Mississippi IRRIGATION MANUAL

MISSISSIPPI STATE UNIVERSITY
EXTENSION

NCAAR
NATIONAL CENTER FOR ALLUVIAL AQUIFER RESEARCH

USDA U.S. DEPARTMENT OF AGRICULTURE | MISSISSIPPI STATE UNIVERSITY

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Section 1: Introduction

BACKGROUND

The Lower Mississippi River Basin is one of the United States' most productive and intensively irrigated agricultural regions, with 90% of the basin's irrigation water coming from the Mississippi River Valley Alluvial Aquifer (MRVA, fig. 1.1). Overdrawing this shallow, productive aquifer is negatively impacting agricultural productivity and profitability, base flows of streams, water quality, and aquatic and riparian habitats. Currently, scientists from U.S. Department of Agriculture's Agricultural Research Service (USDA ARS) and Mississippi State University are conducting research and extension activities on water-related issues at the National Center for Alluvial Aquifer Research (NCAAR).

HISTORY

The National Center for Alluvial Aquifer Research (NCAAR) was established by Congress in 2017 as a cooperative program between USDA ARS and the Mississippi Agricultural and Forestry Experiment Station at Mississippi State. NCAAR was created to address the water resources challenges in the Mississippi River Alluvial Aquifer.

MISSION

The mission of NCAAR is to conduct research and provide information on issues surrounding water use for agriculture and natural resources in the Lower Mississippi River Basin.

OBJECTIVES

NCAAR aims to produce and communicate research directed at the conservation and sustainability of water resources for agriculture. This research includes developing water-efficient cropping systems, improving water capture, improving water distribution systems and irrigation efficiencies, enhancing the use of water-saving irrigation management options, and developing economic risk assessment tools that enable producers to identify profitable, water-efficient production options.

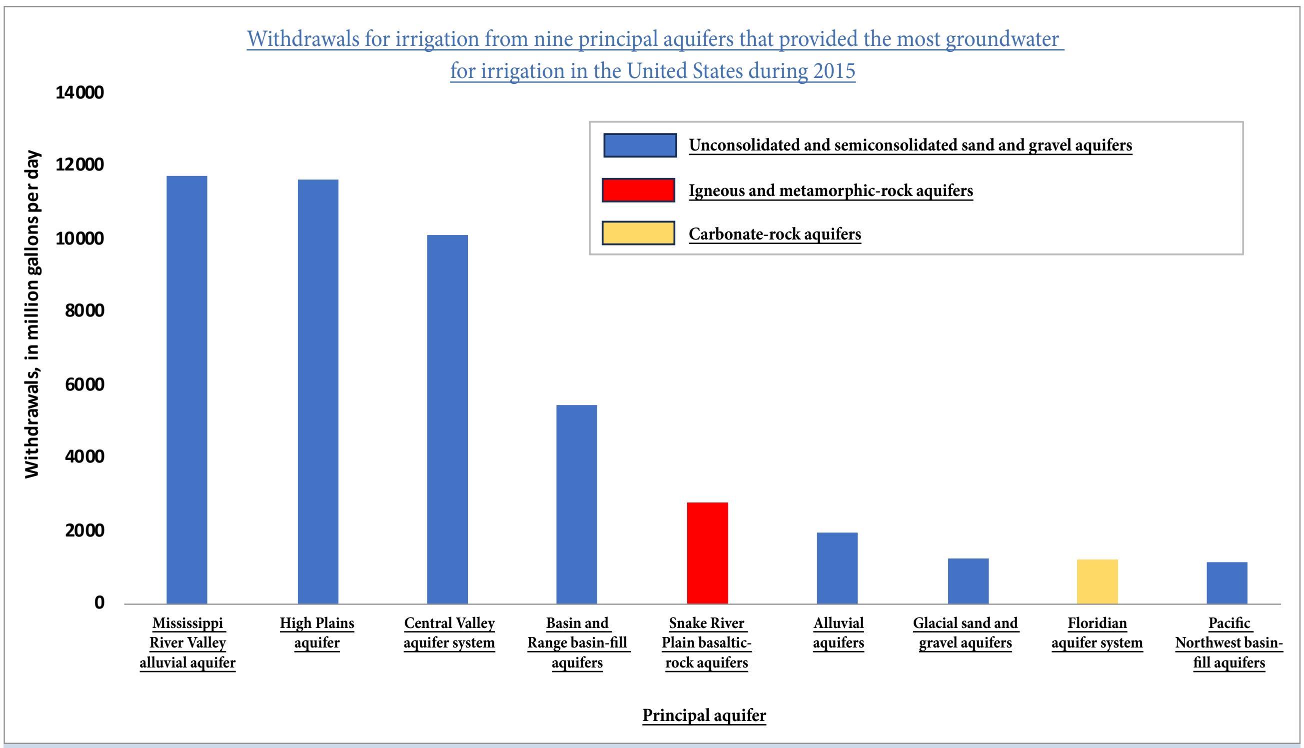

Figure 1.1. Groundwater irrigation withdrawals by aquifer (million gallons per day [mgpd])

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Section 2: Agronomics

SOIL CHARACTERISTICS

Physical Properties

The term *soil* refers to the weathered and fragmented outer layer of the Earth's terrestrial surface. Fragmenting and weathering, which break down parent material to form soil, are the result of both physical and chemical processes. Erosion caused by wind and water is the most visible soil-creating process.

A given volume of soil consists of four parts: mineral matter, organic matter, water, and air (fig. 2.1). The mineral and organic matter of a soil store nutrients required by crops. Changes in environment, erosion, and cultural practices can change soil makeup. The relative amounts of mineral and organic matter determine the physical properties of soil. The remaining volume of soil, composed of spaces between the mineral and organic matter, is the pore space. The pore space is filled with varying amounts of water and air.

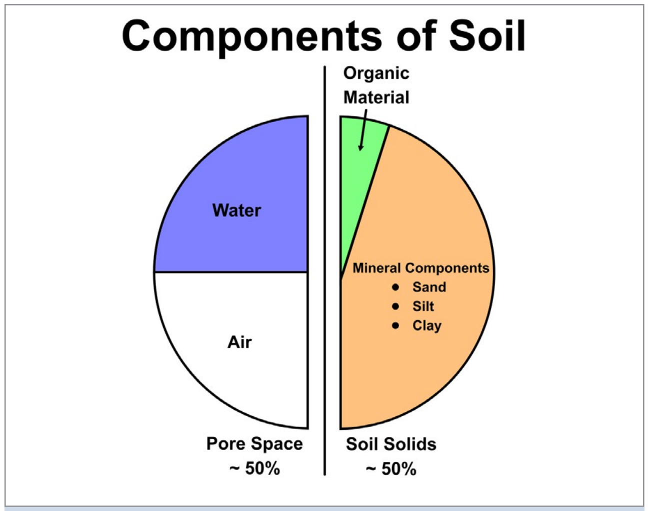

Figure 2.1. The four components that make up a given volume of average soil

Credit: JasonHS via Wikimedia Commons, Creative Commons Attribution-ShareAlike 4.0.

Coarse soils, such as sands and gravels, have relatively large pores; however, the number of pores is small when compared to a finer soil. Finer soils, like clays or clay loams, have relatively small pores, but many, many of them. The small but abundant pores allow finer soils to hold more water (fig. 2.2).

Soil Texture

Soil texture is determined by the relative amounts of three groups of soil particles or **soil separates**. The three soil separates are sand, silt, and clay. Texture provides a means to physically describe soil by feel or by measuring the proportion (percentage) of the three soil particle size ranges. A coarse soil has a relatively large amount of **sand** and feels gritty. A **silt** soil has the texture and feel of flour. A **clayey** soil may feel slick or sticky, depending on its water content. A loam soil has nearly equal amounts of sand, silt, and clay. The relative sizes of the three **soil separates** are compared in Figure 2.3. Sand particles can be seen by the naked eye. A microscope must be used to see silt particles. An electron microscope is needed to see clay particles.

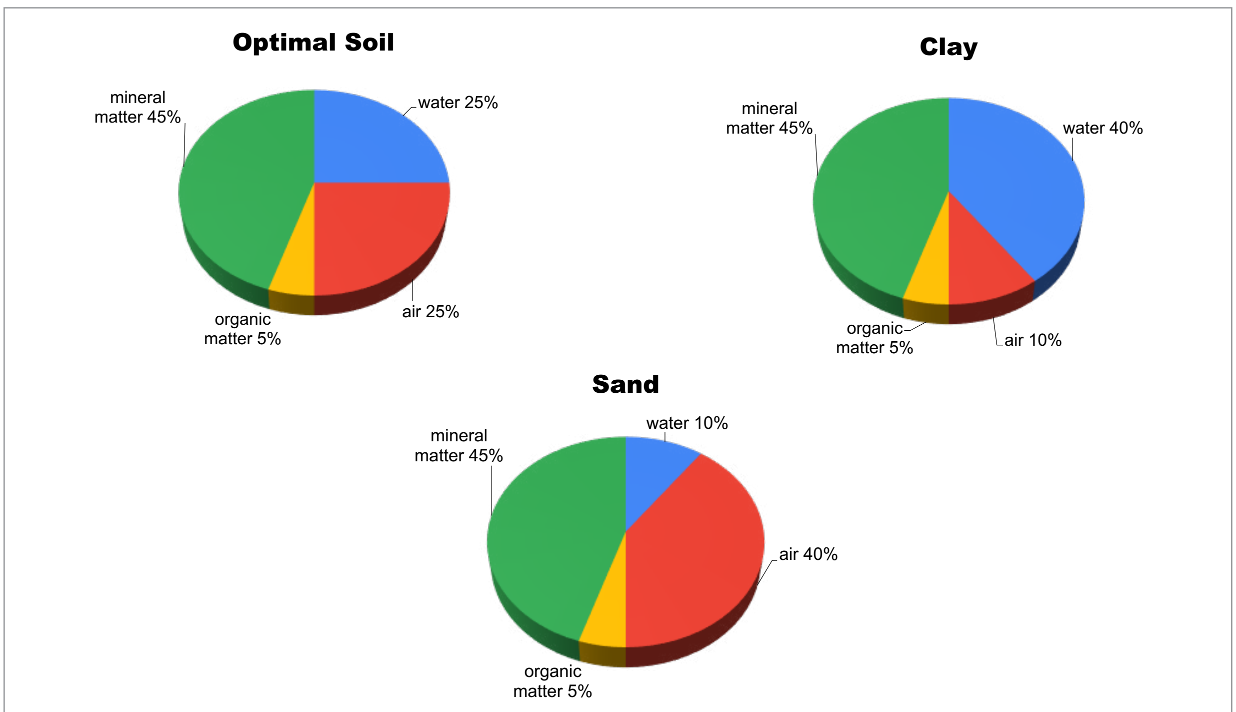

Figure 2.2. The four components of soil by soil type

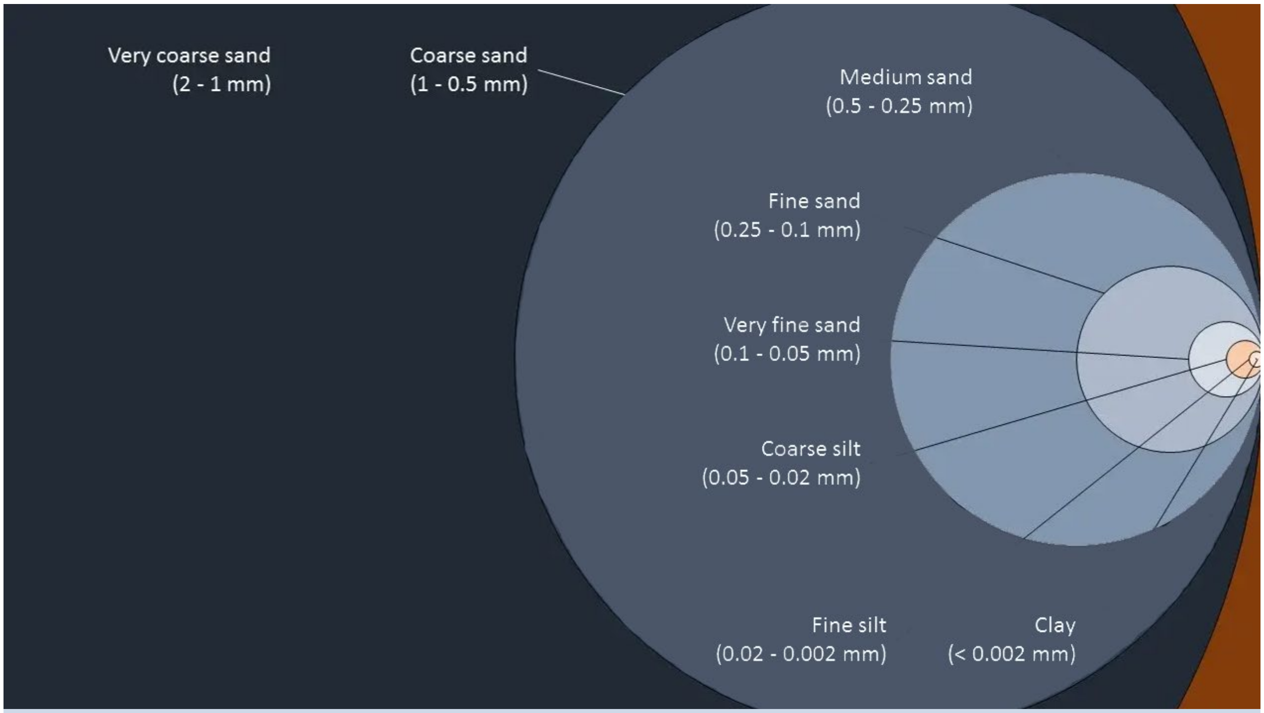

Figure 2.3. Relative sizes of soil separates: sand, silt, and clay

Credit: Antonio Jordán, Creative Commons Attribution-ShareAlike 3.0.

A **textural triangle** (fig. 2.4) is used to describe soil texture. The three sides of the triangle represent the percentages of sand, silt, or clay. The intersection points of three lines from each side of the triangle determine how the soil texture will be classified. For example, if a soil has 20 percent clay, 40 percent sand, and 40 percent silt, it is a loam (*see the triangle in the area labeled* loam).

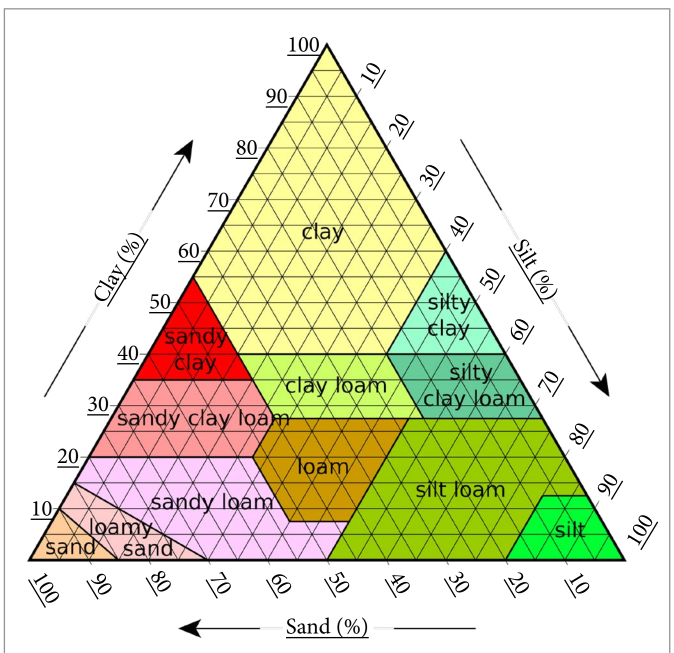

Figure 2.4. Soil textural triangle

Credit: Christopher Aragón via Wikimedia Commons, Creative Commons Attribution-Share Alike 4.0

Soil Structure

Soil structure refers to the arrangement and organization of soil separates or individual soil particles into units called soil aggregates. The arrangement of **soil aggregates** gives soil its structure. There are three broad categories of soil structure—single grained, massive, and aggregated. Generally, the most desirable structure for plant growth is aggregated, especially in the critical early stages of germination and seedling establishment. The principal types of soil aggregates are platy, prismatic, columnar, blocky, and granular (fig. 2.5).

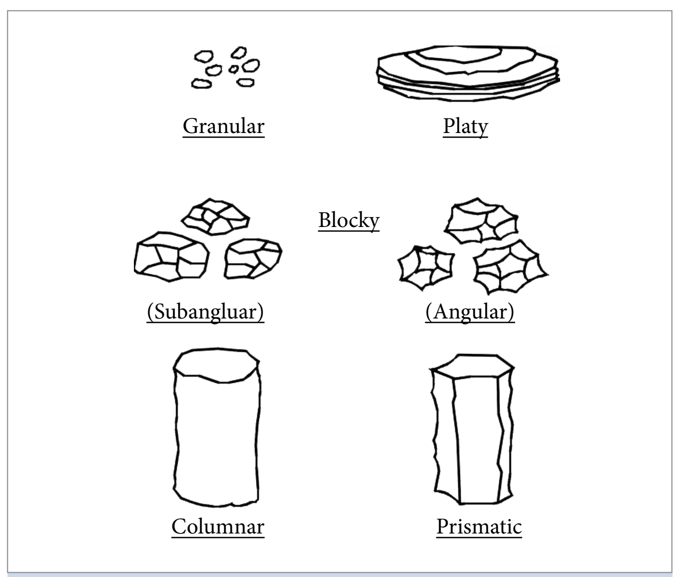

Figure 2.5. Types of soil aggregates

Credit: University of Nebraska-Lincoln

The processes that form aggregates are as follows:

- wetting and drying
- freezing and thawing
- decaying organic matter
- activity of roots, small animals, and bacteria
- soil tillage

The wetting/drying and freezing/thawing actions, as well as root and animal activity, push particles back and forth to form granules. Decaying plant residues and bacterial slimes coat these granules and bind them together to form aggregates. Tillage can expose soil near the surface to the destructive forces of erosion. Repeated traffic, especially when soil water content is high, destroys near-surface aggregates and compacts the soil.

A soil's physical properties are expressed numerically by the following characteristics: particle density, bulk density, and pore space or porosity.

Particle Density

Particle density is the weight of a given soil particle per unit volume. In other words, it is the weight of a soil particle or separate, divided by the volume of that soil particle or separate. In most mineral soils, the average particle density is between 2.6 and 2.7 grams per cubic centimeter (g/cm^3). By contrast, organic matter typically has a particle density of about 0.8 g/cm^3. Water, by definition, has a density of 1 g/cm^3.

Bulk Density

Bulk density of a soil is defined as the weight per unit volume of soil. A unit volume of soil includes both the solids and the pore space (fig. 2.6). Bulk density is important because it reflects the porosity of a soil. Loose, porous soils have lesser bulk densities than tight, compacted soil. The bulk density of a soil increases with compaction. Bulk density indicates how easily a soil will till, how easily water will infiltrate, how it will hold water, and how suitable it is for growing plants.

Using the numbers shown in Figure 2.6, the bulk density for this example is determined as:

$$\text{Bulk density } B_V = \text{Mass of soil} / \text{Volume of soil unit} = 1.3 \text{ g} / 1.0 \text{ cm}^3 = 1.3 \text{ g/cm}^3$$

In other words, the soil in this example is 1.3 times heavier than the same volume of water.

The particle density for this example is:

$$\text{Particle density} = \text{Mass of soil} / \text{Volume of solids} = 1.3 \text{ g} / 0.5 \text{ cm}^3 = 2.6 \text{ g/cm}^3$$

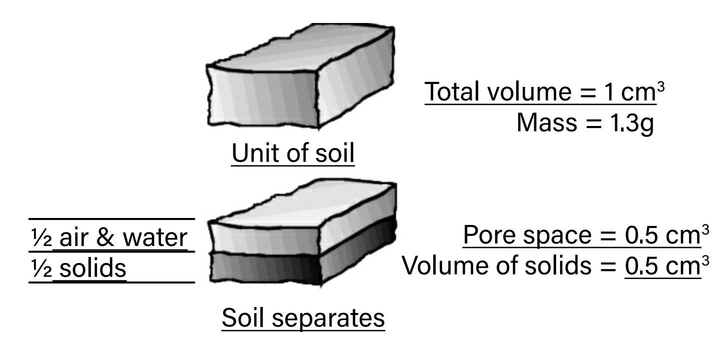

Figure 2.6. Bulk density and particle density
Credit: University of Nebraska-Lincoln

Typical soil bulk densities for fine sands, silt loams, and silty clay loams are 1.5, 1.35, and 1.25 g/cm^3, respectively.

Stable soil aggregates are important in a soil because they help maintain good soil structure. Good soil structure translates into low bulk densities (1.3–1.5 g/cm^3). If an aggregate is crushed, its bulk density increases and pore space decreases. High bulk densities (>1.6 g/cm^3) can result from compaction. Compaction can result from tilling a soil when it is wet. Compaction caused by wheel traffic can increase the bulk density to a depth of at least 1 foot. Smearing (the destruction of soil structure caused by shearing) can create what's called a tillage pan. Figure 2.7 illustrates the concept of compaction from tillage or traffic or both. As a rule of thumb, bulk densities greater than 1.7 to 1.8 g/cm^3 impede root penetration.

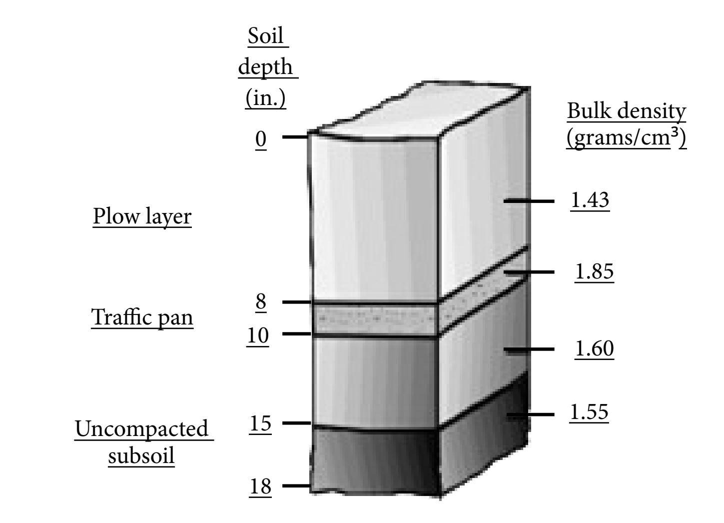

Figure 2.7. Tillage and traffic compaction
Credit: University of Nebraska-Lincoln

Soil Porosity

The space between soil particles is the **pore space**. This pore space contains varying amounts of water and air. Soil porosity depends on soil texture and structure. Soils with lesser bulk densities have greater porosities. Good porosity is essential to adequate soil aeration, water drainage, and root penetration. Silty and clayey soils have smaller pores but many more pores than a sandy soil. Water can be held tighter in small pores than in large pores. For this reason, a clay loam with its many small pores can hold more water than a sand. Even though the individual soil particles and pores are larger in sands, the porosity or total pore volume is less in sands than in silty or clayey soils. This characteristic causes the bulk density to be greater for sands.

THE SOIL PROFILE

Soil is the weathered remains of parent material. All soils have distinctive characteristics reflecting the parent material and the forces which formed it. A mature soil profile consists of six layers or horizons (fig. 2.8). These layers or horizons are represented by the letters O, A, E, B, C, and R. Immature soils lack some of these layers. The O horizon is a layer of soil created by decomposed organic matter or humus. The A horizon, or topsoil, is the surface layer and usually has the greatest organic matter content. Soil horizon E is a complex layer that is mostly sand, quartz silt particles, and other materials that can't be leached away. Anything that can't be leached out of the soil is left behind and makes up this layer. Soil horizon B is the subsoil layer. All the materials, such as minerals that are leached from the soil horizon A and E, make up this layer in the soil profile. Soil Horizon C is the parent material layer. The Earth's surface deposits created this layer. Together, the A, B, and C horizons form the soil profile. Soil horizon R is made up of bedrock. The rocks typically found in this layer include limestone, quartzite, sandstone, basalt, and granite ("The Ultimate Guide to Soil Horizons" 2019).

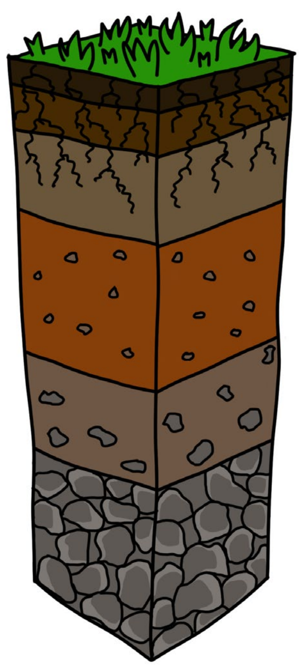

Figure 2.8. The six soil layers or horizons

Credit: Lewi1224 via Wikimedia, Creative Commons Attribution-Share Alike 4.0 International.

SOIL WATER

The following segments related to soil water are adapted from "Soil Water," written by D. Yonts and B. Benham for the Irrigation Home Study Course published by the University of Nebraska-Lincoln Plant and Soil Sciences eLibrary (https://passel2-stage.unl.edu/view/lesson/bda727eb8a5a/3).

Available water capacity and water-holding characteristics of soils are critical to water management planning for irrigated and dryland crops. Deciding what crop to plant, how much to plant, when to irrigate, how much to irrigate, when to apply nitrogen, and how much nitrogen to apply depends, in part, on the water-holding capacity of soils.

Soil Water Definitions

To adequately discuss soil water, you must be familiar with the following terms:

Soil water: water contained within or flowing through the soil profile. Surface water must infiltrate the soil profile to become soil water. Groundwater is subsurface water in sufficient quantity that wells or springs can use it.

Excess soil water or gravitational water: water that drains or readily percolates below the *active root zone* by the force of gravity. Since drainage takes time, part of the excess water may be used by plants before it moves out of the root zone.

Available soil water: water that is retained in the soil and can be extracted by the plant. The **available soil water** is most important for crop production. It is the water held by the soil between **field capacity** and **permanent wilting point**.

Field capacity: the water content of a soil at the upper limit of the **available soil water** range. It is the amount of water remaining in a soil after the soil has been saturated and allowed to drain for approximately 24 hours.

Permanent wilting point: the lower limit of the **available soil water** range. When plants have removed all the available water from a given soil, they wilt and will not recover. Figure 2.9 illustrates the concepts of **field capacity** and **permanent wilting point**.

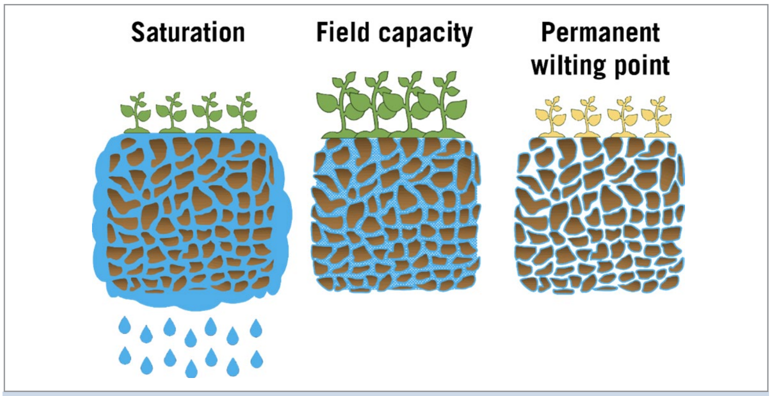

Figure 2.9. Soil saturation, field capacity, permanent wilting point, and soil water retention

Credit: University of Georgia Extension

Minimum allowable balance: the **soil water content** at which crops begin to experience water stress. Plants can use approximately 50 percent of the available soil water without experiencing water stress (a shortage of water). Normally, the **minimum allowable balance** is 50 percent of the **available soil water**. For example, if your soil is a uniform loam with available soil water of 2.0 inches/foot, and the crop's active root zone is 3 feet, then the available soil water in the active root zone is 2.0 inches/foot times 3 feet, or 6.0 inches. The **minimum allowable balance** in that 3-foot active root zone would therefore be 6.0 inches times 50%, or 3.0 inches.

Unavailable water: soil water held so firmly to soil particles by adsorptive soil forces that it cannot be extracted by plants. Unavailable water is still present when soil is drier than **permanent wilting point**.

Based on these definitions, soil water is classified into three categories:

- excess soil water or gravitational water
- available soil water
- unavailable soil water

Available water is further broken down into readily available water, with no plant stress, and less available water, with plant stress likely. Figure 2.10 is a schematic representation of soil water reservoir components. The size of the reservoir depends on the crop's active rooting depth.

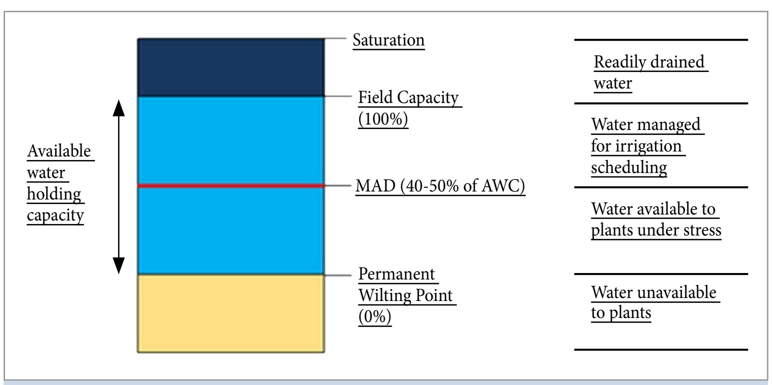

Figure 2.10. Soil water reservoir components

Credit: University of Minnesota Extension

Soil Water Retention

Despite the belief that soil absorbs water, water is "held" in the soil in two ways: 1) as a film coating on soil particles, and 2) in the **pore space** between particles (fig. 2.9). When water infiltrates into the soil from either precipitation or irrigation, the pore spaces are nearly filled with water. During and immediately after a rain or irrigation, the greatest vertical movement of water occurs in the soil. After this initial movement, as the soil reaches **field capacity**, water movement continues due to gravity and capillary action. Capillary action is important for retaining water in the soil pores.

Small tubes (capillary tubes) can be used to illustrate capillary action. Like soil pores, capillary tubes come in different diameters. When one end of a capillary tube is placed in water, water will rise in the tube because the capillary action is stronger than the pull of gravity. Because capillary action is stronger than gravity, water will never completely drain through the soil profile. Some water will always be held in the soil profile. Water rises farther in small capillary tubes than in larger ones. Larger capillary tubes correspond to coarser textured soils (sands have large pores). Smaller capillary tubes correspond to finer textured soils (clays have small pores). Capillary action can best be explained with an illustration, Figure 2.11.

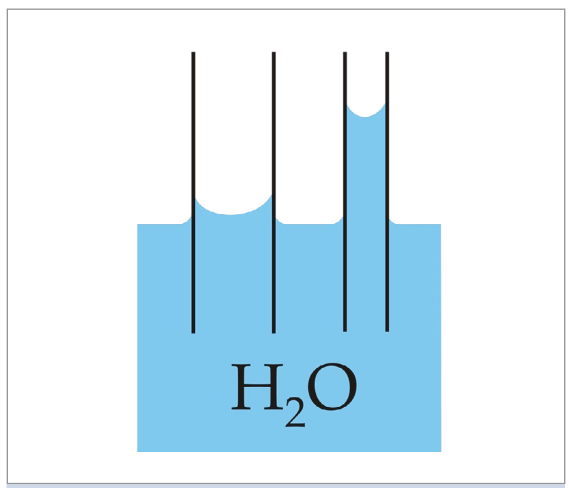

Figure 2.11. Capillary action is illustrated by how far water rises in tubes of different diameters.

Credit: via Wikimedia Commons, Creative Commons Attribution-Share Alike 2.5 Generic

Figure 2.12 illustrates how water will be drawn up into three soil types. Three tubes containing soils of differing textures are placed upright in a tub of water. The water rises highest in the clay because it has the smallest pores. The clay soil exerts the greatest capillary action on the water. The fine sand having the larger pores exert the least force.

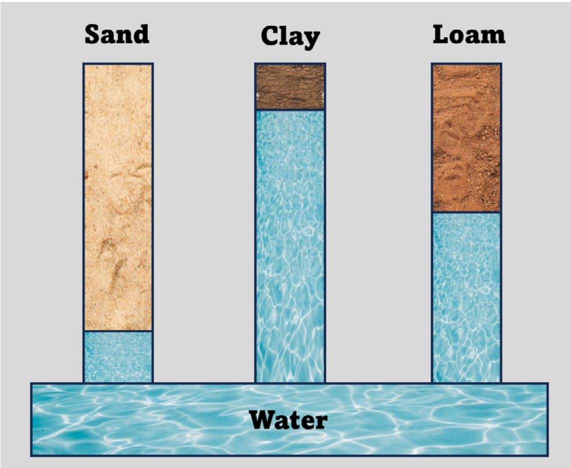

Figure 2.12. Capillary action illustrated by the relative height of wetting for three soil textures

Figures 2.11 and 2.12 illustrate how water is held in soils. The capillary action or *tension,* which holds water in the soil, is most important to plant growth. Smaller pores hold water with more tension (negative pressure) than larger pores. As soil dries, the tension of the remaining water increases. Plants can extract less and less water as the soil water tension increases.

Available Water Capacities

A soil's water storage characteristics are very important for irrigation management. Since the size and number of pores in soils are directly related to **soil texture**, soil texture is the indicator for how much water a soil can hold. Table 2.1 can be used to determine the amount of available soil water that a soil of a given texture will hold. This is its available water capacity. Figure 2.13 shows the actual quantity of water stored for four soil textures. The numbers are presented on an inches-per-foot basis.

TABLE 2.1. Available water capacity based on soil texture

Textural classes	Available water capacity in inches/foot of depth
Coarse sand	0.25–0.75
Fine sand	0.75–1.00
Loam sand	1.10–1.20
Fine sandy loam	1.50–2.00
Silt loam	2.00–2.50
Silty clay loam	1.80–2.00
Silty clay	1.50–1.70
Clay	1.20–1.50

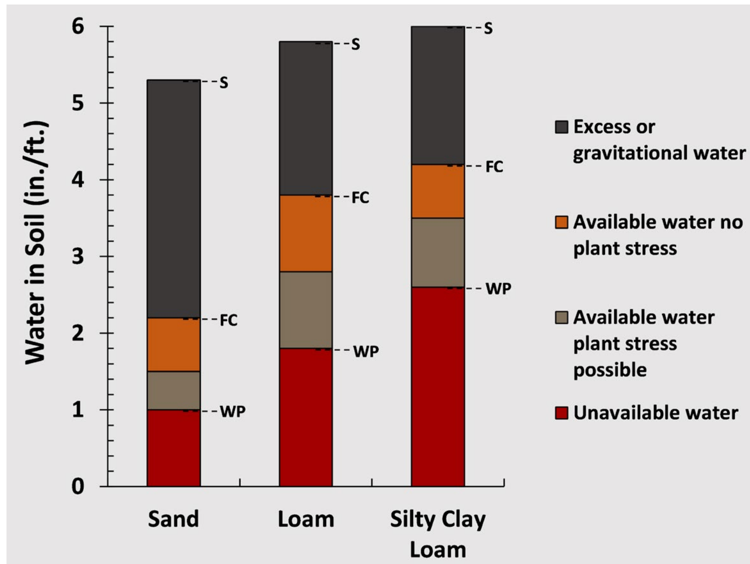

Figure 2.13. Soil water components in three common soil types
Credit: USDA, University of Nebraska-Lincoln

Knowing the soil water content in the crop's active root zone and the available water capacity is key to applying the right amount of irrigation at the right time—that is, **irrigation scheduling**. Soil water holding characteristics are important for irrigation system selection, irrigation scheduling, crop selection, and maintaining groundwater quality. Since soil can hold only so much water, excess or gravitational water moves out of the crop root zone toward the groundwater table. Many nutrients and chemicals move with the water and can eventually be found in the groundwater, thereby degrading the quality of this resource.

Infiltration

To this point, we've discussed how and why the soil holds water, where soil water is retained, and how much water may be stored in a variety of soil types. With that background, let's turn our attention to how water moves into the soil profile. **Infiltration** is the process by which water enters the soil. **Intake rate** or **infiltration rate** is the speed at which water can be taken into soil during an irrigation or rainfall event.

To see how infiltration changes, we'll look at the infiltration at the upper end of a row being furrow irrigated. Figure 2.14 illustrates a typical infiltration curve for this soil. In this example, when water first enters the furrow, the **initial infiltration rate** at the top of the field is about 1.5 inches per hour. After 2 hours, the **intake** rate has decreased to just under 0.5 inches per hour. This means that after 4 hours, total infiltration is equal to 2.4 inches and the **infiltration rate** is close to the **basic infiltration rate** of 0.25 inches per hour. For a 12-hour irrigation, the total infiltration at this location is 4.6 inches, with a little over half that amount being infiltrated in the first 4 hours.

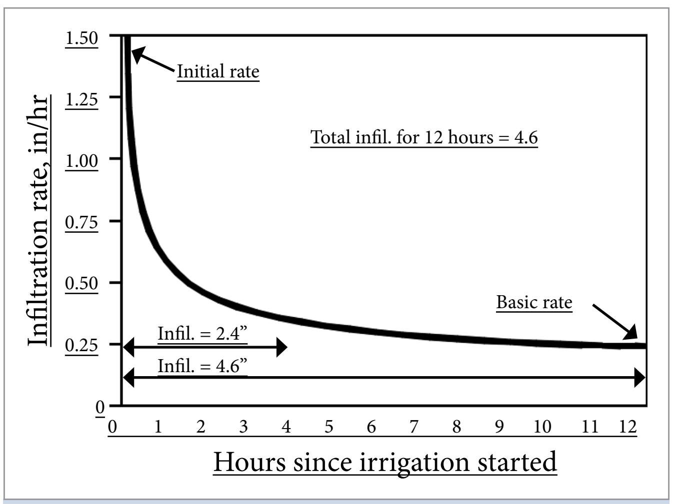

Figure 2.14. Typical infiltration curve for soil
Credit: University of Nebraska-Lincoln

The Natural Resources Conservation Service (NRCS) groups soils into one of four intake families, based on the soil's basic infiltration rate (from greatest to least—A, B, C, D). The NRCS and county soil surveys can provide information about the soils in your area. This and more information are also available using the web soil survey at http://websoilsurvey.nrcs.usda.gov/app/HomePage.htm. A range of basic infiltration rates for four common soil textures is presented in Table 2.2. Some typical generic infiltration curves for different soils are shown in Figure 2.15. For a sandy soil, both the initial and basic infiltration rate are usually greater than that for a silt loam. The basic infiltration rate for a very sandy soil may be almost as great as the initial rate for a very fine textured soil.

TABLE 2.2. Range of infiltration rates for several soil textures

Basic infiltration rate, inch/hour	Soil texture
0.50–0.75	Fine sand
0.35–0.50	Sandy loam
0.25–0.40	Silt loam
0.10–0.20	Clay

SOURCE: University of Minnesota Extension

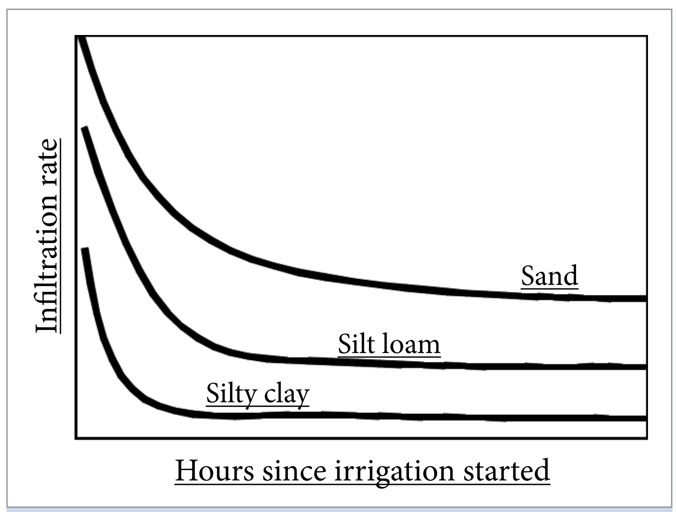

Figure 2.15. Typical infiltration curves for different soil texture
Credit: University of Nebraska-Lincoln

Infiltration rates change over the growing season. At any given time, they will likely vary across a field, even though the soil appears uniform. Soil surface conditions (wet or dry, cloddy or smooth, cracked or solid, compacted or loose) also affect infiltration. Plant residue left on the soil surface acts to disperse the energy of rain and sprinkler droplets. Reducing the energy of these droplets reduces compaction from the force of the droplets and inhibits soil surface crusting that sometimes occurs. Partially incorporating crop residues can enhance infiltration by providing avenues of water entry into the soil. Tillage may or may not increase infiltration. Deep tillage, like that performed with a chisel, generally increases infiltration rates by increasing surface roughness, which increases the opportunity for water to move into the soil. While proper tillage can increase infiltration rates, excessive or improper tillage can cause compaction at or near the soil surface. Compaction decreases infiltration rates. Soil slope also affects infiltration. Water applied to a steeper sloping field will obviously have less opportunity to infiltrate and more opportunity to run off.

Water Movement in Soil

How water moves once in the soil is an important factor in determining the suitability of land for irrigation. Movement or **redistribution** of water in the soil is dependent upon the size, number, and continuity of the soil pores.

Water movement through fine-textured soil into underlying sand and gravel does not occur until the finer material above the gravel is fully saturated (fig. 2.16a). Because the smaller pores in the finer material in the upper layer have a greater attraction for the water than the relatively larger pores on the underlying layer, the water moves laterally and fills the upper layer before moving into the coarse material below. Remember, the fine-textured soil was able to move water higher in the soil column. After the upper layer becomes saturated, water enters the underlying layer (fig. 2.16b). The practical implication is that in shallow soils underlain by sands, like those found in the Platte River Valley, water movement is slowed by the underlying coarse sand and gravel layer.

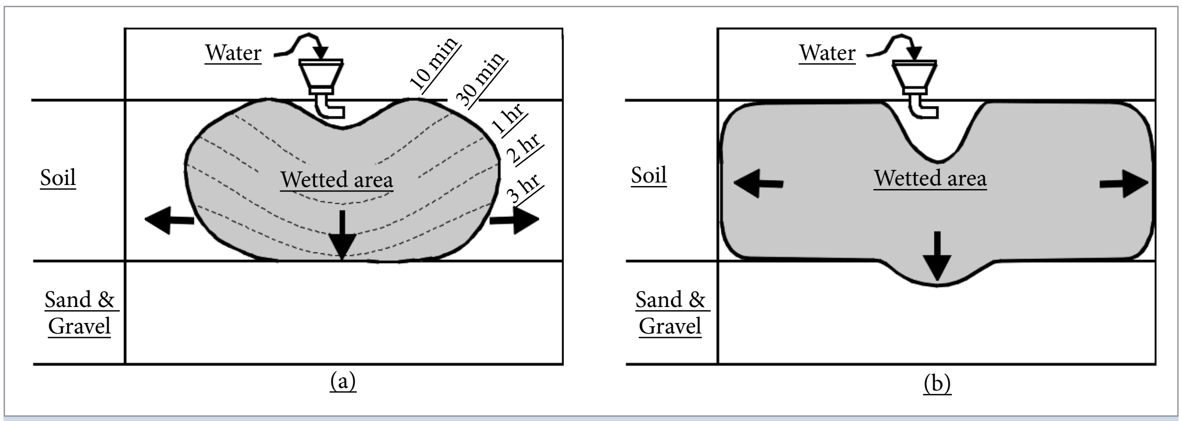

Figure 2.16. Water infiltrating into soil underlain by coarse sand and gravel
Credit: University of Nebraska-Lincoln

What happens to water movement if the upper soil layer is underlain by a finer textured material like clay? As Figure 2.17a illustrates, water moves rapidly into the clay. Compared to the overlying layer, the smaller pores associated with clay layer attract more water. This causes the clay to wet immediately when the wetting front reaches the layer. Although the clay layer wets rapidly, the small pores hold the water tightly and effectively retard the advance of the wetting front. The slowing of the wetting front causes lateral water movement in the overlying coarse soil. Finally, after the clay layer is saturated, the wetting front will move below the clay (fig. 2.17b). The situation illustrated in Figure 2.17 is typical of soils with buried claypans.

The claypan restricts the downward (or upward) movement of water. If a claypan is at or near the soil surface, excessive **runoff** may become a problem during rainfall or irrigation events, even though the soil below the clay pan is dry. A subsurface clay layer also can cause the soil above it to become fully saturated, forming a perched water table. Perched water tables often cause drainage and aeration problems in the upper soil layers.

Properly managing the soil water is the goal of both dryland and irrigated producers. Familiarity with soil water terms and the processes that control soil water management are critical for proper management.

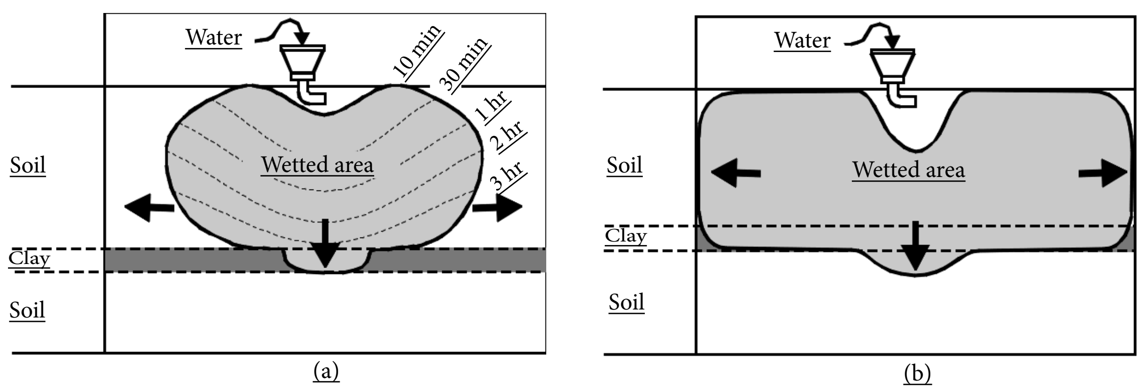

Figure 2.17. Water infiltrating into soil underlain by clay layer
Credit: University of Nebraska-Lincoln

Section 3: Irrigation Scheduling

This section is adapted from Colorado State University Extension's Irrigation Scheduling factsheet by I. Broner (https://extension.colostate.edu/docs/pubs/crops/04708.pdf) *and University of Minnesota Extension's "Irrigation Scheduling" section of the Irrigation Programs web page* (https://extension.umn.edu/soil-and-water/irrigation#irrigation-scheduling-469460).

Irrigation scheduling is the decision of when and how much water to apply to a field. Its purpose is to maximize irrigation efficiencies by applying the exact amount of water needed to replenish the soil moisture to the desired level. While irrigation scheduling saves water and energy, all irrigation scheduling procedures consist of monitoring indicators that determine the need for irrigation.

TYPES OF IRRIGATION SCHEDULING METHODS

Soil Moisture Sensors for Irrigation Scheduling

Depending on the technology they use, soil moisture sensors are divided into two categories:

- sensors that measure volumetric water content
- sensors that measure soil tension when placed in the soil profile

Soil moisture sensors measure or estimate the amount of water in the soil. These sensors can be stationary or portables, such as handheld probes. Stationary sensors are placed at predetermined locations and depths in the field, whereas portable soil moisture probes can measure soil moisture at several locations.

Volumetric Water Content Soil Moisture Sensors

Volumetric water content is the volume of liquid water per volume of soil. It is usually expressed as a percentage. For example, 25% volumetric water content (VWC) means 0.25 cubic inch of water per cubic inch of soil.

When compared with the maximum amount of water that the soil can hold or field capacity, VWC measurements can be used to measure soil water deficit for irrigation scheduling:

Soil water depletion/deficit (inches) = soil water content at field capacity (inches) - current soil water content (inches)

Note: The percent of soil water content measurements must be multiplied by the depth of the root zone to give total water in that soil depth. For example: If a 12-inch soil profile has a VWC of 9%, then:

- total water in a 12-inch profile = 0.09 × 12 inches = 1.08 inches water
- if field capacity is 18%, the soil water depletion/deficit = (0.18 × 12 inches) - 1.08 inches = 1.08 inches

Soil Water Deficits and Crop Stress

For irrigation scheduling, it's important to understand the soil water content at which a crop begins to experience stress. In general, most crops begin to experience stress when soil water depletion/deficit is 30–50% of available water holding capacity (AWC). This is called *management allowable depletion* (MAD) or *irrigation trigger point.*

MAD can vary depending upon crop, growth stage, and an irrigation system's pumping capacity. For more information, see the University of Minnesota (UMN) Extension's "irrigation management strategies by growth stage/season" (https://extension.umn.edu/irrigation/irrigation-management-strategies#strategies-by-season%2Fgrowth-stage-1702910). Irrigation should be triggered when the percentage of soil water depletion is equal or close to the percentage of MAD.

Volumetric water content (VWC) can be used to calculate the percentage of soil water depletion using the following formula, where PWP is permanent wilting point and FC is field capacity:

$$\%\ \text{soil water depletion} = [1 - (\text{Sensor VWC}\ \% - \text{PWP}\ \% / \text{FC}\% - \text{PWP}\%)] \times 100$$

Field capacity can be measured very easily in the field using soil moisture sensors. The VWC measurement provided by the soil moisture sensor after 12–24 hours of heavy irrigation or rain is the field capacity of the soil.

Soil Water Tension or Matric Potential Sensors

Soil water tension indicates the energy required by plant roots to extract water from soil particles. As soil water is removed from soil, soil tension increases. Soil tension is expressed in centibars (cb) or bars of atmospheric pressure. When the soil is full of water, soil water tension is close to zero. For coarse textured soils, AWC is 50% depleted when soil tension is at 25–45 cb. In these soils, a crop should be irrigated before the sensor indicates 25–45 cb (Irmak 2014).

However, soil tension measurements are soil specific and can be inaccurate. Depending on your crop and soil observations, soil tension limits should be refined. For example, note the soil tension at the earliest indication of water stress and always make sure that you irrigate before it reaches that point.

You can also track your water movement by taking a measurement right after irrigation. If your bottom sensor after irrigation has a zero reading, you might have irrigated more than required, but if it shows no movement, that means you irrigated less than necessary.

Evapotranspiration-based Irrigation Scheduling or Water Balance Method

The status of the soil water for an irrigated crop needs monitoring regularly to assist the irrigation manager in making irrigation decisions. Typically, irrigation scheduling can be done in two ways. One is by directly monitoring soil water by using soil moisture sensors. The other way is to use weather data to account for soil water in the rooting depth by the soil water balance approach. This method is usually referred to as *weather-based* or *evapotranspiration-based (ET_c- based) irrigation scheduling* or *water balance method*.

How to Use the Water Balance Method

Estimating soil water using the water balance approach is done by accounting for all the incoming and outgoing water from the soil root zone. Major inputs include precipitation (P) or rainfall and irrigation (Irr). Outputs include ET_c, runoff (R) and deep percolation (DP). Daily soil water depletion in the rooting zone is calculated using this equation:

$$\text{Equation 1. } Dc - Dp = ET_c - P - Irr + R + DP$$

Dc stands for soil water deficit (net irrigation requirement) in the rooting zone on current day, *Dp* is the previous day soil moisture deficit, ET_c is crop evapotranspiration on the current day, *P* is precipitation for the current day, *Irr* is the irrigation amount for the current day, *R* is the surface runoff, and *DP* is the deep percolation.

Since it is very difficult to estimate R and DP in the field, these variables can be accounted for by setting Dc to zero whenever water additions (P and Irr) to the root zone are greater than water subtractions (Dp + ET_c) (Andales 2015). Using these assumptions, Equation 1 can be simplified to:

$$\text{Equation 2. } Dc = Dp + ET_c - P - Irr$$

Estimating Initial Soil Moisture and Soil Water Deficit

Before beginning the water balance calculations, you should know the initial soil moisture. You can estimate initial soil moisture using gravimetric soil water sampling, the hand-feel method, or soil moisture sensors. Good resources for more information are the University of Minnesota Extension's web pages on "Estimating Soil Moisture Based by Feel and Appearance Method" (https://extension.umn.edu/irrigation/estimating-soil-moisture-feel-and-appearance-method) and "Soil Moisture Sensors for Irrigation Scheduling" (https://extension.umn.edu/irrigation/soil-moisture-sensors-irrigation-scheduling).

From the initial soil moisture content, soil water depletion/deficit (Dc) for the successive days can be estimated using Equation 2. The estimated soil water deficit (Dc) from the water balance equation is then compared with maximum allowable depletion (MAD)—which is usually 50% of total available water (TAW) in the root zone—to make irrigation decisions. Remember that TAW = available water holding capacity (AWC) rooting depth.

Plants start to experience water stress once the soil water deficit/depletion in the root zone is greater than the root zone MAD. Generally, irrigation should be initiated when Dc approaches MAD. However, if the irrigation system has limited capacity, then the irrigator should not wait for Dc to reach MAD and should irrigate more frequently.

Discussions about MAD, AWC and TAW are available in UMN Extension's Basics of Irrigation Scheduling (https://extension.umn.edu/irrigation/basics-irrigation-scheduling). More information about MAD strategies and pumping capacity can be found in UMN Extension's Irrigation Management Strategies (https://extension.umn.edu/irrigation/irrigation-management-strategies).

Estimating Crop Water Use or Crop Evapotranspiration

Evapotranspiration (ET_c) is the biggest subtraction from the water balance equation (Equation 2). The ET_c changes throughout the growing season due to weather variations and crop development.

Crop water use or ET_c depends on many factors. These include:

- crop type
- growth stage
- climatic conditions (Parameters that have a major effect on a crop's daily water use include the maximum and minimum temperatures, solar radiation, humidity, and wind.)
- management and environmental conditions
- soil moisture and similar factors

Estimating Soil Moisture by Feel and Appearance Method

A common way to estimate the soil water deficit is by the feel and appearance method. First, collect soil samples in the root zone with a soil probe or spade. Next, estimate the water deficit for each sample by feeling the soil and judging the soil moisture as outlined in Table 3.1. Next, take soil samples at several depths in the root zone and at several places in the field. Finally, use these estimated deficits to estimate the total soil water deficit in the root zone. This method requires frequent use to develop consistent estimates.

TABLE 3.1. Guide for judging soil water deficit based on soil feel and appearance by soil texture

Moisture deficiency	Coarse texture (loamy sand) AWC = 0.6–1.2 inches/ foot	Sandy texture (sandy loam) AWC = 1.3–1.7 inches/foot	Medium texture (loam) AWC=1.5–2.1 inches/foot	Fine texture (clay loam) AWC = 1.6–2.4 inches/foot
0.0 inch/foot (field capacity)	Leaves wet outline on hand when squeezed	Appears very dark, leaves wet outline on hand, makes a short ribbon	Appears very dark, leaves wet outline on hand, will ribbon out about 1 inch	Appears very dark, leaves slight moisture on hands when squeezed, will ribbon out about 2 inches
0.2 inch/foot	Appears moist, makes a weak ball	Quite dark color, makes a hard ball	Same as above	Same as above
0.4 inch/foot	Same as above	Same as above	Dark color, forms a plastic ball, slicks when rubbed	Dark color, will slick and ribbons easily
0.6 inch/foot	Appears slightly moist, slightly sticks together	Fairly dark color, makes a good ball	Same as above	Same as above
0.8 inch/foot	Appears to be dry, will not form a ball under pressure	Slightly darker color, makes a weak ball	Quite dark, forms a hard ball	Quite dark, will make a thick ribbon, may slick when rubbed
1.0 inch/foot	Same as above	Lightly colored by moisture, will not ball	Fairly dark, forms a good ball	Fairly dark, makes a good ball
1.2 inches/foot	Dry, loose, single grains flow through fingers (wilting point)	Very slight color due to moisture, loose, flows through fingers (wilting point)	Slightly dark, forms weak ball	Will ball, small clods will flatten out rather than crumble
1.4 inches/foot	—	Same as above (wilting point)	Lightly colored, small clods, crumbles fairly easily	Same as above
1.6 inches/foot	—	—	Same as above	Slightly dark, clods crumble
1.8 inches/foot	—	—	Slight color due to moisture, powdery, dry, sometimes slightly crusted but easily broken down in powdery condition (wilting point)	Some darkness due to unavailable moisture, hard baked, cracked, sometimes has loose crumbs on surface (wilting point)
2.0 inches/foot	—	—	—	Same as above (wilting point)

Irrigation Scheduling Checkbook Method

As the University of Minnesota Extension explains on its irrigation website, the checkbook method of scheduling enables irrigation farm managers to monitor a field's daily soil water balance (in terms of inches of soil water deficit), which can be used to plan the next irrigation. This method requires that you monitor the crop's growth, know your soil texture or textures in the rooting zone, observe and log the maximum air temperature each day, and measure and log the rainfall or irrigation applied to the field. A spreadsheet is available for download from the North Dakota State University at https://www.ag.ndsu.edu/irrigation/documents/checkbook_irrigation_scheduling_2.5. The checkbook spreadsheet will automatically estimate evapotranspiration and soil water deficits (Wright 2018).

IRRIGATION INITIATION AND TERMINATION

Corn Irrigation Initiation

This segment is adapted from the 2023 article "When Should We Start Irrigating Corn to Enhance Yield Potential" by E. Larson of MSU Extension (https://www.mississippi-crops.com/2023/05/27/when-should-we-start-irrigating-corn-to-enhance-yield-potential/).

Corn develops about 75% of its root mass during the late vegetative stage. Premature irrigation is unnecessary and often detrimental to corn growth and productivity in a high rainfall environment. It is not uncommon to have dryland "corners" out-yield irrigated fields for this likely reason. The optimal time to trigger initial corn irrigation is right when soil moisture becomes limiting (fig. 3.1). The Midsouth transition into summer challenges corn because the corn is making huge physiological strides. However, inadequate soil moisture is not nearly as limiting as usually perceived at this early stage. Consequently, vegetative wilting is a poor indicator of when to initiate irrigation if you haven't first checked soil moisture conditions.

The key factor to determine crop needs is to make a conscientious effort to evaluate soil moisture throughout the root zone and over time. Soil moisture availability can be assessed using simple traditional tools, such as a shovel, probe, auger, or soil moisture sensing technologies. To enhance plant health and productivity, it is crucial to allow plants to tap into this pre-established moisture and encourage root development before initiating irrigation.

Premature or excessive irrigation or rainfall promote nitrogen loss and instigate additional plant nutrition issues associated with saturated soil; therefore, it ultimately reduces corn yield potential. A conservative irrigation strategy is preferable during vegetative stages in high rainfall environments.

The first and only corn grain yield component determined prior to tassel is the number of kernel rows per ear. Potential early season yield-limiting drought stress during mid-vegetative stages would be manifested in considerably fewer kernel rows per ear on dryland compared to irrigated corn grown in otherwise similar culture. Data collected from the MSU Extension Corn Hybrid Demonstration Program show that this rarely occurs in Mississippi! Conversely, substantial soil saturation prior to tassel is an often-encountered issue that certainly reduces corn yield potential with excessive irrigation or abundant rainfall.

To fully support increasing crop needs and avoid moisture deficit, corn irrigation should be scheduled more generously as the crop approaches the critical tassel and early reproductive stages. An accepted rule of thumb is that corn at V10 growth stage (55–60 inches tall) is about 2 weeks from tassel. As recommended by long-term corn irrigation studies conducted by Kansas State University and Pioneer Hi-Bred International Inc., the transition between irrigation strategies should occur shortly after the V10 growth stage.

Corn Irrigation Termination

Safely terminating irrigation while optimizing kernel development and yield potential is the most important management decision. The main factor in this decision is to estimate when the crop will reach maturity relative to the soil moisture profile. Improper timing will either limit yield potential if terminated too early or unnecessarily waste money and labor if terminated too late. Fortunately, the steps needed to help make this process accurate and reliable can be easily outlined.

Corn kernels mature from the outside-in when hard starch begins forming at the dent stage. At that stage the kernel crown will become hard and attain the bright, shiny yellow color of mature kernels. This starch accumulation will steadily progress toward the base of the kernel (where it attaches to the cob). This progression can be monitored by movement of the milk-line or hard starch. The milk-line is the borderline between where hard starch has occurred and where the kernel has a soft, doughy consistency and is still developing.

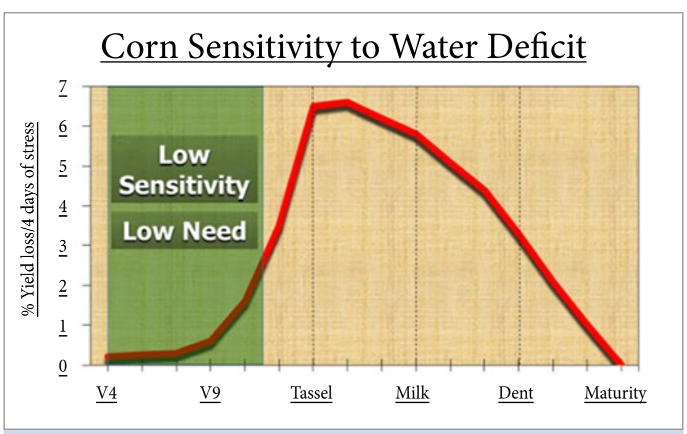

Figure 3.1. Corn sensitivity to water deficit

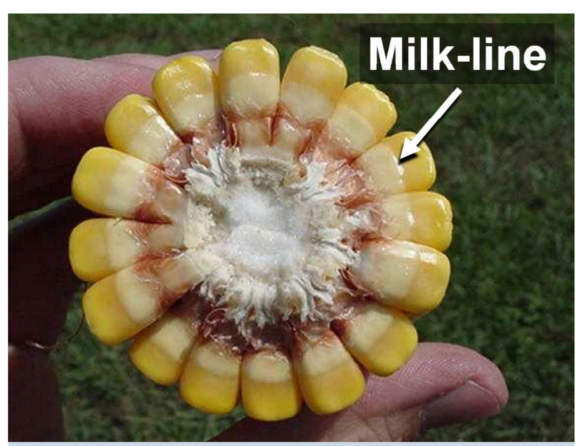

Figure 3.2. The milk-line has progressed halfway through the kernels on this ear.

The milk-line can be monitored by breaking an ear in half and observing the cross-section of the top half of the ear (side opposite to the embryo). If this color disparity between layers is not evident, its location can be confirmed by poking the seed coat with a fingernail into the soft, doughy layer near the kernel base and repeating progressively toward the crown of the kernel, until hard starch is felt.

The milk-line progression through the entire kernels lasts about 24 or 25 days. Each quarter of the kernel fills starch over about 6 days. Therefore, if a milk-line that has progressed one-quarter of the way through the kernel, the corn has approximately 18 more days to maturity. The formula used to calculate this example is as follows:

$$24d - (24d \times 25\% \text{ milk-line}) = 18 \text{ days to maturity}$$

After estimating the time to physiological maturity, evaluate soil moisture reserves to assess whether enough moisture is present to carry the crop to maturity using any of the methods described in the previous section (ideally soil moisture sensors). MSU's Corn Verification Program and RISER Program offer the following key lessons (fig. 3.3):

- Mississippi grown corn is fully capable of drawing moisture from at least 36-inches deep during late reproductive stages, if soils or compaction don't limit water infiltration or root growth.
- The daily soil moisture use rate diminishes considerably as corn approaches maturity, particularly after the dent stage, compared to early reproductive stages. Data show a fully charged soil profile may provide ample moisture for an irrigation cycle up to 15–18 days after dent stage, compared to only 9–12 days during peak water use near tassel.
- Corn's ability to tolerate stress also increases considerably as it approaches maturity. This allows drier irrigation thresholds for termination. In cases where soil moisture is marginal within 5 days of maturity, supplemental furrow irrigation does not generally result in yield gains.

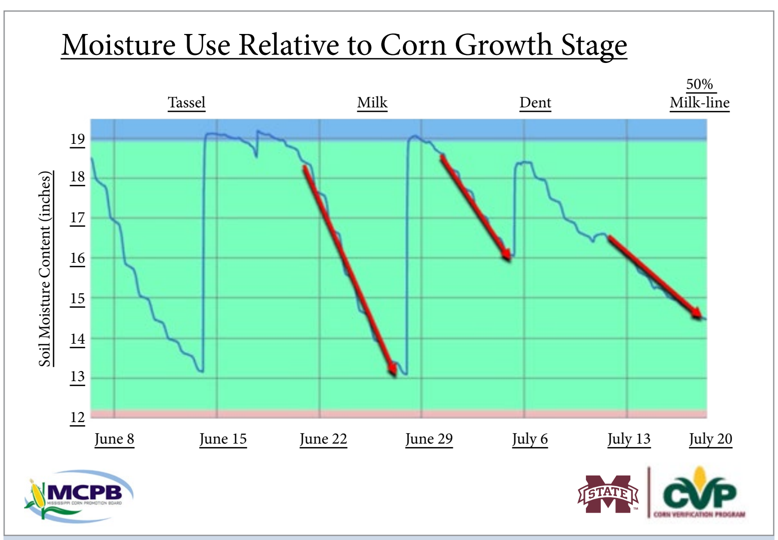

Figure 3.3. Moisture use relative to corn growth stage

Soybean Irrigation Initiation

This segment is adapted from the 2022 article "Soybean Irrigation Initiation" by T. Irby and D. Gholson of MSU Extension (https://www.mississippi-crops.com/2022/06/18/soybean-irrigation-initiation-2/).

The first step in determining when to initiate irrigation in soybean is to properly identify the growth stage of the crop. The commonly recognized soybean reproductive growth stages are as follows:

- R1: first flower anywhere on plant
- R2: first flower in the upper two nodes
- R3: 3/16 inches long pod in upper four nodes
- R4: 3/4 inches long pod in upper four nodes
- R5: beginning seed
- R6: seed completely filling the pod cavity
- R7: mature pod on the main stem of the plant
- R8: 95% of pods mature in color

With respect to moisture needs in soybean, irrigating during the vegetative phase provides little to no yield benefit. The reason to apply irrigation during the vegetative stages is to promote adequate vegetative growth and node development. During the reproductive phase, soybean yield loss due to drought stress is most severe.

Specifically, stress associated with lack of available soil moisture during the pod development (R3–R4) and pod fill (R5–R6) stages of reproduction has the greatest impact on soybean yield. Soybean can use 0.25 inch of water per day during reproductive development. Stress from lack of moisture between R3 and R4 may result in fewer pods and between R5 and R6 may result in decreased seed size.

The next step is to determine the available soil moisture as the crop moves into these reproductive stages. A recommended method of determining available soil moisture is using soil moisture sensors.

Remember, evaluation of sensor readings at different depths should reveal the active rooting zone. If a sensor has little or no movement, remaining in the 0 to 20 cb range over a period of a few days, the roots have most likely not developed to that depth. On the other hand, if the sensors are progressively moving upward 5–10 cb per day, most likely roots are developed and using moisture at that depth.

If the soybean crop is at R2 and the moisture sensors indicate that the soil profile is not fully charged, it is best to initiate irrigation to ensure adequate soil moisture is available as the crop moves into the pod development stages.

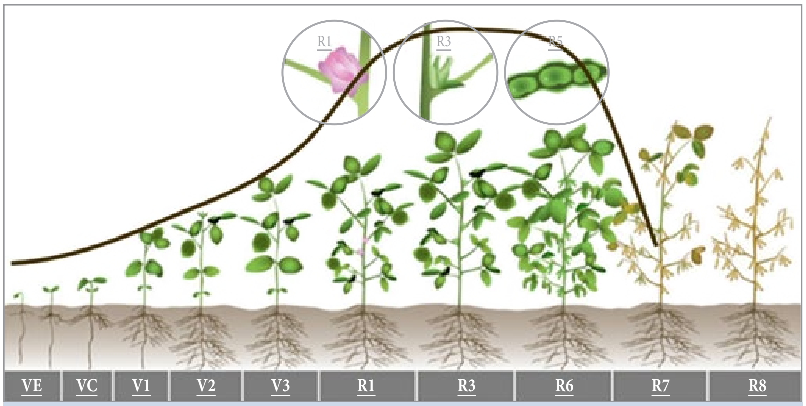

Figure 3.4. Irrigation initiation at different soybean reproductive stages

Soybean Irrigation Termination

The first step in deciding when to terminate irrigation, regardless of soybean planting date, is to properly identify what growth stage the crop is in. The article "Identifying Late Season Soybean Growth Stages" (https://www.mississippi-crops.com/2020/08/21/identifying-late-season-soybean-growth-stages-2/) contains both descriptions and pictures that will help in identifying the key growth stage for irrigation termination. Keep in mind that if you are growing an indeterminate variety, observations for identifying the growth stage should come from pods in the upper four nodes of the plant. In determinate varieties, observations can be made anywhere on the plant (Irby 2020).

With respect to yield loss because of drought stress, previous research suggests that a yield reduction will occur if soybean do not have adequate soil moisture during pod fill (beginning at the R5 stage). This yield reduction would simply result from not having enough moisture for seed to reach their full potential. Therefore, the goal in timing irrigation termination is to make sure that adequate soil moisture is available to ensure that the soybean seeds reach maximum size.

Specifically, if adequate soil moisture is present and the crop has reached the R6.5 growth stage, when the soybeans have separated from the pod membrane, irrigation can be terminated. In the case of indeterminate varieties, be mindful of the fact that there may be some pods in the lower part of the plant that are approaching R7 while pods in the upper four nodes still need water to finish filling. Remember, terminating irrigation too soon can result in smaller seed and therefore reduce the overall yield potential.

The easiest way to identify the R6.5 growth stage is to open the pod and observe if the seeds easily separate from the protective membrane within the pod. If so, irrigation can be terminated.

Soil moisture sensors are excellent tools to aid in deciding when to terminate irrigation in soybean. These tools, coupled with proper identification of the crop's growth stage, can provide the information needed to estimate the time until the crop reaches physiological maturity and the availability of soil moisture up to that point. For example, if the soybean crop is at the R6 growth stage (seeds completely fill the pod and are squared off), a timely rainfall or well-timed irrigation could allow that crop to reach physiological maturity. The expected time from R6 to R6.5 will vary, depending on planting date and maturity group, but soybean will generally require 7 to 10 days to transition from R6 to R6.5. The later the planting date, the later the expected date at which the R6.5 growth stage is achieved, so for some of our acres, you still have several days to go to be able to safely terminate irrigation. Be mindful of environmental and field conditions in later-planted soybean to ensure that irrigation during the early fall will not create extra challenges for harvest operations.

Cotton Irrigation Initiation

This segment is adapted from the 2018 article "Cotton Irrigation" by D. Dodds of MSU Extension (https://www.mississippi-crops.com/2018/07/07/cotton-irrigation-2/).

Cotton irrigation is not a clear-cut process. In simplistic terms, cotton growth stage and soil moisture status drive our irrigation decisions. Cotton growth stage is pretty straightforward: Ensure that your soil profile has adequate moisture as cotton begins to bloom. Water and nutrient demands increase when cotton begins to bloom, and these demands tend to top out at or shortly after peak bloom (3–4 weeks after first bloom).

Soil moisture status is somewhat more complicated. For years, we have made irrigation decisions using one or all of the following: experience, a pre-determined schedule, or digging a hole and observing moisture levels—and more. Over the past 5 years or so, tremendous emphasis has been placed on using soil moisture sensors to determine soil moisture status and irrigation needs. Two types of sensors are commonly used to monitor soil moisture status. Soil matric type sensors (including Watermark sensors) measure the force with which water is pulling away from the sensor. Based on MSU data, we recommend triggering irrigation when a weighted sum from these types of sensors reaches -90 kilopascal.

Cotton Irrigation Termination

This segment is adapted from the 2018 article "Cotton Irrigation Termination" by D. Dodds of MSU (https://www.mississippi-crops.com/2018/08/11/cotton-irrigation-termination-3/).

For furrow irrigated fields, irrigation should be terminated at first cracked boll. If adequate moisture is present in the soil profile and your crop has open bolls, terminate irrigation. However, if you are in an area that has been dry or not irrigated, or both, for an extended period *and* your crop is not yet opening, a final furrow irrigation application is recommended. In these situations, be cautious of delaying irrigation (when no rainfall has been received) to facilitate bolls opening. Our data indicates that irrigation *may* be terminated as much as 2 weeks prior to first cracked boll; however, in our research we have always received some appreciable rainfall between 2 weeks prior to first cracked boll and 3 weeks after first cracked boll. In short, if you lack moisture in the soil profile and your crop is not open, make one final furrow irrigation.

For pivot irrigated fields, apply a final irrigation up to 10 days after first cracked boll when you are lacking moisture in the soil profile. The 10-day discrepancy between furrow irrigation and pivot irrigation is due to the amount of water delivered to the crop in an irrigation event. It is not uncommon for up to 3 acre-inches of water to be delivered when furrow irrigating, whereas 0.5″–1.0″ per acre is typically delivered when using pivot irrigation.

We do not recommend irrigating past these times, because our data has not shown yield or fiber quality gains from doing so. In addition, irrigating past these times becomes carries risks and rewards. Numerous pathogens can cause hardlock or boll rot or both. When irrigating as bolls are opening, you are providing moisture in the crop canopy, which can enhance the environment for these plant pathogens to cause these conditions. The disease triangle suggests that you need the host (cotton), the pathogen (likely present), and the environment (which you enhance or make more favorable by adding additional moisture into the crop canopy) to coexist to cause a disease problem. Generally, about 40-45% of the total crop yield is from nodes 5 to 8/9. These bolls are the ones likely to be most susceptible to boll rot and hardlock, and you should try to avoid the onset of these problems at all costs.

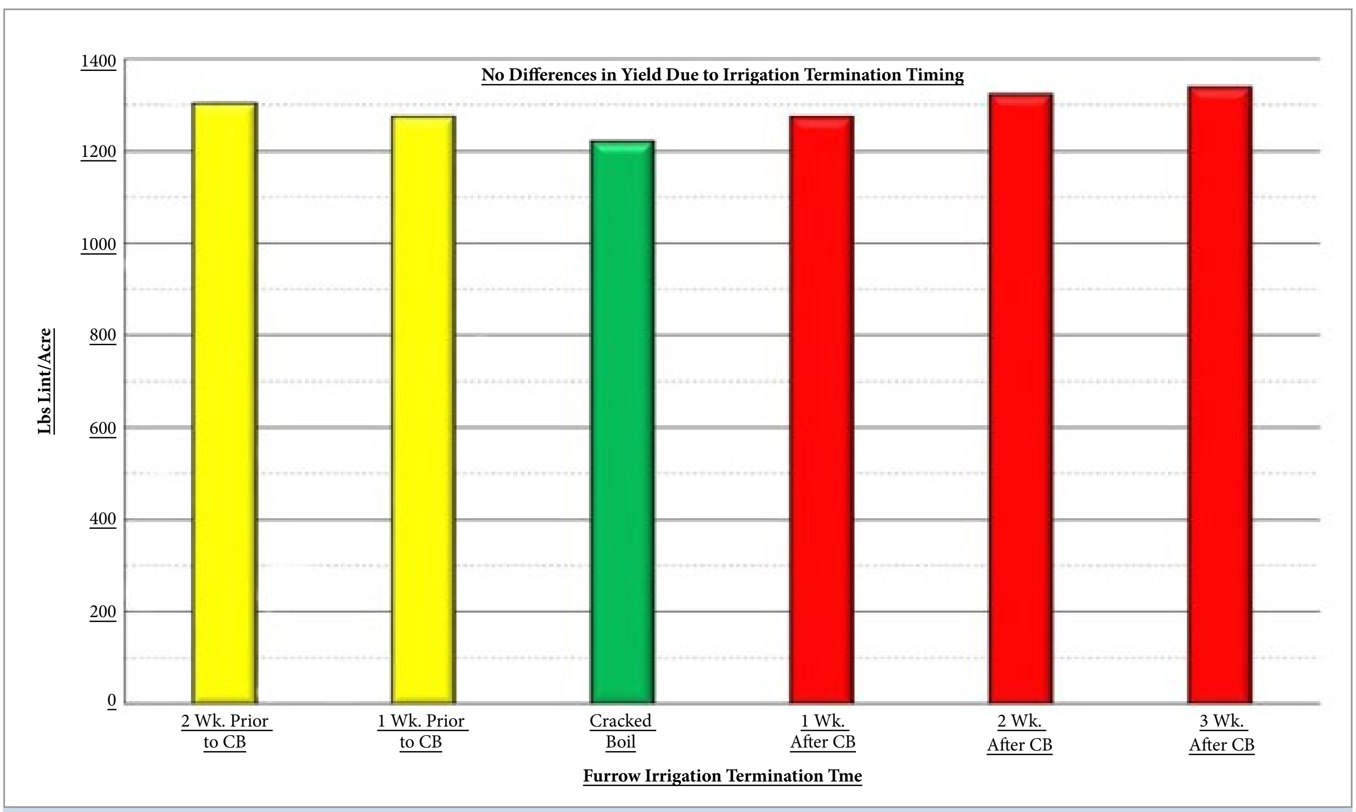

Figure 3.5. Furrow irrigation and termination timing in cotton

Sensor Type: Watermark Soil Moisture Sensor

These segments are adapted from Irrometer Watermark Series: Scientific Background, MSU Extension Publication 3536 (04-21), by J. Rix, H. Lo, D. Gholson, and M. Henry (http://extension.msstate.edu/publications/irrometer-watermark-series-scientific-background).

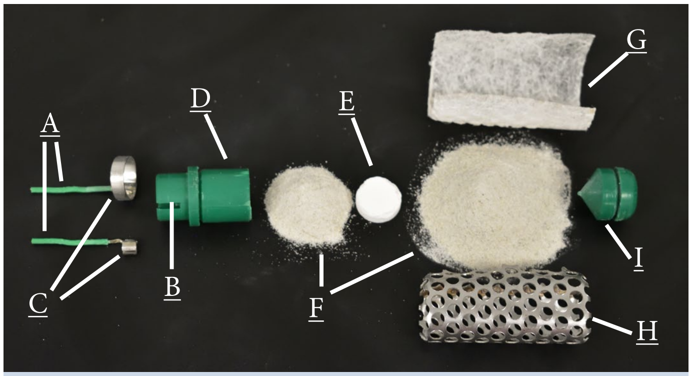

Figure 3.6. Watermark sensor components (exploded view)

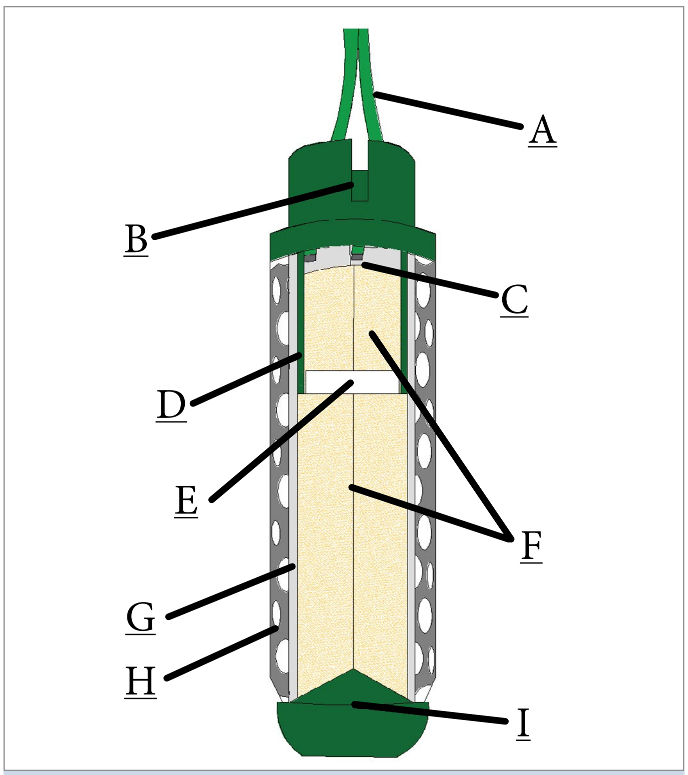

Figure 3.7. Watermark sensor components (cutaway view)

Sensor Components

Figures 3.6 and 3.7 show what a Watermark sensor looks like when it has been taken apart. Each component is labeled and described as follows.

Legend

A. Two 20 AWG wires: electrical connectors between the measurement device (e.g., datalogger) and the electrodes (C).

B. Weep slot: drain for standing water above the sensor sleeve (D).

C. Two electrodes: concentric, ring-shaped, stainless steel bands; the measurement device reads the electrical resistance between these bands.

D. ABS sensor sleeve: compartment with water content that changes the electrical resistance between the electrode (C).

E. Gypsum wafer: source of salinity buffering for water inside the sensor sleeve (D).

F. Loose, graded sand: material that water moves through between the outside soil and the electrodes (C).

G. Mesh fabric: filter that allows water but not sand (F) to pass through.

H. Steel cage: protection for the mesh fabric (G).

I. ABS plug: cap for the bottom of the sensor.

Wetting and Drying

A porous material pulls water into its pores more strongly when it is dry than when it is wet. The strength of this pull can be referred to as tension, which is measured in centibars (cb). Just as a wet pool of water will soak into a dry sponge, water in the soil will flow from a point of lower tension to a point of higher tension.

If a Watermark sensor has good contact with the soil, water can move freely between the outside soil and the sand inside the sensor until tension is equal at both places. When the soil outside is wetting and has a lower tension than the sand inside the sensor, water flows from the soil into the sensor as in Figure 3.8a. When the soil outside is drying and has a higher tension than the sand inside, water flows from the sensor into the soil as in Figure 3.8b.

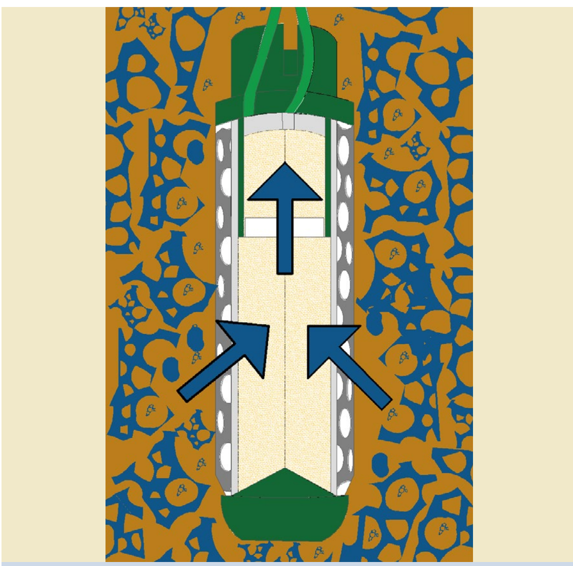

Figure 3.8a. Water absorption when wetting

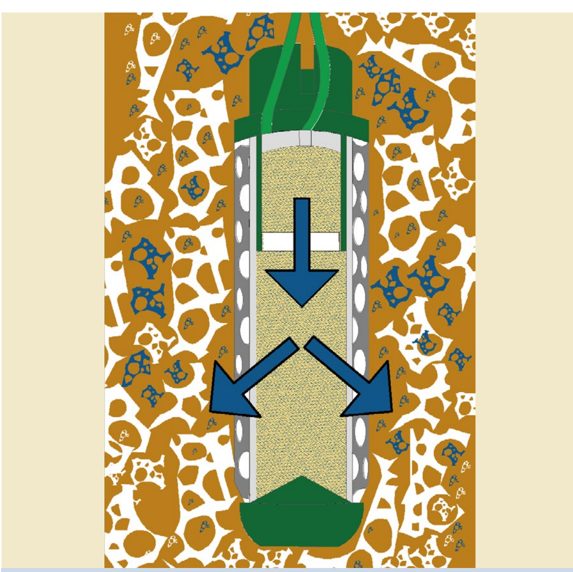

Figure 3.8b. Water release when drying

Determining Tension

Increasing the tension inside the sensor decreases the water content inside the sensor sleeve, which in turn increases the electrical resistance between the electrodes. The exact mathematical relationship that links the tension inside the sensor to the electrical resistance between the electrodes is called a *calibration equation.*

Using this calibration equation, the tension of the outside soil can be estimated from the electrical resistance between the electrodes by assuming that the tension of the outside soil equals the tension inside the sensor. However, if the sensor has poor contact with the soil or no longer follows the calibration equation (which can occur as components degrade over time or under other circumstances), the estimated tension of the outside soil could be inaccurate.

Temperature Effects

Watermark sensors can be affected by temperature. Given a constant actual tension of the outside soil, increasing the temperature inside the sensor sleeve decreases the electrical resistance between the electrodes. In turn, the estimated tension of the outside soil decreases.

Figure 3.9 illustrates how soil temperature fluctuations can alter the day-night trend in readings for a 6-inch Watermark sensor early in the season. Nevertheless, temperature-based corrections have not been recommended for agronomic crops in Mississippi. That's because when the crop canopy tends to be large, uncorrected Watermark readings are averaged across multiple depths to schedule multi-day irrigation cycles.

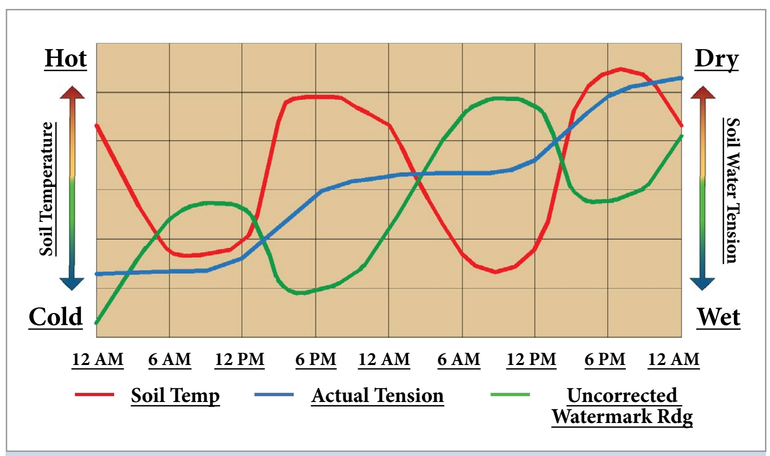

Figure 3.9. Soil temperature fluctuations in readings for a 6-inch Watermark sensor early in the season

Watermark Construction Guide

This segment is adapted from Irrometer Watermark Series: Construction Guide, MSU Extension Publication 3538 (12-20), by J. Rix, H. Lo, D. Gholson and M. Henry (http://extension.msstate.edu/publications/irrometer-watermark-series-construction-guide).

Follow this step-by-step guide to make the Watermark sensors easier to install at the intended depths and easier to remove at the end of the season.

PREPARATION

Use the tools and supplies pictured in Figure 3.10. Fifteen feet of sensor wires is usually convenient.

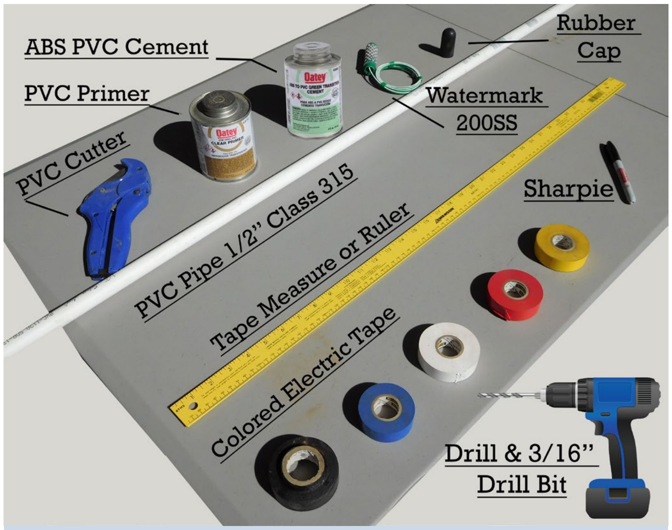

Figure 3.10. Tools and supplies to build a Watermark sensor

One set of 6-inch, 12-inch, 24-inch, and 36-inch sensors will require one 10-foot stick of half-inch Class 315 PVC pipe (fig. 3.11). Select the correct PVC specifications to avoid frustrations later. Be sure to use thin-wall PVC (fig. 3.12).

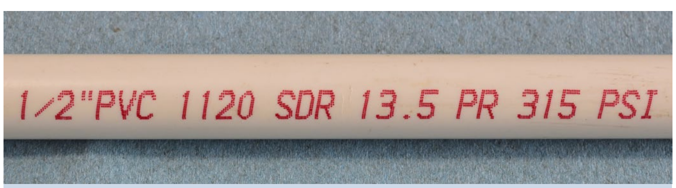

Figure 3.11. Half-inch class 315 PVC pipe

Figure 3.12. Use thin-walled PVC pipe.

ABS-PVC transition cement is best for joining the ABS sensor collar to a primed PVC section. Using a different cement can increase the risk that the sensor and PVC will separate during removal.

ASSEMBLY

Step 1: Using the PVC cutter, cut a PVC length that is 10 inches longer than the intended sensor depth to simplify sensor removal. Following the color code in Table 3.2 for that sensor depth, wrap a ring of colored electrical tape 4 inches from one end of the cut PVC section.

TABLE 3.2. The color of tape to use based on sensor depth

Sensor depth	PVC length	Tape color
6 inches	16 inches	blue
12 inches	22 inches	white
24 inches	34 inches	red
36 inches	46 inches	yellow

Step 2: Using the electric drill and a 3⁄16-inch drill bit, make a weep hole 1/4 inch from the untaped bottom end of the PVC section (fig. 3.13).

Figure 3.13. Drill the weep hole.

Step 3: Apply PVC primer at least 1/2 inch inside the bottom end of the PVC section. Be ready for drips (fig. 3.14).

Figure 3.14. Apply PVC primer.

Step 4: After a few minutes of drying, thread the sensor wires from the bottom end of the PVC section to the top end until the sensor collar meets the bottom end. Bundle the extra wire (fig. 3.15).

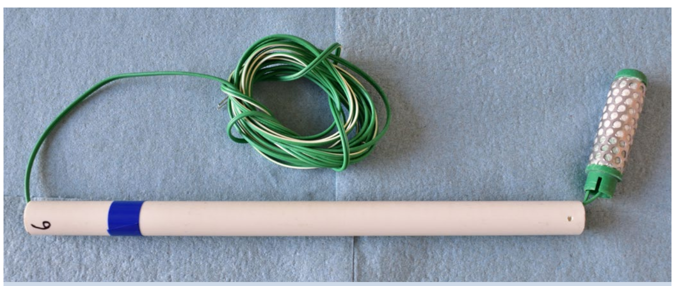

Figure 3.15. Thread the sensor wires through the PVC section.

Step 5: Carefully apply an appropriate amount of ABS-PVC transition cement to the sensor collar (fig. 3.16).

Figure 3.16. Apply ABS-PVC cement to the sensor collar.

Step 6: While aligning the sensor weep slot with the drilled weep hole, push the sensor collar fully into the bottom end of the PVC section. Ensure that the weep hole will allow water to drain out (fig. 3.17).

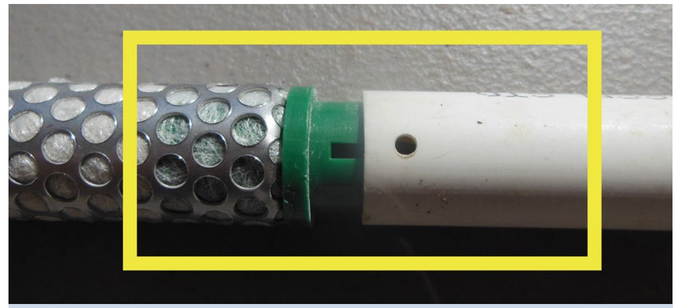

Figure 3.17. Align sensor weep slot with drilled weep hole.

Step 7: Wrap a ring of black electrical tape so that the distance between the bottom of the tape and the middle of the attached sensor equals the intended sensor depth. After installation, the bottom edge of the black electrical tape should be flush with the ground. Placing a rubber washer around the PVC section can reduce water flow down the installation hole (fig. 3.18).

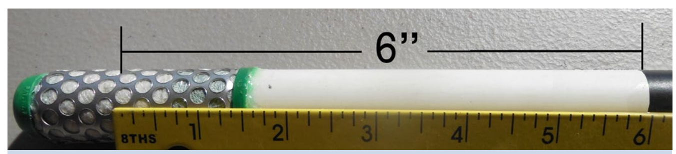

Figure 3.18. Wrap pipe with black electrical tape to intended sensor depth.

Step 8: Slide a rubber cap onto the top end of the PVC section. The construction is now complete (fig. 3.19)!

Figure 3.19. Add a rubber cap.

Watermark Sensor Location Selection

This segment is adapted from Irrometer Watermark Series: Location Selection, MSU Extension Publication P3539, by J. Rix, T. H. Lo, M. E. Henry, and D. M. Gholson (http://extension.msstate.edu/publications/irrometer-watermark-series-location-selection).

Where sensors are installed affects the likelihood that the readings are suitable for irrigation scheduling. This step-by-step guide will help you select an appropriate sensor location for a field.

REPRESENTATIVE AREA

First, choose a representative area within the field. Such an area can be identified based on experience and observations, along with soil, yield, and aerial maps. Table 3.3 suggests criteria for consideration and the associated reasons.

TABLE 3.3. Recommended criteria for selecting appropriate location for sensor

Recommendation	Reason
Place sensors in an area with the major soil type, typical terrain, and average yield (fig. 13.20).	Avoid making irrigation decisions based on abnormal areas.
Place sensors 1/2 to 2⁄3 of the way down the furrow (fig. 3.21).	Avoid over-wetted areas near the crown and the tail end of the field.
Place sensors at least two planter passes inward from the field edge (fig. 3.21).	Avoid edge effects (e.g., tree lines, pesticide drift).

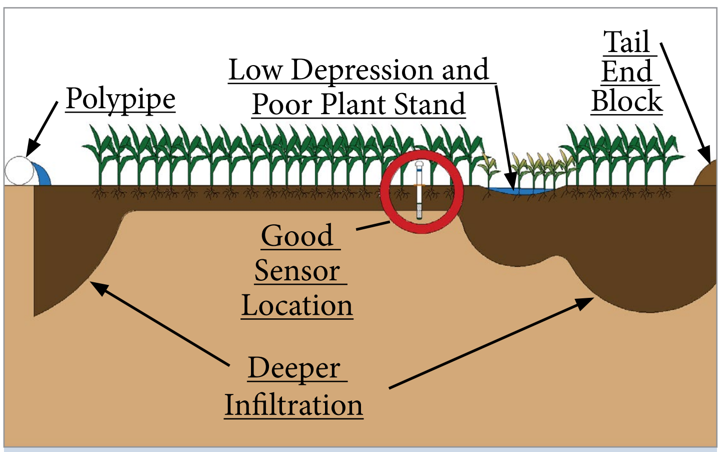

Figure 3.20. Place sensors in area with typical terrain, major soil type, and average yield.

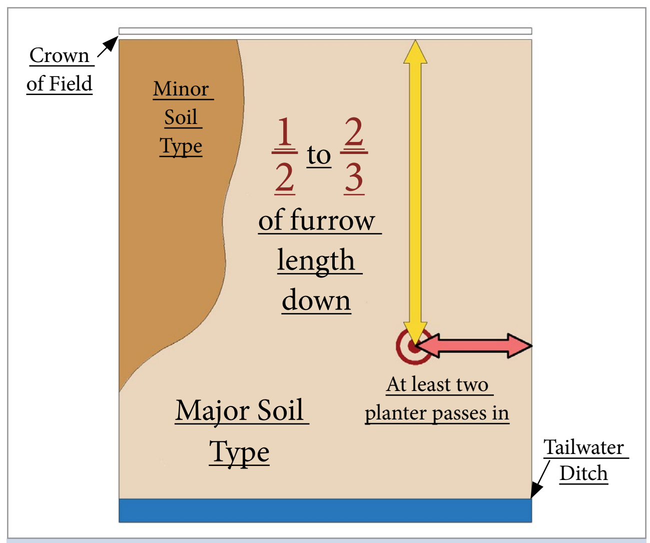

Figure 3.21. Place sensors 1/2 to 2/3 of furrow length down and two or more planter passes in.

IDEAL CROP ROWS

Second, choose a crop row that is least disturbed by field operations. Installing in a swing row minimizes the risk of sensor damage by tractors and implements. Also, wheel traffic produces compacted, hard furrows, which infiltrate less water than uncompacted, soft furrows. For example, if a field is typically farmed using a tractor with dual rear wheels and 8-row implements, the ideal crop rows for sensor installation would be the first and last rows of each 8-row pass (fig. 3.22).

Figure 3.22. Place sensors in ideal crop rows.

OPTIMAL POSITION FROM THE ROW

Third, choose a position that fairly portrays both crop water uptake and furrow water infiltration. The recommendation is to install the sensors 2 to 3 inches perpendicular from a stretch of healthy, well-spaced plants toward the adjacent wetted furrow (Fig. 3.23).

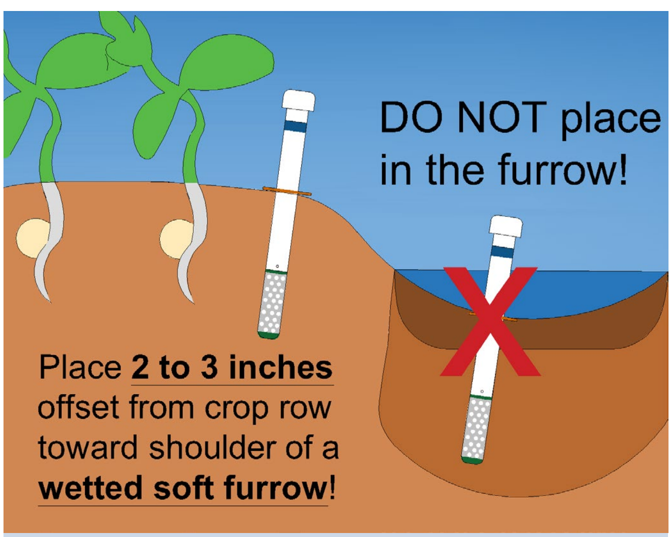

Figure 3.23. Place sensors toward shoulder of wetted furrow row.

Placing sensors in the furrow or on the edge of the raised bed may result in centibar readings that are too low. Such positions tend to stay wetter than other parts of the crop root zone. In contrast, placing sensors in the center of the raised bed may result in centibar readings that are too high if furrow water never wicks to the middle of the bed. This problem occurs more commonly in coarser soils with less lateral water movement.

SUGGESTED SPACING AND DEPTH

Finally, choose the exact spots and depths where sensors will be installed. Each sensor should be next to a good, uniform plant stand without skips. Spacing sensors roughly 1 foot apart in the row direction usually keeps the sensors of the same set close enough to reduce potential soil variability but far enough to reduce potential interference during and after installation. To capture the soil water status of the entire active root zone throughout the season, sensor depths of 6, 12, 24, and 36 inches are generally recommended for each sensor set (fig. 3.24).

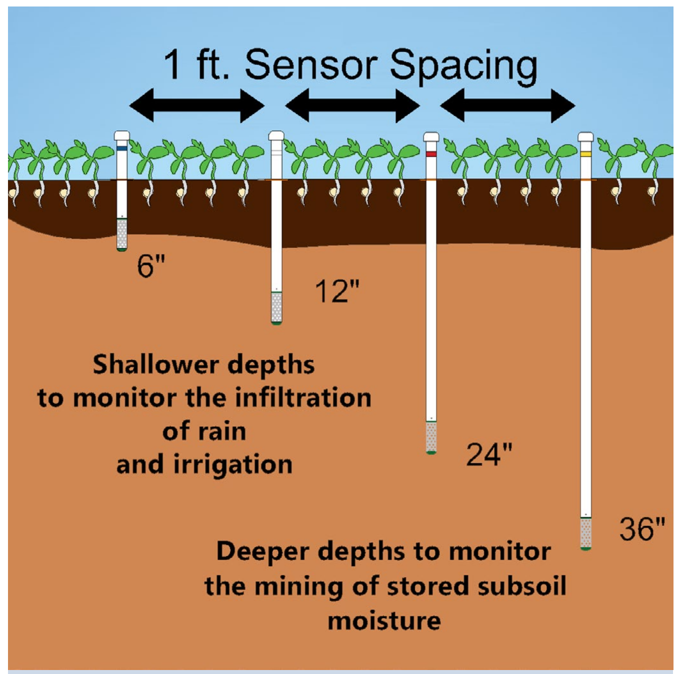

Figure 3.24. Choose the exact spots and depths for sensor installation.

Watermark Installation

This segment is adapted from Irromark Watermark Series: Installation Procedures, Mississippi State University Extension Publication 3540 (01–20), by J. Rix, H. Lo, D. Gholson, and M. Henry (http://extension.msstate.edu/publications/irrometer-watermark-series-installation-procedures).

Proper installation increases the likelihood that sensors will accurately portray the wetting and drying of the crop root zone. To install a set of Watermark sensors properly, follow this step-by-step guide.

WHEN TO INSTALL

Consider sensor installation as soon as you can confidently assess the stand of the emerged crop. To minimize plant disturbance, install sensors during the early vegetative growth stages—VC to V3 for soybean, V1 to V4 for corn, and cotyledon to first square for cotton. Late installations commonly result in incorrect sensor placement and excessive shoot and root damage, both of which can lead to centibar readings that tend to be too low.

PRECONDITIONING

Precondition sensors before installation to shorten the time the sensors take to acclimate to the surrounding soil after installation. This preparation involves artificially wetting and drying sensors in the following manner.

Day before installation

Soak for 30 minutes in the morning with the water level halfway up the sensors.

Drain the water out of the bucket, and let the sensors dry for the rest of the day.

Refill the bucket to a similar water level and soak overnight before field installation (fig. 3.25).

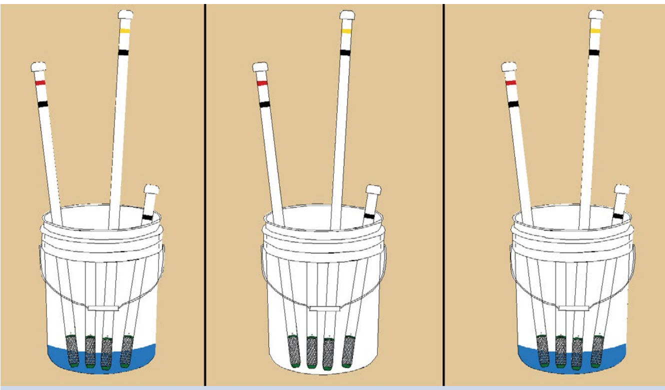

Figure 3.25. Soak sensors in the morning, drain and let dry for rest of day, then soak overnight.

Day of installation

Install the sensors wet but ensure all excess water in the PVC pipe has drained out of the weep hole (fig. 3.26). Without proper preconditioning, sensor readings may misrepresent the soil water status for much of the growing season.

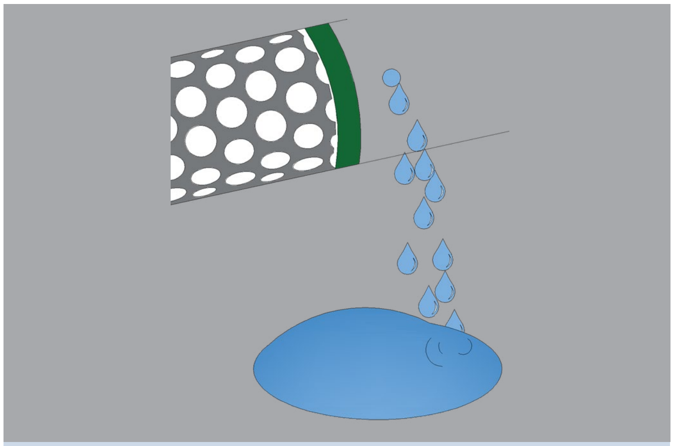

Figure 3.26. Drain all excess water in PVC pipe.

INSTALLATION

Gather the necessary tools (fig. 3.27). For the 6-, 12-, 24-, and 36-inch sensors, draw, tape, or etch markings onto the soil probe bit 7.5, 13.5, 25.5, and 37.5 inches, respectively, from its cutting edge.

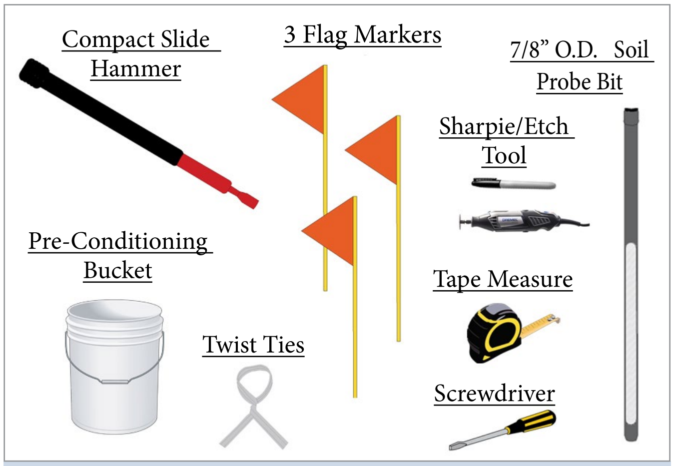

Figure 3.27. Tools needed for installation

Step 1: At the selected location, create a vertical hole for the 6-inch sensor. Keep pushing deeper until the marking corresponding to this sensor depth is even with the soil surface. If the soil is compacted, use a 7/8-inch OD auger bit with a cordless drill or gas power head (fig. 3.28).

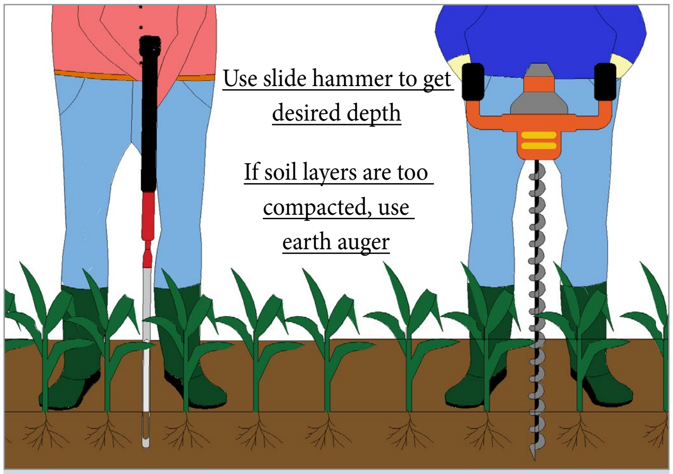

Figure 3.28. Create a vertical hole in the soil.

Step 2: Create a thick slurry by thoroughly mixing powdered soil (preferably sieved) with preconditioning water. Pour this smooth "batter" (not "broth" or "paste") into the hole to fill it halfway (fig. 3.29).

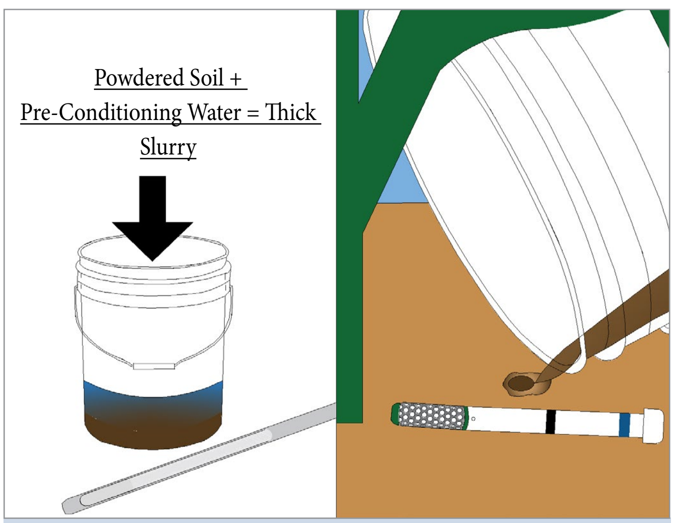

Figure 3.29. Create a soil-water slurry and pour into hole, filling halfway.

Step 3: Push the sensor down into the hole until the bottom of the black electrical tape is even with the soil surface. Some of the slurry should ooze out. Around the lip of the hole, pack down the existing soil and then a mound of additional soil, holding down the rubber washer (if used) to further reduce water leakage into the hole (fig. 3.30).

Figure 3.30. Place the sensor in the hole, packing down and mounding soil.

Step 4: Repeat steps 1–3 for each of the 12-, 24-, and 36-inch sensors. Space the sensors about 1 foot apart. Place a flag at the sensor location and at both the top and bottom ends of its crop row to make finding the sensor set easier.

Step 5: If hooded spraying or cultivating is still planned, bundle the wires with twist ties. Connect the sensors to the datalogger/telemetry unit after those field operations (fig. 3.31). You may need a screwdriver to connect the wires to the measurement device.

Figure 3.31. Connect the sensors to the datalogger or telemetry unit.

Measurement Devices for Watermark Sensors

This segment was adapted from Irrometer Watermark Series: Measurement Devices, MSU Extension Publication P3537 (03-21), by J. Rix, H. Lo, D. Gholson, and M. Henry (http://extension.msstate.edu/publications/irrometer-watermark-series-measurement-devices).

A measurement device reads a Watermark sensor by determining the electrical resistance between the electrodes inside that sensor and then reporting the corresponding soil water tension. Three types of measurement devices and their advantages and disadvantages are described.

HANDHELD METERS

A handheld meter (fig. 3.32) has a pair of alligator clips for attaching temporarily to the bare ends of a pair of sensor wires. After a sensor has been connected in this manner, press the buttons according to the manufacturer's instructions to display the sensor's present reading on the screen of the meter.

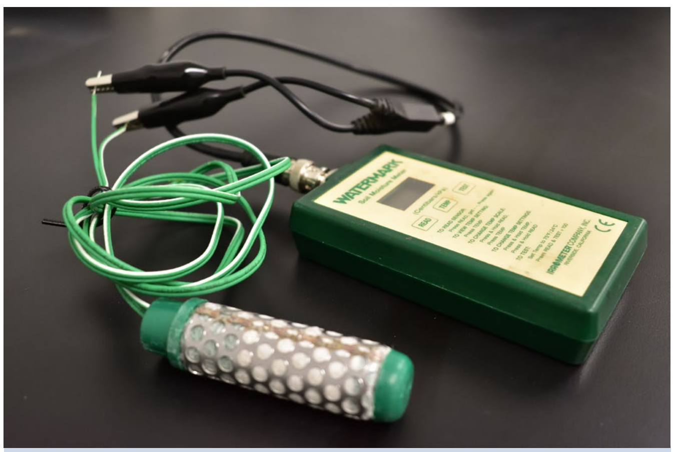

Figure 3.32. Handheld meter

For convenient access, the pair of original sensor wires can be spliced to a pair of extension wires that run along the crop row out to one end of the field. To avoid affecting the readings, the manufacturer recommends using waterproof direct-bury splice kits and underground feeder (UF) wire that is 18 AWG for lengths up to 1,000 feet, 16 AWG for lengths up to 2,000 feet, and 14 AWG for lengths up to 3,000 feet.

Among the three device types, the handheld meter demands the smallest initial investment and can read the largest number of sensors during the same season. Furthermore, no subscription costs and no additional in-field obstructions are involved. On the other hand, you have to check the sensor in the field, and you will see only its present reading at each visit. Unless you visit frequently enough to capture trends, scheduling irrigation and catching errors may be difficult.

TRADITIONAL DATALOGGERS

A traditional datalogger (fig. 3.33) has several pairs of circuit terminals, and each pair can be joined to a pair of sensor wires throughout the season. The reading from each connected sensor is taken by the datalogger on a programmed schedule. These readings are stored and can be transferred via a cable from the datalogger to a computer. The datalogger can be located near its sensors, or it can be placed at an end of the field by adding extension wires (as described previously).

Figure 3.33. Datalogger

A traditional datalogger requires a medium initial investment and no subscription costs. Besides financial considerations, criteria for selecting a particular datalogger model may include potential obstructions to field operations, data displays without a computer, system reliability, and maximum number of connected sensors.

TELEMETRY UNITS

A telemetry unit (figs. 3.34 and 3.35) also connects with sensors by wires and reads those sensors on a programmed schedule. However, it can even transmit the readings wirelessly to an off-site computer server. You can view and download those readings primarily through web browsers or mobile apps.

Figure 3.34 and Figure 3.35. Telemetry units

In some systems, each telemetry unit transmits its data independently over a cellular network. In other systems, multiple nearby "nodes" communicate via radio with the same base station, which transmits the collected data over a cellular network.

The greatest strength of telemetry is that users can see past and present readings anytime and anywhere with internet access through a smartphone, tablet, or computer. In addition, some user interfaces have convenient features that can help with irrigation decision-making (for example, automatic alerts) and trend visualization (for example, interactive graphs, such as those shown in fig 3.36). These capabilities are especially desirable for busy users who manage many fields and/or control irrigation systems remotely. To learn more about telemetry systems, visit https://www.ncaar.msstate.edu/outreach#showcase.

The tradeoffs to such benefits are the largest initial investment among the three device types, the need for service subscription payments, and the potential need for hardware (for example, antenna, solar panel) above the canopy. Ultimately, the best measurement device is the one with characteristics that are most compatible with your operation.

Figure 3.36. Telemetry user interface with interactive graphs illustrating trends

Scheduling Irrigations for Watermark Sensors

This segment was adapted from J. Rix, H. Lo, D. Gholson, and M. Henry's Irrometer Watermark Series: Irrigation Triggers, MSU Extension Publication 3541 (10-20) (http://extension.msstate.edu/publications/irrometer-watermark-series-irrigation-triggers).

An irrigation trigger is the point at which an irrigation cycle starts. Starting too wet wastes water and energy, while starting too dry reduces yield. Here, we give guidance on how to select an appropriate trigger for each irrigation system and how to schedule irrigation using Watermark data.

INTERPRETING WATERMARK DATA

Watermark data can serve as a gauge for the soil water "fuel tank" of the crop. Figure 3.37 illustrates how to interpret the weighted average centibars (cb) within the active root zone. Centibars are low when wet and high when dry.

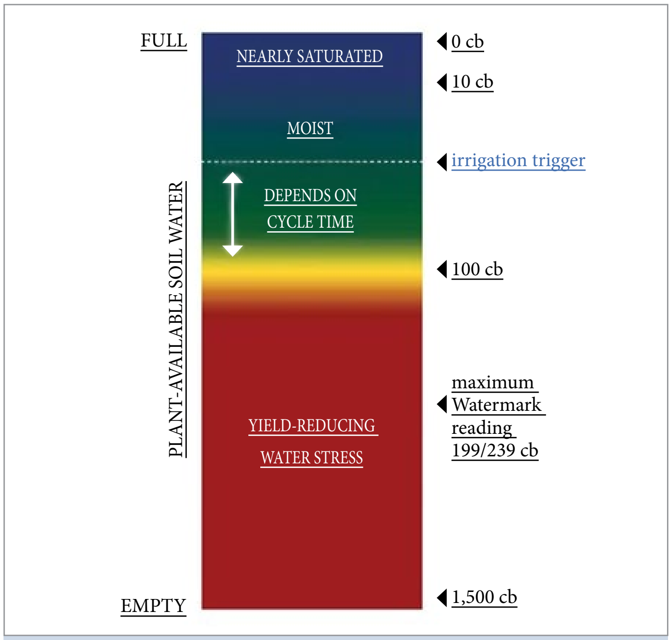

Figure 3.37. Irrigation trigger for a soil water "fuel tank"

CALCULATING THE WEIGHTED AVERAGE

The number of Watermark sensors within the active root zone can depend on crop growth and soil properties. To obtain the weighted average:

1. Find the column in Table 3.4 that corresponds to the number of sensors currently included within the active root zone. Once the centibars from a particular sensor have been increasing progressively for some time, this sensor is included for the rest of the season.
2. Perform the multiplication in each cell of that column.
3. Add up the result from each cell of that column.

TABLE 3.4. Template for weighted average calculations

Sensor depth	Two sensors	Three sensors	Four sensors
6"	0.5 × ___ cb	0.25 × ___ cb	0.17 × ___ cb
12"	0.5 × ___ cb	0.25 × ___ cb	0.17 × ___ cb
24"		0.50 × ___ cb	0.33 × ___ cb
36"			0.33 × ___ cb

These calculations may be automated by the Watermark average calculator at https://www.ncaar.msstate.edu/outreach/wmavg.php or by other web tools and services.

CHOOSING AN IRRIGATION TRIGGER

Previous research indicates that yield-reducing water stress tends to occur when the weighted average exceeds 100 centibars. The longer the cycle time for an irrigation system, the farther below 100 centibars the weighted average should be when triggering the start of a new irrigation cycle. Table 3.5 suggests general triggers for irrigation cycles of various durations.

TABLE 3.5. Irrigation triggers for different irrigation cycle times

Irrigation cycle (days)	Trigger (cb)
1	100
2	92
3	84
4	76
5	68
6	60
7	52
8	44

Example: Take as an example an irrigation system with one well supplying water to four fields that are irrigated one after another. The time it takes to irrigate each field is 28, 25, 21, and 19 hours, respectively. Thus, the cycle time is 93 hours or nearly 4 days. According to Table 3.5, a trigger of 76 centibars may be appropriate.

Figure 3.38 is an example of Watermark data early in the irrigation season. Notice that more sensors are included in the weighted average as the centibars in the deeper sensors begin to increase.

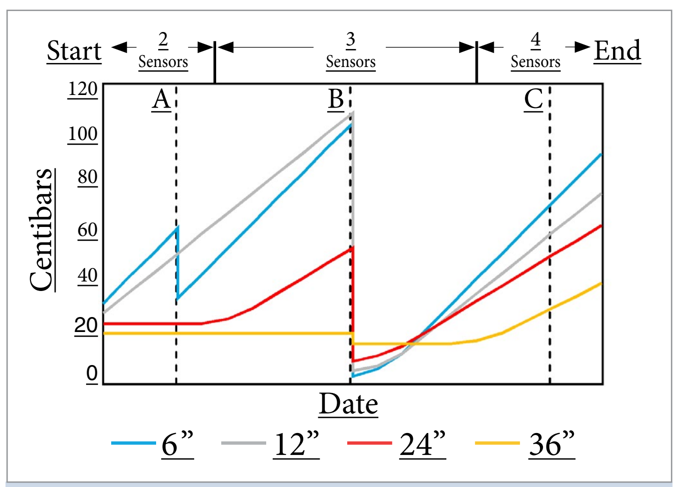

Figure 3.38. Number of Watermark sensors included in weighted average

During the first quarter of the graph, only the 6-inch and 12-inch centibars are increasing, so only two sensors are included in the weighted average for example date A.

TABLE 3.6. Weighted average calculations for three example dates

Sensor depth	Date A (two sensors)	Date B (three sensors)	Date C (four sensors)
6 inches	0.5 × 62 cb = 31 cb	0.25 × 104 cb = 26 cb	0.17 × 72 cb = 12 cb
12 inches	0.5 × 52 cb = 26 cb	0.25 × 108 cb = 27 cb	0.17 × 60 cb = 10 cb
24 inches		0.50 × 54 cb = 27 cb	0.33 × 51 cb = 17 cb
36 inches			0.33 × 30 cb = 10 cb
Weighted average	31 cb + 26 cb = 57 cb	26 cb + 27 cb + 27 cb = 80 cb	12 cb + 10 cb + 17 cb + 10 cb = 49 cb

During the middle half, the 24-inch centibars are increasing, so three sensors are included for example date B. During the final quarter of the graph, the 36-inch centibars are increasing, so all four sensors are included for example date C.

Table 3.6 shows the weighted average calculations on the three example dates. Based on the chosen trigger of 76 centibars, irrigation would be suggested for example date B but not for example dates A and C.

Sensor Type: Sentek Drill & Drop

The Sentek Drill & Drop is a multisensor capacitance probe that measures volumetric water content (VWC). Expressed as a percentage or as a decimal fraction, VWC identifies how much of the soil volume is occupied by water. Suppose a soil sample of 10 cubic inches contained 3 cubic inches of water. The VWC of this sample would be 30%, 0.3 $inch^3/inch^3$ (cubic inches of water per cubic inch of soil), or 0.3 inch/inch (inches of water per inch of soil).

The VWC of a soil increases with wetting and decreases with drying. Figure 3.39 shows the VWC at twelve depths as reported by Drill & Drop probes in a Sharkey soil near Stoneville, MS. The soil started wet and dried gradually over 5 weeks with minimal rain and no irrigation while the soybean crop progressed from early R3 to late R5 growth stage. A 0.3-inch rain on July 25 moistened the topsoil slightly, but the root zone was not refilled until 3.4 inches of rain fell on August 13. This example dataset will be used to illustrate four methods of interpreting the depth-by-depth Drill & Drop data for scheduling irrigation.

Profile Volumetric Water Content

The profile VWC can be calculated by averaging the VWC across multiple depths. The range of depths to include in this average might be specified by independent knowledge of root water uptake or be determined by sensor detection of which depths are or had been experiencing root water uptake. In Figure 3.39, the maximum depth of root water uptake appeared to increase from 26 inches to beyond 46 inches.

Profile VWC increases with wetting and decreases with drying. Figure 3.40 shows the profile VWC across the top 40 inches for the example dataset. One way to schedule irrigation is to wait until profile VWC becomes lower than the selected trigger.

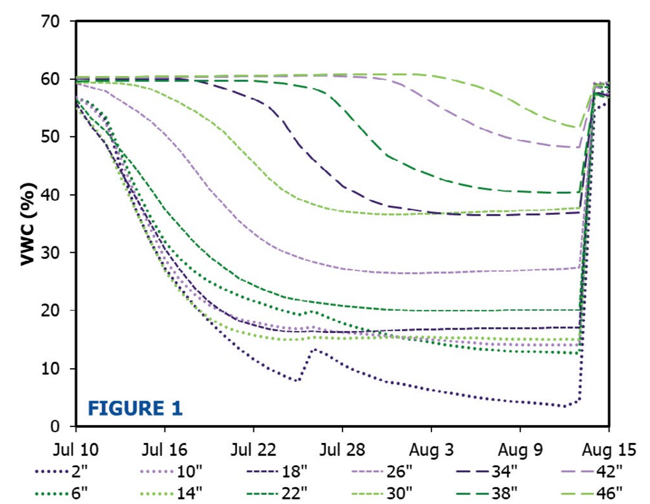

Figure 3.39. Example: profile volumetric water content (VWC)

Profile Depletion

Depletion is the difference between the current VWC and the full (but not excessive) VWC level (also known as *field capacity*). In Figure 3.39, the full VWC level was around 59%. The profile depletion can be calculated by averaging the depletion across multiple depths. The range of depths to include in this average should be chosen based on root water uptake, just like for profile VWC as explained in the previous section.

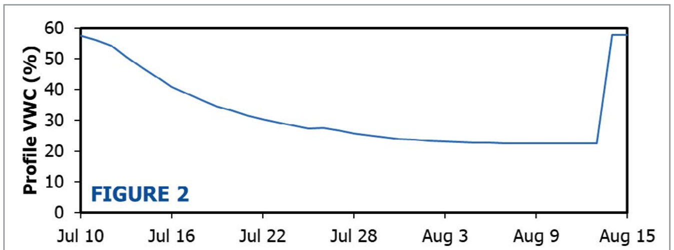

Figure 3.40. Example: profile VWC across top 40 inches for dataset

Profile depletion decreases with wetting and increases with drying. Figure 3.41 shows the profile depletion across the top 40 inches for the example dataset. One way to schedule irrigation is to wait until profile depletion becomes higher than the selected trigger.

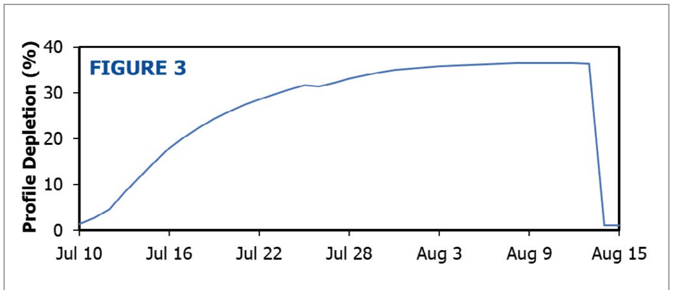

Figure 3.41. Example: profile depletion across top 40 inches for dataset

RATE OF PROFILE DEPLETION

The rate of profile depletion is the increase in profile depletion during a day with no rain and no irrigation. Over a period with steady weather and crop canopy conditions, a reduced rate of profile depletion would suggest that the crop is not getting enough water from the soil (at least immediately around the probe). To normalize the effect of significant changes in weather or canopy, the sensor-observed rate of profile depletion on each day can be divided by a model-expected rate of profile depletion on the same day.

Figure 3.42 shows the (unnormalized) rate of profile depletion across the top 40 inches for the example dataset. The rate of profile depletion reached its peak on July 12 (the third day of drying) and then hovered around a plateau before dropping sharply from July 16 (the seventh day of drying) onwards. One way to schedule irrigation is to wait until the rate of profile depletion descends from its plateau and becomes lower than the selected trigger.

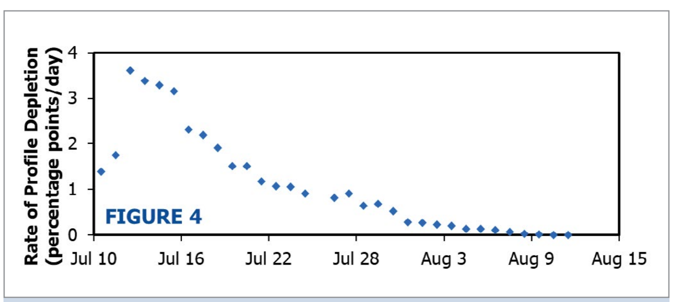

Figure 3.42. Example: unnormalized rate of profile depletion across top 40 inches for dataset

MEDIAN DEPTH OF DAILY DEPLETION

The median depth of daily depletion represents the center depth of root water uptake. Half of the daily increase in depletion occurs above the median depth of daily depletion while the other half occurs below it. Even after the crop completes developing its root system, the median depth of daily depletion is not constant. Instead, it fluctuates in response to soil moisture distribution. When soil moisture is abundant throughout the root zone, root water uptake tends to be concentrated at shallow depths. Thus, the median depth of daily depletion would be relatively shallow. When easily extractable water has been exhausted at shallower depths but remains available at deeper depths, root water uptake tends to migrate downward. Thus, the median depth of daily depletion would be relatively deep. Both trends can be seen in Figure 3.39.

Figure 3.43 shows the median depth of daily depletion for the example dataset. The median depth of daily depletion reached its minimum on July 12 (the third day of drying) and then increased with further drying. One way to schedule irrigation is to wait until the median depth of daily depletion rises from its minimum and becomes larger than the selected trigger.

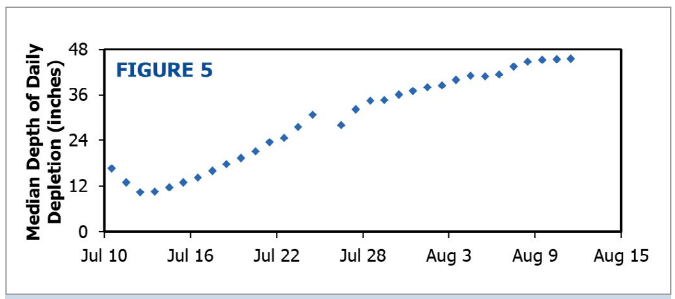

Figure 3.43. Example: Median depth of daily depletion for dataset

Conclusion

Although multiple methods exist for interpreting Drill & Drop data, the methods differ in reliability to indicate optimal irrigation timing across diverse scenarios on Mississippi row-crop farms. Research is being conducted to assess the reliability of various methods and to establish appropriate triggers for the most reliable method or methods. The findings will be presented in future publications.

Section 4: Types of Irrigation Systems

FURROW IRRIGATION

Furrow irrigation is one method of surface irrigation. Furrows are sloping channels cut into the soil surface, into which relatively large, but nonerosive, streams of water are directed. As water moves down the furrow, it infiltrates into the soil laterally as well as vertically. Furrow irrigation can be implemented very efficiently on soils and fields well suited to this method. Furrow irrigation can, however, be very inefficient if the soils and other factors are not properly considered in developing and managing the system. (Pros and cons are listed in Table 4.1.)

Conventional Furrow Irrigation

This segment is adapted from B. Benham's "Furrow Irrigation Management" chapter of the Irrigation Home Study Course offered by the University of Nebraska-Lincoln Plant and Soil Sciences eLibrary (https://passel2-stage.unl.edu/view/lesson/bda727eb8a5a/11).

Uniform application of water is not possible with a conventional furrow irrigation system. Uniformity can be improved, however, through a basic understanding of the system and the willingness to make the necessary management changes. The number of gates opened or tubes set (the set size) has a significant impact on how fast the water advances across the field and the amount of water being applied. Soil texture, slope, and surface conditions (whether the furrow is smooth or rough, wet or dry) all influence how quickly water advances down the furrow.

Set size should change during the season and year-to-year to match changing soil conditions. Using a small set (relatively few gates open) and a long set-time can result in a uniform irrigation but will produce excessive runoff. Running too many furrows, however, can result in slow water advance and virtually no runoff, which will cause poor water distribution and deep percolation losses. Efficient irrigation is obtained by almost filling the crop root zone, applying water uniformly and either minimizing or utilizing runoff.

Computerized Hole Selection

This segment is adapted from the University of Arkansas Cooperative Extension Service's Computerized Hole Selection web page (https://www.uaex.uada.edu/environment-nature/water/agriculture-irrigation/computerized-hole-selection.aspx).

CHS refers to a computer software application that designs and evaluates furrow irrigation systems. CHS uses pipe friction loss, pipe elevations, flow rate, and pressure to calculate punched hole sizes in lay-flat tubing (flexible polyethylene pipe) for uniform application of water, even in systems with varying row lengths. Down-row uniformity means rows are watered evenly, reducing tailwater, improving irrigation efficiency, and conserving water and energy. In most cases, using CHS has the potential to reduce water usage and irrigation cost by 25% or more. Two types of CHS tools commonly used are Delta Plastics Pipe Planner and PHAUCET (Pipe Hole and Uniform Crown Evaluation Tool).

Surge Irrigation

Surge irrigation is the intermittent application of water along a furrow to improve distribution uniformity. It works on the principle that dry soil infiltrates water faster than wet soil.

When soil is wet, the surface soil particles consolidate and form a seal. When water is re-introduced in a wet furrow, the wetting front moves quickly past the wetting zone to dry soil. At the wetting interface, dry soil slows the advance. This phenomenon allows for a faster advance through the field with less deep percolation and better application uniformity. The result is a more even distribution of water in the rooting zone from the polyethylene tubing to the tail ditch and reduced nutrient loss from deep percolation near the poly-tubing.

Surge irrigation works through a program of cycle times that account for the advance of the furrow. These cycle times must be set by the user. A valve that simply moves from one set to another at a uniform or constant time interval is not surge irrigation.

TABLE 4.1 Pros and cons of furrow irrigation

Pros	Cons
2–3 acre-inches of irrigation water can be applied at once to recharge depleted moisture in the root zone.	Land needs to be graded to assure uniform distribution of irrigation water.
Initial capital investment, other than land grading, is relatively low.	Furrow irrigation is not efficient on sandy soils; water soaks in before it reaches end of field.
Water can be used even if it contains a moderate amount of colloidal material.	It is difficult to apply small amounts (< 1 acre-inch) of irrigation water.
Water is not applied directly to plants, which reduces scalding of crop foliage.	In some soils, lateral spread of water across beds is not adequate to provide full irrigation.

SOURCE: D. Reinbott, University of Missouri Extension

Some tailwater is necessary for surge irrigation to be effective. The intermittent application reduces the tailwater volume because the water is moving as a pulse over the sealed furrow to the end of the furrow. Its velocity decreases as it moves along the furrow, so it has more time to infiltrate before it leaves the furrow. When set properly, very little tailwater leaves the furrow.

Definitions

Advance time: Time required for the wetting front to advance from the crown to the end of the furrow.

Recession time: Time for the wave front to recede from the furrow. Essentially, this is when the majority of the tailwater has stopped draining from the field.

Opportunity time: Time for water to infiltrate into the soil. The more opportunity time water has contact with the soil, the more volume is infiltrated.

Soak time: Time after the advance has completed when the remainder of the set time is used to meet the required application depth.

Application depth: The depth of irrigation applied during surge irrigation. This depth should be between 2.5 and 3.0 acre inches.

Number of cycles: The number of advance cycles (water on/water off) used to complete a surge advance program. Generally, surge advance times increase during the surge program, although some surge programs have a longer first advance than second advance before increasing.

On-time: The time water is applied to a given side.

Off-time: The time water is not applied to a given side.

Cycle-time: The time required to complete an on/off cycle (sum of on-time and off-time).

Irrigation set time: The total irrigation time includes advance and soak times. The set time for row crops should always be less than 40 hours. If using a computerized hole selection (CHS) plan, you must add the time for each set together to calculate the irrigation set time. For example, if a surge is being used on two 24-hour sets, the total time is 48 hours, so the sets should be divided into three sets.

Computerized Hole Selection for Surge Irrigation

For the surge valve to improve the down-furrow (top to bottom of field) distribution uniformity, surge irrigation sets **must** be planned by using a CHS tool such as Pipe Planner or PHAUCET.

To lay out surge irrigation, two irrigation sets must be combined. For example, if an irrigation set was used to irrigate a 35-acre field or set, then it must be divided into two sets of equal size (17.5 acres) or similar size (20 and 15 acres). Combine the irrigation time for each set to get the total irrigation set time. **It is recommended not to exceed a total time of 40 hours; 24 hours is preferred.** Ideally, sets should be reduced to 24- to 30-hour total irrigation set times.

When possible, locate surge valves at risers, valves, or bonnets. Due to valve motion, it is preferable not to have any lay-flat pipe supplying irrigation water to a surge valve. A surge valve can be used for multiple sets in a field. For example, a 40-acre field can be divided into four 10-acre sets, and the valve is used for two sets at a time, then switched to the other two. Place a short piece of rigid pipe in the valve and secure it with polyethylene pipe tape to make it easier to connect pipes. Use pipe clamps to secure the lay-flat pipe to the valve between surge sets.

Anatomy of a Surge Valve

A surge valve consists of an electronic controller and an aluminum mechanized valve that diverts water from one side to the other (referred to as right and left sides). P&R Surge Systems valves have advance and soak cycle modes. The valve starts out in the advance mode and then moves into the soak mode after the advance time is reached. It continues indefinitely in the soak mode until it is shut off.

Programming the advance time in a surge valve is critical. Once you reach the soak phase in the program, you cannot go back to the advance phase. Set the anticipated time of the advance phase slightly less than the actual advance time observed in the field. In many cases, surge irrigation advance time is about half the normal time.

Use CHS to plan the surge time. For example, if a CHS plan calls for a 24-hour set time, then expect a 12-hour advance. However, the advance time is highly variable, so use your experience to determine the advance; monitor the advance during the first irrigation until you know or can predict it. For example, if a 24-hour set is required to put on 2.5 acre-per-inch application depth and you observe that the advance is halfway through the field at 9 hours, then adjust the advance time down from 24 to 18 hours.

Guidance on setting a surge valve for different soils and conditions is provided below. However, there is no hard-and-fast rule; experiment with the valve to get the best results.

Sandy Soils

Surge valves are especially useful in sandy soils because the challenge with these soils is minimizing deep percolation and getting water through the furrow. Set the valve as normal but expect a longer advance time than 50 percent of the irrigation set time. Use default cycle times. Increasing the number of cycles may improve irrigation.

TABLE 4.2. Surge valve STAR Controller recommendations for clay soils

Advance setting	Default cycles/side setting	Custom cycles/side recommendation
Input by user	Under custom tab	Use down arrow to adjust
5	4	4-1 (3) total
10	5	5-2 (3) total
15	6	6-2 (4) total
20	6	6-2 (4) total
30	6	6-2 (4) total

Silt Loams

Surge valves are especially useful in silt loams that seal. In silt loams that do not seal and infiltrate well, use the same process as for sandy soils. For silt loams that seal, you likely will need to make substantial changes to the program. In the sealing silt loams, the advance is often much less than expected. For example, for a set time of 24 hours, the advance may be completed in 6 hours. Adjust the advance time to 5 hours and increase the number of advance phases by one or two. Operate the valve in soak mode for the remainder of the irrigation set. Reduce the flow rate to increase opportunity time.

Clay Soils (Cracking)

The surge valve should be used only in the advance mode in cracking soils. Set the advance time to the total irrigation set time. Do not operate in soak mode. Reduce the number of advance cycles to only three or four. The surge valve works in clay soil because, in the off cycle, the soil cracks seal up and allow the advance to move quickly through the furrow on the next advance. Table 4.2 lists recommended advance settings.

The number of cycles per side should equal the default setting minus two. Total cycles per side should never be less than three.

Unbalanced Set Sizes

Two sets of different sizes can still be surge irrigated. For example, if one set is 15 acres and another is 20 acres, the valve can be adjusted to increase the advance times for each set. In this example, the valve will divert water to the 15-acre set 43 percent of the time, and it will divert water to the 20-acre set 57 percent of the time. This setting can be input directly into the valve through a custom menu.

Operation

Surge valves operate on solar power and a battery. Check the voltage of the battery and solar panel through the custom menu (hold the button down for 3 seconds on a P&R). Valve controllers need to be charged and turned off in the off-season. During the season, shut them off after an irrigation event or else they will continue to move the valve and drain the battery. The oscillation of the valve can dislodge it from the water source, so use a circle lock or horseshoe clamp to secure it. When starting irrigation, change the valve from the right or left side using the change button; this does not advance the program when done during the first advance cycle. The valve pauses before switching completely over. This setting can be changed in most valves if high flow rates cause a water hammer.

The benefits of surge irrigation are not always apparent from visual observation alone. Soil moisture sensors or monitoring units can be useful in evaluating effectiveness and optimizing surge irrigation program settings. Surge reduces the advance time in some situations and increases it in others. Reducing the advance time results in water savings. An increased advance time typically indicates that more water has been applied to the soil; likely, fewer irrigations will be necessary, which means less total irrigation water will be needed to meet crop water demand.

Summary

Surge irrigation is the intermittent application of water in furrow irrigation to improve down-furrow efficiency and reduce deep percolation. It uses a programmed, automated valve with lay-flat pipe that is planned with set sizes. Surge irrigation must be adapted and adjusted to field conditions and soil type. Plan surge irrigation sets for a total irrigation time of 24 hours, and use CHS to determine lay-flat pipe hole-punch plans (Gholson 2020).

TABLE 4.3. Pros and cons of flood irrigation

Pros	Cons
Low initial investment for equipment is required.	Least efficient form of irrigation. More water loss from evaporation, infiltration, and runoff.
Runoff water can be recycled to improve efficiency.	Building and taking down levees is labor intensive.
Side-inlet flood saves 60% of water compared to cascade.	Land usually needs grading to enable uniform water distribution.

SOURCE: D. Reinbott, University of Missouri Extension

FLOOD IRRIGATION

Flood irrigation supplies water to a field through pipes or ditches. Water flows over the ground and through the crop. Levees and gates are often used to control water depth. In Mississippi, flood irrigation is commonly used in rice fields while utilizing AWD (alternate wetting and drying), multiple inlet, straight levee, and contour levee systems. Table 4.3 lists pros and cons of flood irrigation.

What is AWD?

Information in this segment is adapted from the Rice Knowledge Base's "Saving Water with Alternate Wetting and Drying," published by the International Rice Research Institute at http://www.knowledgebank.irri.org/training/fact-sheets/water-management/saving-water-alternate-wetting-drying-awd, *with input from R. M. Lampayan, S. Yadav, and E. Humphreys.*

Alternate Wetting and Drying (AWD) is a water-saving technology that farmers can apply to reduce their irrigation water consumption in rice fields without decreasing its yield. In AWD, irrigation water is applied a few days after the disappearance of the ponded water. Hence, the field gets alternately flooded and nonflooded. The number of days of nonflooded soil between irrigations can vary from 1 day to more than 10 days depending on factors such as soil type, weather, and crop growth stage.

How to Implement AWD

A practical way to implement AWD safely is by using a field water tube, or pani pipe, to monitor the water depth on the field. After irrigation, the water depth will gradually decrease. When the water level has dropped to about 15 centimeters below the surface of the soil, irrigation should be applied to reflood the field to a depth of about 5 centimeters. From a week before to a week after flowering, the field should be kept flooded, topping up to a depth of 5 centimeters as needed. After flowering, during grain filling and ripening, the water level can be allowed to drop again to 15 centimeters below the soil surface before reirrigation. Alternate Wetting and Drying can be started a few weeks (1–2 weeks) after transplanting. When many weeds are present, AWD should be postponed for 2–3 weeks to assist with weed suppression by the ponded water and improve the efficacy of herbicide. Local fertilizer recommendations for flooded rice can be used. Apply nitrogen fertilizer preferably on the dry soil just before irrigation.

What is Multiple-Inlet Irrigation?

This segment is adapted from "Multiple Inlet Approach to Reduce Water Requirements for Rice Production" by E. D. Vories, P. L. Tacker, and R. Hogan, published in Applied Engineering in Agriculture in 2005 (http://www.ars.usda.gov/sp2UserFiles/Place/36221500/cswq-0215-174368.pdf).

With flooded rice culture, water usually fills the highest paddy first, and then as each paddy is filled, water flows over into lower paddies. However, that makes it hard to know exactly how much water to pump so that all paddies are filled without losing any from the lowest paddy. We found that an alternative method, multiple-inlet irrigation, would save water (24% on average) and produce the same or slightly better yields. In multiple-inlet irrigation, a pipe is run through the field and holes are placed so that each paddy is concurrently watered instead of receiving overflow from a higher paddy.

Contour Levee

This and following segments on rice irrigation systems are adapted from "Rice Production in the United States," published on November 3, 2021, by George Baird, AFM, AAC (https://peoplescompany.com/blog/rice-production-in-the-united-states).

Fields have levees or dikes that follow the natural contour. The levees are laid out by surveyors who provide markers in the field that farmers can follow pulling a levee plow. The goal of using levees is to maintain a water depth across the field of 2 inches on the top side of the levee and no more than 4 inches on the lower end. The levees are checked daily to make sure proper water levels are being maintained, with gates adjusted throughout the growing season to ensure proper levels are maintained.

Straight Levee

Fields involve a leveling and design plan. Producers hire leveling crews to come in and set up their fields to allow them to reduce the number of levees, making the field more efficient to operate. Operating a field set up in this manner has several advantages. Having fewer levees and/or levees set up straight allows producers to complete early season application of fertilizer and chemicals with ground rigs rather than resorting to airplanes. It allows for decreased water usage and increased yields with fewer levees to deal with.

Zero Grade Rice

Fields are also set up mechanically, but they are designed to be flat rather than having a consistent slope across the field. The absence of levees makes it possible for early season applications by tractor and spray rigs before flooding. Like straight levee fields, the goal is to reduce water usage and increase operator efficiency to achieve higher yields and returns. With zero grade fields, there are interior ditches around three sides of the fields. When it is time to flood the field, the interior ditches are pumped with water and then water will uniformly come across the fields from three sides. Zero grade fields use about half the water that contour levee fields use. This benefits the producer. Since rice is typically grown on the heavier ground, setting up a field to be zero grade can limit crop rotation, compared to a straight levee field. Wet growing seasons could be harmful to crops such as corn and soybeans on these heavier flat fields.

ROW RICE

Row rice is the newest method in rice production, with acreage increasing each year. Rice is drilled directly into a row that has been bedded in a traditional method. The initial early season applications are done mechanically and in a similar manner. Rather than maintain a continuous flood, the goal is to maintain a wet soil profile throughout the growing season using an alternative wetting system (AWS). Weather and soil types can make timing vary, but the producer would typically irrigate the rice field or water the rice down the row from 2 to 3 days a week or 4 to 6 days a week. It is possible that this water reduction can increase weed pressure, which in return drives up chemical costs. However, row rice also allows crop rotation traditionally not considered with rice. Each of these systems are viable options with associated benefits and should be given consideration when improving a property or when assessing a property for an acquisition.

CENTER PIVOT IRRIGATION

The following segments related to center pivot irrigation are adapted from "Sprinkler Irrigation Basics," written by B. Kranz and published as part of the Irrigation Home Study Course offered by the University of Nebraska-Lincoln Plant and Soil Sciences eLibrary (https://passel2-stage.unl.edu/view/lesson/bda727eb8a5a/3).

Sprinkler Irrigation Basics

The term *sprinkler irrigation* describes a variety of irrigation systems, all of which use sprinklers to distribute water. These systems can be stationary or mobile. For example, a towline is stationary, and center pivot or large volume guns are mobile. We can link sprinkler irrigation's success to the system's ability to work on many crops, to apply water uniformly and efficiently, and to deliver water under a wide range of climatic and field conditions.

When sprinkler irrigation first started, the term was synonymous with systems that used impact sprinklers to distribute the water. More recently, the term has been expanded to describe a broad range of impact sprinklers and spray nozzles. Most of the development in sprinkler technology has been directed at center pivot applications, however, in the process some new sprinklers have been developed for use with towlines and side rolls (Kranz n.d.). Table 4.4 lists pros and cons of center pivot irrigation.

TABLE 4.4. Pros and cons of center pivot irrigation

Pros	Cons
Efficient on medium- and coarse-textured soils.	Deep ruts can form on clay soils from center pivot tires.
Water can be applied at low rates (< 0.1 acre-inch).	Frequent applications may be needed to recharge soil depleted by crop.
Fertigation and chemigation can be used for plant nutrition or pest control by injecting chemicals into the irrigation water.	Sprinkler nozzles can clog with poor quality water.
Center pivot systems can be programmed to start and stop at specified angles or time.	Scalding can occur on crop foliage.

SOURCE: D. Reinbott, University of Missouri Extension

Center Pivot Irrigation Systems

A center pivot is a water distribution pipeline anchored at one end and allowed to rotate or pivot about the stationary end. The system length can vary from 300 feet to more than 2,600 feet. Water is supplied to the pivot point resulting in a circular irrigated area. Beginning at the pivot point, each additional foot of system length must irrigate an area that increases as the system length squared. For a 1,300-foot-long center pivot making a complete circle, the first 130 feet of the system irrigates 1.2 acres, and the last 130 feet of the system irrigates 23 acres. To distribute the same amount of water to every portion of the field, the last 130 feet of the system must receive more than 19 times more water than the first 130 feet. This causes the pressure to be greater at the pivot point than at the end of the system (Kranz n.d.).

Determining System Requirements

Selecting a sprinkler package for a center pivot can involve several conflicting issues. Owners and managers can choose from an array of sprinkler types, many of which can perform adequately. Your selection should be based on accurate field-based information and careful consideration of the interaction among several factors. First, determine the area to be irrigated by the system. Since most new sprinkler installations involve center pivots, examples for other installations are not provided (Kranz n.d.). If you are interested in calculating the area irrigated for other systems, contact your local MSU Extension agent.

DRIP IRRIGATION

Drip irrigation delivers water drop by drop to crop roots. Water is supplied under low pressure through plastic tubing manufactured with emitters to regulate flow rate. Tubing can be placed on the ground or buried beneath the soil surface. Table 4.5 lists pros and cons of drip irrigation.

TABLE 4.5. Pros and cons of center drip irrigation

Pros	Cons
Saves water by minimizing evaporation.	Method cannot be used with high iron content water because emitters become clogged.
Nutrient losses from leaching are reduced.	Maintenance is required to keep system going.
No land grading is required.	Chewing on tubing from insects and rodents can cause water leaks.
Can be used in irregularly shaped fields.	Mowers and trimmers can slice tubing.

SOURCE: D. Reinbott, University of Missouri Extension

Section 5: Pumping Plant Efficiency

This segment is adapted from B. Stringam's "Pump Efficiency" in Irrigating Pumping Plant Efficiency Testing, LSU AgCenter Pub. 3241 (https://lsuagcenter.com/~/media/system/5/4/1/5/5415313155f4f48edeefe4b3bc2a85b2/pub3241jpumpefficiency.pdf).

EFFICIENCY SIGNIFICANCE

Selecting a proper pumping system will conserve fuel or electricity and decrease the annual pumping costs. Inefficient and poorly chosen pumping systems can increase annual costs dramatically. There also is a possibility excessive wear will occur on the pumping plant, and water may be wasted.

PUMP EFFICIENCY

Pump efficiency is defined as the ratio of water horsepower output from the pump to the shaft horsepower input for the pump. Water horsepower is determined by the flow rate and pressure delivered from the pump. The shaft horsepower is delivered to the pump from the power unit, which usually is an electric motor or internal combustion engine. If a pump was 100 percent efficient, the mechanical horsepower input would be equal to the water horsepower output by the pump. No pump is 100 percent efficient, so the mechanical horsepower input will be greater than the water horsepower output. Lower efficiencies are due to energy losses caused by friction and leakages originating from pressure differentials within the pump case and due to more complex issues. The efficiency of a particular pump is estimated by determining pump flow rate and total head.

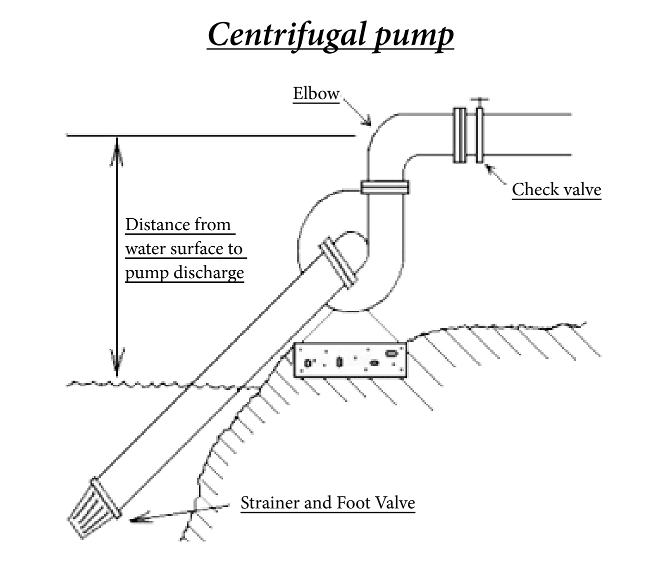

Figure 5.1. Measuring total head for centrifugal pump

Credit: Stringam, 2013

TOTAL HEAD

Total head is determined by measuring the distance from the source water surface to the output of the pump, as well as the pressure the pump is producing at the pump outlet. If this value is measured for a centrifugal pump, the distance from the water surface to the pump outlet needs to be measured as indicated in Figure 5.1.

In addition, the pressure at the pump outlet also needs to be measured. The total head can then be determined by knowing that 2.306 feet of water is equal to 1 pound per square inch of pressure (psi). For example, if the distance from the water surface to the pump outlet was 8 feet and the pressure measured at the pump outlet was 60 psi, the total pressure head would be:

$$H = 8 + (60 \times 2.306) = 146.4 \text{ feet}$$

Total head can be determined for a deep well turbine pump, as well. Again, the distance from the pumped water surface to the pump outlet must be measured. (See Figure 5.2) There will always be a drop from the static water surface to the pumped water surface. The pressure that is delivered at the pump outlet also is measured.

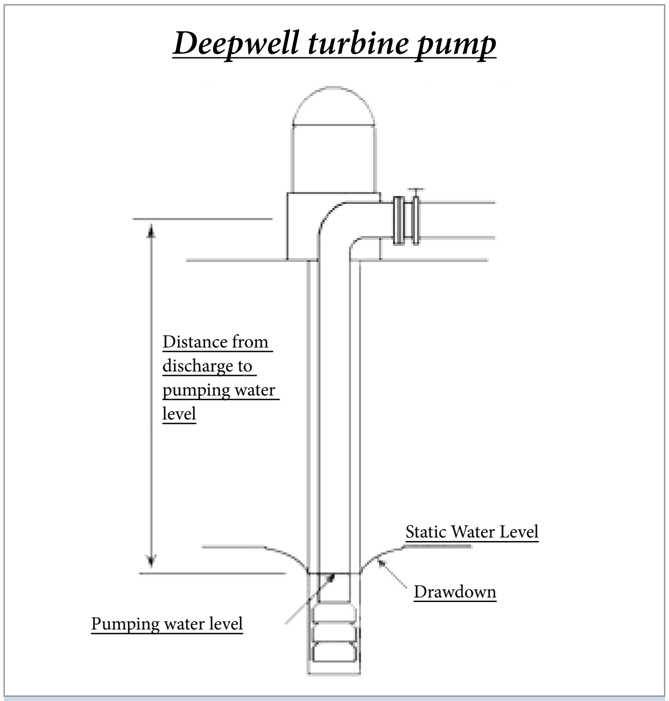

Figure 5.2. Measuring intake head for a deepwell turbine pump

Credit: Stringam, 2013

Example: If the distance from the pumped water surface to the pump outlet was 134 feet and the pressure measured at the pump outlet was 60 psi, the total pressure head would be:

$$H = 134 + (60 \times 2.306) = 272.4 \text{ feet}$$

FLOW RATE

Flow rate is the total water volume that passes through a fixed point over time. Flow rate can be measured using a flow meter. Numerous flow meters are available, but an ultrasonic flow meter usually is the most convenient flow meter to use.

Figure 5.3 Ultrasonic flow meter

Credit: Stringam, 2013

This flow meter can be programmed to read flow rate in whatever units are required, but gallons per minute usually is the measurement used.

DETERMINING PUMP EFFICIENCY

Water horsepower can be calculated by using this formula, where H is the total head of the water in feet and Q is the flow rate in gallons per minute:

$$WHP = HQ / 3960$$

Example: If the flow rate for the previous centrifugal pump was 654 gallons per minute, the water horsepower for the pump would be:

$$WHP = 146.4 \times 654 / 3960 = 24.2\ WHP$$

If the same flow rate was used for the previous turbine pump example, the water horsepower would be 44.98 WHP. Pump input horsepower is determined by measuring the speed and torque of the motor shaft input to the pump. Once these two values have been determined, pump efficiency is a simple calculation that can be determined by this formula:

$$\eta = hp_{water} / hp_{pump}$$

Example: If the horsepower input to the previous centrifugal pump example was 33 horsepower, the pump efficiency would be:

$$\eta = 24.2 / 33 = 0.73 \text{ or } 73\%$$

Section 6: Economics of Irrigation

This section was written by Dr. Nicolas Quintana-Ashwell, assistant research professor and agricultural economist at the National Center for Alluvial Aquifer Research.

Farmers can save time and money using accurate information on the cost to irrigate and the trade-offs involved in initiating and terminating irrigation. The Mississippi State University irrigation termination online app (MiTOOL) is an enhanced pumping cost calculator accessible by scanning the QR code or at https://www.ncaar.msstate.edu/outreach/mitool.php. The tool has step-by-step instructions to customize it to specific pump and power plant configurations.

MiTOOL Calculator

THE ANNUAL COST OF IRRIGATION

The two main concerns regarding the cost of irrigation are the cost of establishing and the cost of operating irrigation systems. Both costs can be estimated on annual and per acre basis. However, system configuration and site-specific conditions are critical determinants of these costs, which are almost limitlessly variable. Energy prices are historically volatile and a critical determinant of operational costs as well. Consequently, it is advisable to calculate the specific investment and operation costs to make irrigation decisions. Furthermore, it is best to calculate the annualized per acre costs of irrigation to make choices about upgrading, replacing, or installing irrigation systems. This allows to you to compare alternatives in terms of their costs but also against the expected benefits in terms of ease of management and crop yield gains (which in turn need to be weighed by volatile crop prices).

Estimating the Annualizing Cost of Establishing an Irrigation System

To calculate the equivalent annual cost (EAC) and capital recovery factor (CRF) for each component in an irrigation system, employ the following formula:

$$\text{EAC} = (\text{Initial cost} - \text{Salvage value}) \times \text{CRF};$$

$$\text{CRF} = [i(1 + i)^{\text{time}} / (1 + i)^{\text{time}} - 1]$$

To keep track and facilitate comparison across options, it is useful to build a spreadsheet as shown in Figure 6.1, which shows the required formulation to calculate EAC on a spreadsheet.

Estimating the Annual Per Acre Cost of Operating an Irrigation System

The annual cost of operating an irrigation system depends heavily on what type of season it is run on, water source or well characteristics, the power plant type, pump configuration, and operational requirements such as system pressurization requirements. The number of possible combinations is endless (almost 18,000 calculations are required for the examples in this section). We employ the MiTOOL program to illustrate the type of economic analyses that can applied to different irrigation requirement scenarios under alternative weather and aquifer conditions. We estimate the cost of irrigation employing four irrigation systems:

Item	Quantity required	Cost per unit	Initial Cost	Useful life in years	Salvage portion	Salvage value	EAC (undiscounted)	Discount or interest rate	Capital Recovery Factor	Equivalent Annual Cost (discounted)
Excavation	22000	1.5	=+C2*B2	20	0.8	=F2*D2	=(D2-G2)/E2	0.0204	=I$2*(1+I$2)^E2/((1+I$2)^E2-1)	=(D2-G2)*J2
Reservoir levees	30000	1.5	=+C3*B3	20	0.8	=F3*D3	=(D3-G3)/E3	0.0204	=I$2*(1+I$2)^E3/((1+I$2)^E3-1)	=(D3-G3)*J3
Pumping plant	2	21000	=+C4*B4	20	0.1	=F4*D4	=(D4-G4)/E4	0.0204	=I$2*(1+I$2)^E4/((1+I$2)^E4-1)	=(D4-G4)*J4
Underground line	1320	7	=+C5*B5	20	0.8	=F5*D5	=(D5-G5)/E5	0.0204	=I$2*(1+I$2)^E5/((1+I$2)^E5-1)	=(D5-G5)*J5
Stand with flowmeter	8	243.75	=+C6*B6	20	0.8	=F6*D6	=(D6-G6)/E6	0.0204	=I$2*(1+I$2)^E6/((1+I$2)^E6-1)	=(D6-G6)*J6
Total										=SUM(K2:K6)
Acres covered										160
Total Equivalent Annual Cost per acre										=K7/K8

Figure 6.1. Formulation to calculate equivalent annual cost for investment expenditures. The total per acre cost serves as basis to compare investments that greatly differ in terms of performance and initial cost.

- conventional furrow irrigation: furrow irrigated without irrigation water management (IWM) practices using a conventional continuous-flow delivery system
- conventional furrow irrigation optimized with computerized hole selection (CHS furrow): CHS (using Pipe Planner or PHAUCET), a free computer program that improves irrigation application efficiency by computing flow and pressures along the length of the lay-flat polyethylene tubing and selecting hole sizes so that down-row uniformity is improved across the irrigation, set regardless of furrow length
- IWM furrow irrigation: combination of CHS, surge irrigation, and soil moisture sensors
- sprinkler irrigation: center pivot system, 1/4 mile, 135-acre system as in MSU Budget

There are four irrigation systems with different pressurization requirements (Table 6.1). Costs are calculated for three different application scenarios. The pump discharge pressure requirement is converted to dynamic head and added to the pumping list to compute the energy cost of pumping under those conditions. The irrigation requirement water use scenarios can be interpreted as the amount required by different crops or the requirement for a specific crop under different growing season climatologic conditions.

The baseline scenario is the amounts used under conventional furrow irrigation, while the water-conserving systems present lower water requirements. These more efficient irrigation systems produce similar crop yields based on field research carried out in Stoneville, MS. In the case of furrow systems with computerized hole selection, research showed a reduction in required water applications of 17% (Krutz 2016). The furrow systems with IWM showed a potential reduction of application requirements of 39.5% (Spencer et al. 2019). Finally, preliminary data from a comparative study between sprinkler and furrow irrigation at NCAAR indicates potential savings of 41.6% of water use.

Annual Costs of Operating an Irrigation System

The number of irrigation scenarios is limitless and impossible to effectively analyze—Table 6.2 shows the number of calculations required for the scenarios summarized here.The best way to assess a particular situation is to calculate the irrigations costs under your current conditions and the specifications of your

TABLE 6.1. Water use and pressurization assumptions for select irrigation patterns

Irrigation system	Pump discharge pressure (pounds/ square inch)	High irrigation requirement water use (inches/acre)	Intermediate irrigation required water use (inches/ acre)	Low irrigation required water use (inches/acre)	Acres irrigated
Conventional furrow	5	12	9	6	160
CHS furrow	5	10	7.5	5	160
IWM furrow	5	7.25	5.5	3.6	160
Sprinkler	40	7	5.25	3.5	135

TABLE 6.2. Number of irrigation scenarios with pumping costs computed

Variable and number of scenarios	CONV, CHS, and IWM furrow		Sprinkler	
	Diesel	Electric	Diesel	Electric
Water use levels	3			
Discharge pressure	1			
Pumping lift	3			
Pump engine power	3			
Pump efficiency	3			
Pump flow (GPM)	4		1	
Gear head efficiency	3	1	3	1
Energy price	5	2	5	2
Number of scenarios	14,580	1,944	1,215	162
Total number of cost scenarios	17,901			

alternative scenarios. A total of 17,901 computations are performed to estimate the irrigation cost under four irrigation systems, powered by two different energy sources (including five price scenarios for diesel and two for electric), considering three water use levels, three pumping lift levels, three pump engine power levels, three pump efficiency levels, three gear head efficiency levels, and four pump flow rates.

Given the seemingly limitless number of combinations, we present the average costs of irrigation under the different operational scenarios. Table 6.3 shows the average annual costs across irrigation requirements by source of energy ($3.95 average diesel price per gallon and 0.1315 average electric rate per kwh).

These averages are taken across the variation in the other variables not specified in the table. Even the averages are highly variable, ranging from $4.39 to $40.40 per acre. The highest cost per acre employed a conventional, diesel-powered, furrow irrigation system requiring high water use.

The largest cost difference is when there is a high water-use requirement and the pumping station is diesel powered, in which case savings of $15.71 per acre are achievable on average. If the conversion from conventional to IWM furrow irrigation results in an EAC of less than $15.71 per acre, it would certainly be a profitable conversion if high water use is expected going forward. In this relatively high average diesel price scenario, sprinkler irrigation reduces irrigation costs when also converting to an electric configuration. A key variable determining the energy cost of irrigation is the pumping lift distance. In a depleting aquifer, this translates in increasingly larger irrigation costs. Figure 6.2 illustrates the effects of increasing pumping lift distances; notice the energy cost of irrigation increases at a lower rate for electric systems

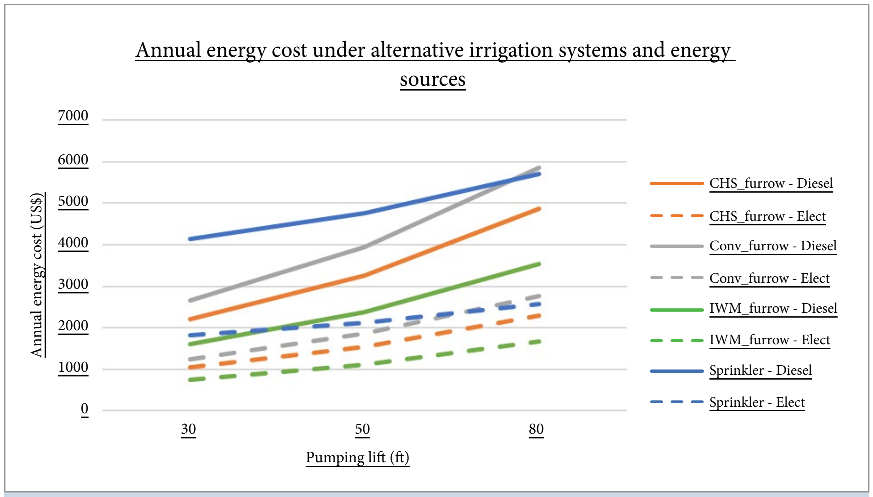

Figure 6.2. Relationship between groundwater pumping cost and pumping lift distance

TABLE 6.3. Average annual irrigation cost by water use intensity, delivery system, and energy

System	Energy source	Annual irrigation cost by water requirement ($/acre)		
		High	Medium	Low
Conventional	Diesel	40.40	30.30	20.20
	Electric	17.42	13.06	8.71
	Average	37.69	28.27	18.85
	(standard deviation)	(18.02)	(13.51)	(9.01)
Computerized hole selection	Diesel	33.63	25.23	16.82
	Electric	14.56	10.92	7.28
	Average	31.39	23.54	15.70
	(standard deviation)	(14.96)	(11.22)	(7.48)
Irrigation Water Management Suite	Diesel	24.69	18.52	12.34
	Electric	10.79	8.09	5.39
	Average	23.05	17.29	11.53
	(standard deviation)	(10.90)	(8.18)	(5.45)
Sprinkler	Diesel	55.93	41.95	27.96
	Electric	25.17	18.88	12.59
	Average	52.31	39.23	26.16
	(standard deviation)	(18.92)	(14.19)	(9.46)
Overall	Average	32.37	24.28	16.19
	(standard deviation)	(17.29)	(12.97)	(8.65)

than for diesel power systems as pumping lifts increase due to aquifer depletion. Similarly, sprinkler systems show a similarly lower rate of cost increases with deeper pumping depths. Notice that electricity-powered systems are less sensitive to increasing pumping lifts. Similarly, it's worth noting that sprinkler irrigation systems have a lower rate of increase due to lift, which suggests they are more economically viable as irrigation water needs to be pumped from deeper wells over time.

Clearly, the price of energy drives the cost of irrigation. Table 6.4 shows the impact of increasing energy prices by irrigation system and energy source. Because the price of energy is a coefficient in the calculation of the pumping cost, the effect of price increases in the future is accentuated in depleting aquifers (increasing pumping lifts). This results in irrigation cost increases that are more than proportional to the increases in energy prices.

Finally, the efficiency of the pumping station is the last important consideration covered in these examples. There are two efficient components: pump efficiency and power unit gear head efficiency.

When using an electric motor to power the pump, the unit is fully efficient as the motor operates the pump directly without need of a driveline. Fuel-powered engines drive pumps using drive shafts or belts, resulting in efficiency losses between engine output and pump operation. Table 6.5 shows the effect of pump and gearhead efficiency combinations. In diesel-powered pumps, overhauls improving pump efficiency from 50% to 80% can result in savings of $16.50 per acre on average across scenarios—even much more in high water use scenarios. Combining a pump overhaul with electrification results in an average saving of nearly $33 per acre on average across these scenarios.

TABLE 6.4. Average costs of furrow irrigation under different price scenarios by irrigation system

Energy source and prices	Annual irrigation cost by irrigation system ($/acre)			
	Conventional	Computerized hole selection	IWM	Sprinkler
Electric				
$0.1142/kwh	11.41	9.55	7.09	16.47
$0.1487/kwh	14.72	12.30	9.09	21.30
Diesel				
$3.00/gal	23.12	19.27	14.18	31.98
$3.50/gal	26.90	22.41	16.46	37.22
$4.00/gal	30.67	25.54	18.74	42.47
$4.50/gal	34.45	28.67	21.03	47.72
$4.75/gal	36.34	30.24	22.17	50.34
Overall average (standard deviation)	**28.27**	**23.54**	**17.29**	**39.23**
	(15.98)	(13.27)	(9.69)	(18.16)

TABLE 6.5. Annual furrow irrigation cost by pump and gear efficiency level

	Annual irrigation cost by gear head efficiency ($/acre)			
	90%	**92.5%**	**95%**	**100% (electric)**
Pump efficiency				
50%	44.44	43.25	42.12	18.54
65%	34.29	33.38	32.51	14.37
80%	27.95	27.21	26.50	11.77
Overall average (standard deviation)	35.56	34.61	33.71	14.89
	(16.02)	(15.59)	(15.18)	(16.14)

Section 7: Additional Tips and Practices

Segments under the next four headings were adapted from Tips for Conserving Irrigation Water in the Southern Region (LSU Ag Center Publication 3241-K), by C. G. Henry, J. H. Massey, H. C. Pringle, L. J. Krutz and B. Stringam.

MEASURE THE FLOW

Install a flow meter or use a portable flow meter to obtain measurements of the flow rate and total flow. Use these measurements to design your irrigation sets, calculate water applied, and schedule your irrigation.

USE TIMERS OR PUMP MONITORS TO SHUT WELLS OFF AT APPROPRIATE TIMES

Timers can be installed and set to turn wells off. This can help to reduce runoff, especially at times when it is not convenient for the manager to be there. In addition, pump monitors generally allow for remote operation and monitoring of pumps through the Internet and cellular connections.

ADDRESS COMPACTION AND SOIL-RELATED FACTORS

Soil compaction reduces the infiltration of rainfall and irrigation water, increasing runoff and decreasing soil moisture available for crop growth. Organic matter increases the water-holding capacity of soils. A comprehensive irrigation efficiency program includes adoption of practices that address plant/water/soil factors that improve the water storage potential of soils.

Several options exist to improve infiltration, including furrow-diking, deep tillage, no-till and cover crops. Experiment to find the solutions that work best on your farm.

TIPS FOR SPRINKLER SYSTEMS

Sprinkler nozzles older than 7 years should be checked annually. Nozzles can be checked for uniformity using catch cans, rain gauges, or irrigauges. Some types of nozzles may wear out faster, especially if the irrigation water source contains sand. One of the most cost-effective ways to improve a pivot or sprinkler system is to update or upgrade the sprinkler package.

For more information on operation and maintenance of center pivot irrigation systems, please visit https://www.aces.edu/wp-content/uploads/2021/05/ANR-2772-Operation-Maintenance-Center-Irrigation_051921L-G.pdf.

FLOW METER CALCULATOR

The following information about the Flow Meter Calculator is adapted from the 2023 "Flow Measurement Series: Flow Meter Calculator," by H. Lo, D. Gholson, N. Q. Ashwell, and A. Deason, all of Mississippi State University Extension.

Water flow meters have become an increasingly common component of agricultural irrigation systems in Mississippi. Besides indicating instantaneous flow rate, many flow meters also include a totalizer. Totalizers keep a running tally of the water amount that has flowed through and been measured by the flow meter. By knowing how much irrigation water has been applied, the performance of an irrigation system can be assessed more accurately. You can use this knowledge to answer questions such as these:

- How does the water amount applied by this irrigation system compare against the water amounts associated with precipitation, evaporation, soil moisture, surface water supplies, groundwater recharge, and so forth? Should changes in system hardware or management behavior be explored?
- What is the cost of each application by this irrigation system? Would the extra expenses from the next application exceed the extra revenue from the expected increase in crop yield?
- How efficient is this irrigation system at using fuel or electricity to lift and pressurize water? Would improvements in the pumping plant be attainable and justified?

Stakeholders have been seeking technical assistance with calculating irrigation water volume and depth based on flow meter totalizer readings. In response to these requests, Mississippi State University Extension professionals at the National Center for Alluvial Aquifer Research (NCAAR) have created a Flow Meter Calculator web tool. The Flow Meter Calculator can be accessed at https://www.ncaar.msstate.edu/outreach/fmcalc.php for free anytime. Figures 7.1. and 7.2 show correct inputs and outputs, respectively, for an example scenario.

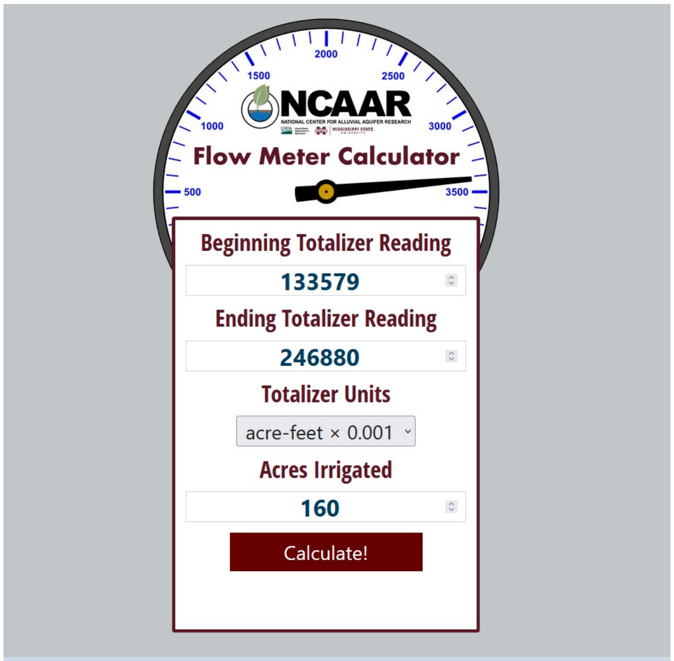

Figure 7.1 Correct inputs to the NCAAR Flow Meter Calculator for the example scenario

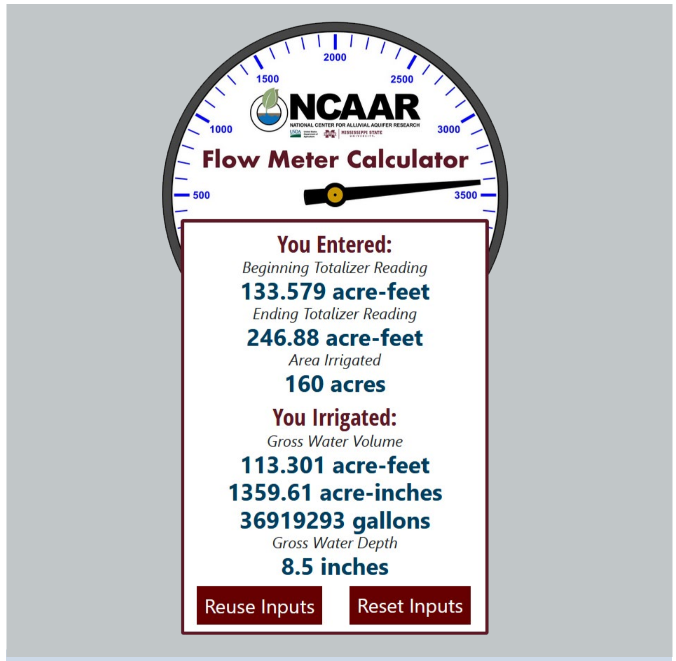

Figure 7.2. Corresponding outputs from the NCAAR Flow Meter Calculator for the example scenario

Description of Inputs (Figure 7.1)

Depending on product design, totalizer readings might be obtained from a mechanical set of rolling digits on the dial face of the flow meter or from an electronic display. The units of the totalizer readings tend to be marked nearby.

Beginning totalizer reading: Enter the nonnegative number equal to the totalizer reading from which the user wishes to start calculating irrigation water volume.

Ending totalizer reading: Enter the nonnegative number equal to the totalizer reading at which the user wishes to stop calculating irrigation water volume.

Totalizer units: Among the options within the dropdown menu, select the one that matches exactly the units of the totalizer readings. Table 7.1 explains what each of the units signify.

Acres irrigated: Enter the nonnegative number equal to the land area in acres that received the irrigation water volume being calculated. If zero is entered instead, the Flow Meter Calculator will calculate gross water volume but not gross water depth.

Description of Outputs (Figure 7.2)

Gross water volume: Calculated as the difference between the beginning and ending totalizer readings, this quantity represents the total amount of irrigation water applied between the two reading times. The Flow Meter Calculator reports the equivalent of this quantity in acre-feet, in acre-inches, and in gallons, respectively.

Gross water depth: Calculated as the ratio of the gross water volume over the irrigated area, this quantity represents the per-unit-area amount of irrigation water applied between the two reading times. The Flow Meter Calculator reports this quantity in inches, just like rain—the increase in depth if the irrigation water were added evenly across a pond the size of the irrigated area. Converting water volumes to water depths enables comparisons among irrigation systems with different irrigated areas.

TABLE 7.1. Five options for the units of the totalizer readings in the NCAAR Flow Meter Calculator

Totalizer Units	Whenever the rightmost digit of the totalizer increases by 1, the flow meter has measured an additional …
acre-feet × 0.001	0.001 acre-feet = 0.012 acre-inches = 326 gallons
acre-feet × 0.01	0.01 acre-feet = 0.12 acre-inches = 3,259 gallons
acre-inches × 0.01	0.00083 acre-feet = 0.01 acre-inches = 272 gallons
gallons × 100	0.00031 acre-feet = 0.0037 acre-inches = 100 gallons
gallons × 1,000	0.0031 acre-feet = 0.037 acre-inches = 1,000 gallons

Example: Before the first irrigation and after the last irrigation of a growing season, a farmer recorded the totalizer of a flow meter that measures all irrigation water for 160 acres. Figure 7.3 shows the appearance of this mechanical totalizer at the two times when it was recorded.

Figures 7.1 and 7.2 give the correct inputs to and the corresponding outputs from the Flow Meter Calculator for this scenario.

FERTIGATION/CHEMIGATION

Fertigation or chemigation is the process of injecting fertilizers or chemicals through an irrigation system. Water amendments such as fertilizers, herbicides, insecticides, and fungicides can save on labor costs and improve crop production. Most common injection devices are venturi, differential pressure tank, or injector pump.

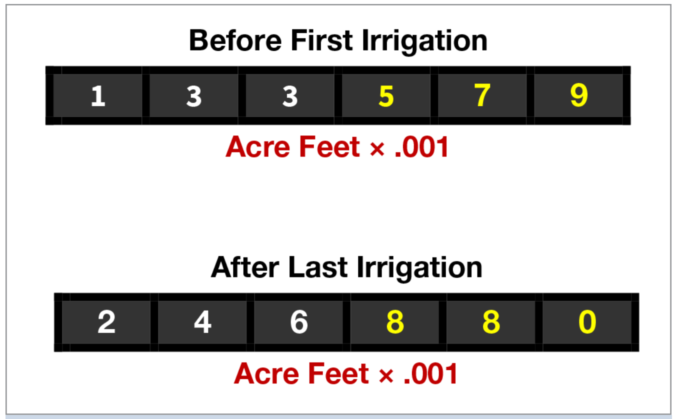

Figure 7.3. Illustration of a flow meter totalizer before the first irrigation (top) and after the last irrigation (bottom) of a growing season for the example scenario

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