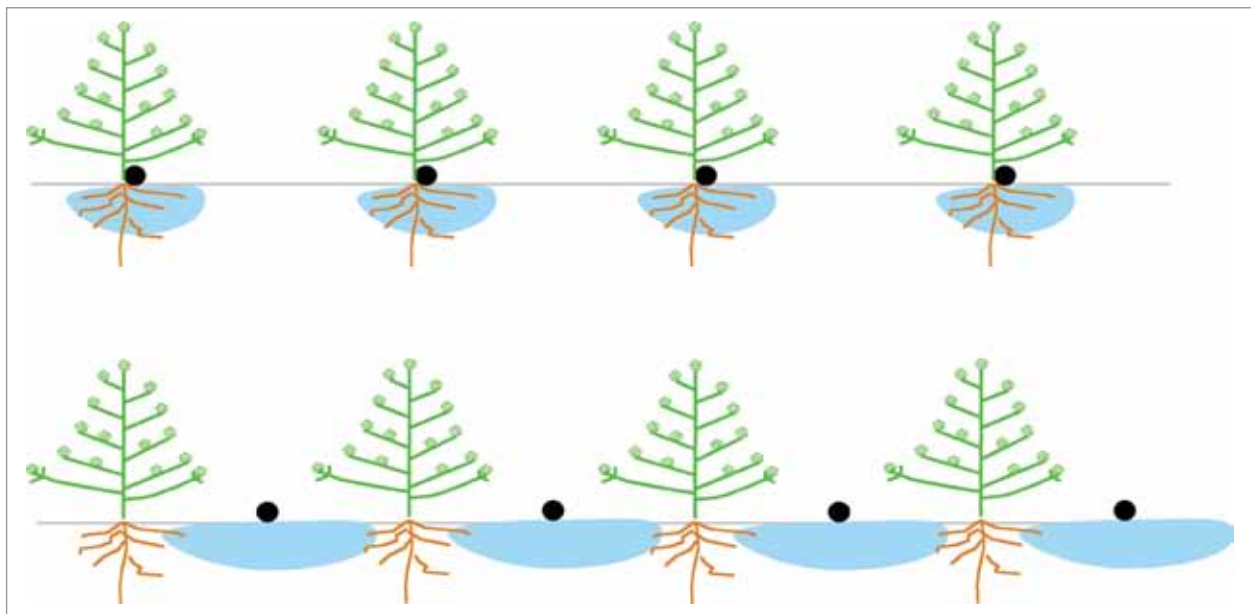


Figure 9.3 – Surface drip irrigation configurations.

valves and infield mainline. This expense does not include equipment, labor, or water conveyance from water source to the field. These costs assume clean well water, smaller rectangular fields, and field lengths less than 700 feet. With proper management these systems can be maintained for 3 to 5 years depending on crop rotation.

Deep SDI installation expenses can range from \$1,100 to \$2,400 depending on water quality and level of electronic control. These systems have life spans much longer (15 to 20 years) than either surface drip or S3DI and, therefore, need higher-quality filtration methods and flush systems. Aside from tubing, the major expenses for SDI are the required filtration and flush systems. Filtration can



range from inexpensive manual to expensive electronic flush systems. These SDI systems need both input and flush mainline along with the associated valves and fittings. Installation will require heavier equipment and more labor.

## Center Pivots

*Calvin Perry*

Center pivot sprinkler irrigation systems are among the most popular mechanical-move systems for applying irrigation water to field crops like cotton, and are used on over half of the sprinkler-irrigated area in the U.S. The basic design concept has been improved and refined, but remains very similar to the original system invented and patented by Frank Zybach in 1948 and 1952, respectively. Because center pivot systems have low labor requirements, apply water very efficiently, can operate unattended for long periods, and now are being automated, they have proven to be very popular, especially in the Southeast U.S. Since the late 1970s, the use of such systems has grown rapidly.

Center pivot systems feature a water supply main-line or lateral that rotates about a fixed point (the center “pivot” point). The galvanized steel or aluminum lateral is supported by a series of “towers” (Figure 9.4) which propel the lateral around in a circular fashion by rubber-tired wheels driven by electric or hydraulic motors mounted on each tower. The towers support the lateral at a height such that the clearance between ground and lateral support trussing is about 10 feet to allow for ample space above most crops.



*Figure 9.4 – A center pivot equipped with drop lines.*

Hoffman, et al. (2007) and Keller and Bliesner (1990) note that center pivot systems have many advantages over other irrigation application methods, including:

- *Potential for automated operation.*
- *Simplified water delivery.*
- *Ability to apply small irrigation depths.*
- *Very high application uniformity.*
- *Ability to improve irrigation management.*



- Ability to apply agri-chemicals (chemigation).
- Ability to activate surface-applied agri-chemicals.
- Little annual setup required.

Disadvantages of center pivot systems include:

- Relatively high initial cost.
- High application rates at outer end of lateral (causing runoff).
- Relatively high pipe-friction losses.
- Circular pattern not matching square fields (leaving dry corners).
- Topographic changes causing potential operating pressure variations.

## Center Pivot Design Considerations

A typical center pivot irrigation system layout and components would include (as shown in Figure 9.5) the pivot point, control panel (user interface), spans between towers, tower drive wheels, truss system supporting the water supply lateral, sprinklers, and often an end gun (with or without an end gun booster pump). For most electric systems, a one-minute timer is used to control the “walk” (i.e., travel) speed of the end tower. The speed of the end tower around the circle controls the depth of application (assuming a constant water supply to the pivot point). A 50% timer setting would correspond to the end tower moving for 30 seconds and then remaining stationary for 30 seconds, since the end tower drive motor is a constant velocity design. Thus, the maximum travel (or “walk”) speed of the center pivot system would be when the timer is set to 100%. All interior towers have switches that energize the respective tower drive motor to start that tower walking whenever the next tower has walked ahead such that the two towers are mis-aligned. Once re-aligned, the switches stop the drive motor.

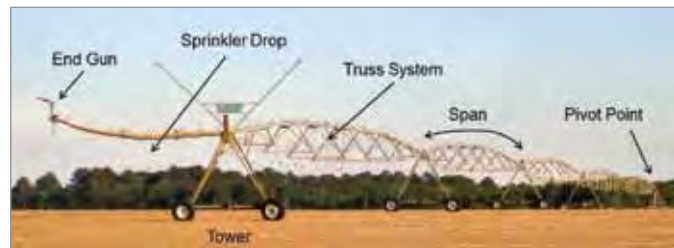


Figure 9.5 – Components of a typical center pivot irrigation system.

## System Dimensions

The lateral spans range in length from 100 to 200 feet with a typical pipe diameter of  $6\frac{5}{8}$  inch (other diameters are offered). Overall center pivot lateral lengths can range from as small as 250 feet to as long as 2,000 feet. Center pivot design professionals will often incorporate various span lengths to maximize the irrigated area of a field. Sprinklers attach to the lateral spans by way of threaded outlets, either directly to the outlet or by way of drop tubes/hoses. End guns at the end of



a lateral are often used to increase the wetted area of a field as this large-volume sprinkler throws water a long distance (often aided by a booster pump).

The entire lateral is usually supplied with sprinkler outlets spaced equally along the pipe. Center pivot manufacturers offer a number of outlet spacings with 30-inch spacing common today. This close spacing allows the design professional to configure the optimal combination of sprinkler type, nozzle size, and spacing. In general, because the outer end of the lateral rotates at a higher speed than the inner span, the application rate per sprinkler will be greater at the end of the lateral than near the pivot point to achieve uniform application depth from end to end.

### Sprinklers



Sprinklers are the devices that actually deliver the water to the plant and/or soil. The purpose of a sprinkler is to take water from the source (such as the pivot lateral) and distribute the water uniformly over an area in droplet form. In order to cover a large area, a sprinkler must throw water a considerable distance. A properly designed sprinkler “package” will take many factors into account including water supply, soil, crop, topography, and atmospheric conditions. High-pressure, impact-type sprinklers, as well as low-pressure, spray-type sprinklers, are used on center pivot

systems. Regardless of type of sprinkler, the system should be designed, as close as practical, to meet the crop water requirements for the crop and area irrigated.

Spray-type sprinklers (referred to as spray nozzles) require considerably less pressure, and thus energy, than impact sprinklers. Often spray nozzles are installed at the end of drop tubes/hoses to release water closer to the crop canopy to reduce wind and evaporative losses. However, spray nozzles have a smaller wetted diameter which causes very high application rates at the outer end of the lateral. In “heavier” soils this often leads to application rates that exceed the soil infiltration rate, causing runoff. Impact sprinklers have large nozzles giving a large wetted diameter which results in lower application rates.

Sprinkler manufacturers today offer an extensive array of spray-type sprinklers along with a few models of impact-type sprinklers. There are spray nozzles available today that have water impact plates that rotate, spin, wobble, or remain fixed to give various water application patterns to meet most conditions. Impact sprinklers come primarily in two formats – low-angle water trajectory and high-angle water trajectory. For a sprinkler package design, the irrigator will be given a “timer chart”



that will indicate the application depth (usually in inches) for various timer percent settings. For example, a chart might indicate that the irrigator select 22% speed to achieve 0.5 inch application depth.

## Irrigation Water Delivery

Irrigation water (surface water or groundwater) is usually supplied to center pivot systems through power take-off (PTO), engine, or electric motor powered pumps. Pumps may supply a single center pivot or may supply multiple center pivot systems. Water for center pivot systems is usually not routed through a filtration system. Flow rates to center pivot systems range from as low as 200 gallons per minute (GPM) to well over 1,000 GPM. Remember that water for irrigation is needed most when water supplies are at their lowest level. Water sources should, therefore, be adequate to supply water during extended dry periods.



The required water supply flow rate for a center pivot can be calculated using the following formula:

$$Q = (453 \times A \times D) / (F \times H)$$

Where:

Q = required system flow rate (gallons per minute or GPM)

A = total area irrigated by system, including end gun (acres)

D = depth of water applied per irrigation (inches)

F = irrigation frequency (days)

H = hours of operation per day (hours)

Example:

You want a 72-acre system to apply 1¼ inches every 3 days operating 20 hours per day.

$$Q = (453 \times 72 \times 1.25) \div 3 \times 20 = 680 \text{ GPM.}$$

## Chemigation

Chemigation refers to the application of a chemical into or through an irrigation system. It includes the application of fertilizers, acids, chlorine and pesticides. Chemigation can save time, reduce labor requirements, and conserve energy and materials. Chemigation is beneficial, however, only to



the extent that the irrigation system is adequately designed, fully functional and properly managed. In many situations, chemigation is as good or better than conventional application methods. Conventional application is still preferred or required, however, for some materials. Never inject any material that is not labeled and recommended for the crop and for injection through the system. Always follow label directions.

There are a number of advantages to using chemigation, including:

- *Uniform Application.*
- *Timely Application.*
- *Reduced Application Costs.*
- *Improved Management.*
- *Reduced Soil Compaction.*
- *Reduced Exposure to Chemicals.*
- *Reduced Environmental Contamination.*

However, to properly employ chemigation with a center pivot irrigation system, an irrigator must consider a number of safety and performance issues. In terms of safety, the irrigator must note that the pumping plant and the chemical injection pump should be interlocked, there should be proper check and vacuum relief valves (anti-siphon devices) installed, a pressure switch should be electrically interlocked with the safety panel on the irrigation system, plus other state-specific safety issues to be followed.

Two basic types of injection methods — the Venturi and the metering pump — are commonly used for injecting fertilizer and other chemicals into irrigation systems. The irrigator must determine the desired injection rate using area, chemical solution volume, and time and then calibrate the injection pump to put out the desired rate.

### **Control Panels/User Interfaces**

The control panel is the user interface for the center pivot irrigation system. Control panel technology spans the range from very basic to very advanced. The primary functions of the control panel are to energize the system, select forward or reverse travel direction, and select travel speed by the percent timer setting. The entry-level basic control panels from center pivot manufacturers provide those functions and little else. As the control panel type moves toward the advanced end of the spectrum, more features are added to the package, including auto-reverse, auto-stop, digital displays, end gun controls, pivot angle, auxiliary controls, auto-speed, programming capabilities, touch screen controls, and remote monitoring and control.

## Surface Irrigation (Flood/Furrow)

Darrin M. Dodds



Figure 9.6 – Furrow irrigation in progress.

Surface irrigation is the oldest and most common form of irrigation (NRCS 2008). Surface irrigation is a broad term applied to irrigation practices through which water is applied to the soil surface and flows gravimetrically across the soil surface.

### Field Geometry

The field in which surface irrigation will be applied must have a positive and continuous grade to facilitate water movement across the field and to prevent water retention (University of Arkansas, 2006). In order to facilitate surface irrigation, many producers perform earth-moving operations in order to gain a

positive and continuous grade utilizing equipment supplied with real-time kinematic (RTK) global positioning systems (GPS). Grades should be a minimum of 0.1% and no more than 0.5%. Grades between 0.15% and 0.3% are considered optimum (University of Arkansas, 2006). Cotton growers typically plant on beds which run from the highest elevation point in the field to the lowest elevation point. Once the crop is established, irrigation water is typically introduced to the field through a pipe system from which irrigation water runs gravimetrically down the furrows to the end of the row. To a lesser extent, growers will plant cotton flat on precision-graded fields, introduce irrigation water at a central point, and allow it to flow freely across a given field.

Row length must also be considered when using surface irrigation. Generally speaking, rows 1,320 feet or less in length are more desirable than longer rows. Excessive row length can lead to problems with soil saturation where irrigation water enters the field, whereas the ends of the rows may have yet to be watered or have only received minimal amounts of irrigation water. Irrigation should be applied for a maximum of 10–12 hours, depending on soil texture, in order to prevent water logging near the point of water introduction (University of Arkansas, 2006). If issues arise with water logging at one end of the field and dry soil at the other, growers should consider reducing the number or rows being watered at one time and/or reduce the length of irrigation runs.

### Water Source

Water used for surface irrigation may come from a variety of sources. In some cases, water is extracted from aquifers using wells equipped with electric or engine-driven pumping systems. However, surface irrigation water may also be extracted from rivers, lakes, or reservoirs. In some



areas of the Cotton Belt, rainfall or melted snowfall is held in impoundments until it is needed for irrigation. Irrigation water used in the siphon tube irrigation system is held in earthen ditches. In some cases, these ditches are lined with concrete or plastic in order to limit water loss through the soil (Sansone, et al., 2012).

Regardless of water source, water quality must be considered when being used for irrigation. Increased salinity of irrigation water is not an uncommon occurrence. Increased salinity in irrigation water typically leads to increased concentration of salts within the plant's root zone (NRCS 2008). In addition, water obtained from aquifers in some areas is high in calcium. Water high in calcium that is used for irrigation can have a similar effect as applying low rates of calcium carbonate, or agricultural limestone, to the soil.

### Irrigation Water Delivery

As mentioned previously, irrigation water is typically delivered to a given irrigation riser through power take-off-driven, engine, or electric powered pumps. Although engine-driven pumps have been standard for some time, some producers choose to use electric pumps. Electric pumps are not standalone units as they must be located in an area where electricity is available. In some areas, cost for use of electric pumps for irrigation is elevated during certain times of the day when general electric demand is at peak use. In order to avoid increased costs, growers should plan irrigation applications around these times.



Irrigation water is typically introduced from a single point on fields that are precision graded and planted flat. Water is supplied to the point of entry through a pumping system, and water is allowed to flow freely across a given field once these entry valves are opened.

### The Siphon Tube System

In most cases, cotton will be planted on beds, and water will be applied to the furrows that are adjacent to each bed. There are a number of ways that water is directed into these furrows. The siphon tube system consists of an aluminum or plastic pipe that is laid over the bank of an open ditch as described above. One end of this tube is submerged in the ditch with the other directed into the furrow that is to be irrigated. Water flows into the submerged end of the tube and is siphoned over the bank and into the furrow. Flow rate is controlled by the diameter of the tube and the elevation difference between the water surface in the ditch and the end of the outlet tube

(Smathers, et al., 1995). Flow rate tends to be very uniform using siphon tubes; however, trash screening devices must be utilized to prevent trash within the irrigation ditch from clogging the siphon tubes.

## Pipe Systems

Pipe systems are very common in surface irrigation systems. Flow rate requirements for pipe systems are approximately 10 gallons per minute per irrigated acre (University of Arkansas, 2006). Irrigation water is supplied to a point of introduction; however, rigid pipe or flexible tubing is attached to the irrigation riser and are used to distribute irrigation water across a large number of rows. Once the pipes are connected to the riser, they run perpendicular to the rows. Gated pipe systems typically use PVC or aluminum pipe with rectangular, adjustable outlets used to control irrigation flow rate. Although rigid, gated pipe systems can be reused from year to year they are becoming less common. Rigid pipe systems cannot be crossed with equipment when conducting field operations, which leads to decreased efficiency and increased labor costs.

## Poly Pipe Systems

Flexible pipe (henceforth referred to as poly pipe) systems are becoming increasingly popular. Poly pipe is attached to an irrigation riser and runs perpendicular to the rows similar to gated pipe. However, holes are punched into the poly pipe manually and, once holes are punched, flow rate can be increased but not decreased. Holes may be blocked if irrigation is not needed in a given row through the use of plugs. Poly pipe is available in several diameters and thickness levels. Thickness of poly pipe will dictate durability with thinner pipe (i.e., 6 mil) being less durable than thick pipe (i.e., 15 mil). As pipe thickness increases, pressure can be increased as well. Generally, pressure should not exceed 3 PSI when using poly pipe. When not in use, poly pipe will lay somewhat flat with some water remaining in the pipe. However, if equipment operators exercise caution, they can cross poly pipe when not in use without damaging it. Poly pipe typically comes in 1,320-foot rolls and, unlike rigid pipe systems, is used for one growing season only. Poly pipe is generally collected at the end of the growing season and recycled.







## Irrigation Water Quality

*Theophilus Udeigwe*

Water quality is an important consideration in irrigation practices because of the effects on crop and soil. Irrigation water of high salt content could harm crops and induce soil degradation. Crop tolerance to salt differs significantly. For instance, cotton could maintain its maximum yield potential in a soil with electrical conductivity of 7.7 dS/m, while corn would only reach 50% of its yield potential under a similar condition. Likewise, the maximum chloride concentration without yield loss are 2,625 and 525 mg/L for cotton and corn, respectively.

Although water quality does not present serious challenges to cotton irrigation in many areas of the humid U.S., routine water quality assessment is still highly encouraged, particularly in drip irrigation systems. Emitter clogging is often a function of water quality and affects the uniformity of water distribution and irrigation efficiency. Emitters could be clogged by physical (e.g., sand and silt), chemical (e.g., salts and metals), and biological (e.g., algae and bacteria) materials. Simple irrigation water quality indicators include electrical conductivity (EC, mmhos/cm or dS/m), sodium adsorption ratio (SAR), total dissolved salts (TDS, mg/L), and bacterial counts (no./ml). Irrigation water of > 100 mg/L suspended solids, > 2,000 mg/L dissolved solids, > 50,000 bacteria (number/ml), and pH > 8.0 could increase the chances of emitter clogging.



# References and Additional Resources

## Section 1 – Why Irrigate Cotton

Grismer, M.E. 2002. Regional cotton lint yield, ETC and water value in Arizona and California. *Agric. Water Manage.* 54:227–242.

Zwart, S.J. and W.G.M. Bastiaanssen. 2004. Review of measured crop water productivity values for irrigated wheat, rice, cotton, and maize. *Agricultural Water Management* 69:115-133.

## Section 2 – Why schedule Irrigation

Grimes, D.W., and K.M. El-Zik. 1990. Cotton. p. 741–748. In B.A. Stewart and D.R. Nielsen (ed.) *Irrigation of Agricultural Crops*. Agron. Monogr. 30. ASA, CSSA, and SSSA, Madison, WI.

## Section 3 – Initiating and Terminating Irrigation for the Season

Vories, E. D., R. Hogan, P. L. Tacker, R. E. Glover, S. W. Lancaster. 2007. Estimating the impact of delaying irrigation for midsouth cotton on clay soil. *Transactions of the ASABE* 50(3): 929–937.

Vories, E.D., J. K. Greene, T. G. Teague, J. H. Stewart, B. J. Phipps, H. C. Pringle, E. L. Clawson, R. J. Hogan, P. F. O’Leary, T. W. Griffin. 2011. Determining the optimum timing for the final furrow irrigation on mid-south cotton. *Transactions of the ASABE* 27(5): 737-745.

## Section 4 – Cotton Water Requirements

Allen, R.G., I.A. Walter, R. Elliot, T. Howell, D. Itenfisu and M. Jensen, 2005: The ASCE standardized reference evapotranspiration equation. American Society of Civil Engineers. Reston, Virginia

Farahani, H.J., T.Y. Oweis, and G. Izzi. 2008. Crop coefficient for drip-irrigated cotton in a Mediterranean environment. *Irrig. Sci.* 26:375-383.

Fisher, D.K. 2004. Simple and inexpensive lysimeters for monitoring reference- and crop-ET. *Proceedings of the 25th Annual International Irrigation Conference*, November 14-16, Tampa, Florida.



Hunsaker, D.J., E. M. Barnes, T. R. Clarke, G. J. Fitzgerald, P. J. Pinter Jr. 2005. Cotton Irrigation Scheduling Using Remotely Sensed and FAO-56 Basal Crop Coefficients. Transactions of the ASAE, Vol. 48(4): 1395\_1407.

Howell, T.A., S.R. Evett, J.A. Tolk, and A.D. Schneider. 2004. Evapotranspiration of full-, deficit-irrigated, and dryland cotton on the northern Texas high Plains. J. Irrig. Drain. Eng. 130:277-285.

## **Section 5 – Water-Sensitivity of Cotton Growth Stages**

Hake, K.D. and G.W. Grimes. 2010. Crop water management to optimize growth and yield. P. 255-264. In James McD. Stewart, Derrick Oosterhuis, James J. Heithold, and Jack R. Mauney (eds) Physiology of Cotton. Springer-Verlag GmbH. Heidelberg, Germany.

Krieg, D.R. 2000. Cotton water relations. P. 7-15. In Derrick Oosterhuis (ed) Special Report 198 Proceedings of the 2000 Cotton Research Meeting and Summaries of Cotton Research in Progress. University of Arkansas Division of Agriculture, Fayetteville, Arkansas. (Available online <http://arkansasagnews.uark.edu/198ms3.pdf>)

## **Section 6 – Sensor-Based Scheduling**

Leib, B. G., J. D. Jabro, and G. R. Matthews. 2003. Field evaluation and performance comparison of soil moisture sensors. Soil Science 168(6):396-408.

## **Section 7 – Irrigation Scheduling Tools**

There are several weather-based scheduling programs now available including online data in a majority of cotton producing states, traveling from west to east:

- California: California Irrigation Management Information System (CIMIS) – <http://www.cimis.water.ca.gov/>
- Arizona: Arizona Irrigation Scheduling System – <http://ag.arizona.edu/crop/irrigation/azsched/azsched.html>
- West Texas: Texas High Plains ET Network – <http://txhighplainset.tamu.edu/>
- South Texas: Crop Weather Program – <http://cwp.tamu.edu/>
- Oklahoma: Mesonet – <http://www.mesonet.org/>
- Arkansas: Irrigation Scheduling Program – [http://www.aragriculture.org/computer\\_programs/irrigation\\_scheduling/](http://www.aragriculture.org/computer_programs/irrigation_scheduling/)



- Missouri: Woodruff charts (<http://ag2.agebb.missouri.edu/irrigate/woodruff/choose1.asp>) and Show Me Irrigator (<http://irrigationtoolbox.com/ReferenceDocuments/TechnicalPapers/IA/2004/IA04-1079.pdf>)
- Alabama: MoisMIS2020 (<http://www.aces.edu/timelyinfo/BioSysEng/2010/May/BSEN-IRR-10-01.pdf>)
- Mississippi: Mississippi Irrigation Scheduling Tool (<http://www.agwater.msucare.com>)
- Tennessee: Management Of Irrigation Systems in Tennessee (MOIST – [http://www.utcrops.com/irrigation/irr\\_mgmt\\_moist.htm](http://www.utcrops.com/irrigation/irr_mgmt_moist.htm))
- Georgia: – Irrigator Pro (<http://www.ars.usda.gov/services/software/download.htm?softwareid=249>)

## Section 8 – Management Considerations for Irrigated Cotton

Hake, K., D. Krieg, J. Landivar, and D. Oosterhuis. 1992. Plant water relations. *Cotton Physiology Today* 3(7). (Available at: <http://www.cotton.org/tech/physiology/cpt/plantphysiology/upload/CPT-July92-REPOP.pdf>)

Wrona, A.F., and D.R. Krieg. 2000. Factors affecting water use. *Cotton Physiology Today* 11(1). National Cotton Council. (Available at: <http://www.cotton.org/tech/physiology/cpt/plantphysiology/upload/CPT-v11No1-2000-REPOP.pdf>)

## Section 9 – Irrigation Systems Overview

### *Drip Irrigation*

Boman, B. S. Smith and B. Tullos. 2002. Control and Automation in Citrus Microirrigation Systems. Circular 1413, Agricultural and Biological Engineering Department, Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida.

Camp, C.R., W.M. Thomas, and C.C. Green. 1993. Microirrigation scheduling and tube placement for cotton in the southeastern coastal plain. *Trans. ASAE* 36(4):1073-1078.

Camp, C.R., E.J. Sadler, and W.J. Busscher. 1989. Subsurface and alternate-middle microirrigation for the southeastern coastal plain. *Trans. ASAE* 31(2):451-456.

Khalilian, A., M. J. Sullivan, W. B. Smith. 2000. Optimum lateral depth for subsurface drip irrigation in coastal plain soils. *Proceedings of the 4th Decennial Irrigation Symposium*. ASAE.

Pitts, D.J., D.Z. Haman and A.G. Smajstrla. 1990. Causes and Prevention of Emitter Plugging in Microirrigation Systems. Bulletin 258, Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida



## **Surface Irrigation**

Natural Resources Conservation Service [NRCS]. 2008. NRCS National Engineering Handbook – Part 623: Irrigation. Chapter – Surface Irrigation. <http://directives.sc.egov.usda.gov/viewerFS.aspx?id=3886>. Accessed: 03 April 2012.

Sansone, C., T. Isakeit, R. Lemon, and B. Warrick. 2012. Texas Cotton Production – Emphasizing Integrated Pest Management. Texas AgriLife Extension Service. <http://lubbocktx.tamu.edu/cottondvd/content/cottondvd/General%20Production/texasottonproduction/tcpemphipm.html> Accessed: 03 April 2012.

Smathers, R.L., B. A. King, and P.E. Patterson. 1995. Economics of Surface Irrigation Systems. University of Idaho Cooperative Extension Service Bulletin No. 779.

University of Arkansas. 2006. Irrigation Methods – Furrow Irrigation Method. University of Arkansas Division of Agriculture. [http://www.aragriculture.org/soil\\_water/irrigation/methods/furrow.htm](http://www.aragriculture.org/soil_water/irrigation/methods/furrow.htm) Accessed: 03 April 2012.

## **Center Pivots**

Hoffman, G.J., R.G. Evans, M.E. Jensen, D.L. Martin, and R.L. Elliott. 2007. Design and operation of farm irrigation systems. Second edition. American Society of Agricultural and Biological Engineers, St. Joseph, MI.

Lascano, R.J. and R.E. Sojka. 2007. Irrigation of Agricultural Crops. Agronomy Monograph 30, Second Edition. American Society of Agronomy, Madison, WI.

Keller, J. and R.D. Bliesner. 1990. Sprinkle and Trickle Irrigation. The Blackburn Press, Caldwell, NJ.

Stetson, L.E. and B.Q. Mecham. 2011. Irrigation. Sixth Edition. Irrigation Association, Falls Church, VA.

## **Irrigation and Water Quality**

Ayres, R.S. and D.W. Westcot. 1976. Water Quality for Agriculture. Irrigation and Drainage Paper No. 29. Food and Agriculture Organization of the United Nations. Rome

Nakayama F. and D. Bucks. 1991. Water quality in drip/trickle irrigation: a review. *Irrigation Science* 12:187-192.

