



February 10, 2015

REPORT #E15-004

Agricultural Irrigation Initiative: Soil Science and the Basics of Irrigation Management

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Acknowledgments

The author would like to extend his thanks and appreciation for support in developing the content of this report, with special thanks to the following individuals:

- Dr. Charles Hillyer and Dr. Chad Higgins of Oregon State University for teaching the author the principles of soil science and irrigation scheduling outlined in this report.
- Dr. Troy Peters of Washington State University for providing editorial review of the document and guidance on improving some concepts presented.
- Jac le Roux of Irrinet, LLC for consistently striving to pragmatically apply these principles in the field, helping to define which principles are most useful to growers.
- David Little of United Ag, LLC for providing editorial review and for offering graphics to illustrate certain points.

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1. Introduction

This report is designed as a companion to the other reports in the series based on the activities in the Northwest Energy Efficiency Alliance's (NEEA's) Agricultural Irrigation Initiative. NEEA is an alliance funded by more than 140 utilities and energy efficiency organizations in Idaho, Oregon, Montana, and Washington working to accelerate the innovation and adoption of energy-efficient products, services, and practices in the Northwest.

The twelve reports in the series address particular areas of NEEA's Agricultural Irrigation Initiative. All twelve reports are available at <http://neea.org/reports>.

Agricultural land and irrigation are intrinsically connected as essential elements in crop production. While soil may appear to be “just dirt” to the non-grower, it has its own branch of science devoted to its numerous characteristics – many of which interact with water in manners that have substantial implications for irrigation decisions. Soil science terminology and principles can be complex and deeply technical. This report provides foundational concepts and definitions to help a novice understand the basics.

Given the industry-specific or scientific natures of some terms used in this report, please refer to the [AgGateway AgGlossary \(http://agglossary.org/wiki/index.php/main_page\)](http://agglossary.org/wiki/index.php/main_page) for definitions.

1.1. Fundamental Relationship between Soil and Water

Soils hold water in the spaces between particles of sand, silt, clay, and gravel, much like a sponge holds water (see Figure 1). The polar nature of water molecules makes them want to stick together, as exemplified when spraying water on a waxed car: the water beads up. Molecular forces also cause a phenomenon at the water-air interface commonly known as surface tension. Molecular forces also cause water to stick to other polar substances. This is called wetting.

When particles in the soil matrix¹ become wetted, surface tension can be strong enough to hold the water suspended in the matrix, overcoming the force of gravity. The easiest way to visualize this phenomenon is by putting a sponge into water; when it is removed, it retains a significant amount of water in the pores inside the sponge's matrix. The smaller the spaces inside the matrix, the harder it is to suck the water out.

1.2. Soil Saturation and Field Capacity

When the sponge is completely full of water with no air left in it, the sponge is saturated. When the sponge is removed from the water source, water will initially drain from the sponge, after which the sponge (or soil, in this case) will stop draining. In soil science, this phenomenon is called field capacity (FC), defined as the maximum amount of water that can be held, long-term, against the pull of gravity – in common soil science usage, the point at which the “soil is full.”

¹ The soil matrix is the assemblage of mineral particles of various sizes, shapes, and chemical characteristics, together with organic materials, in various stages of decomposition and living soil populations.

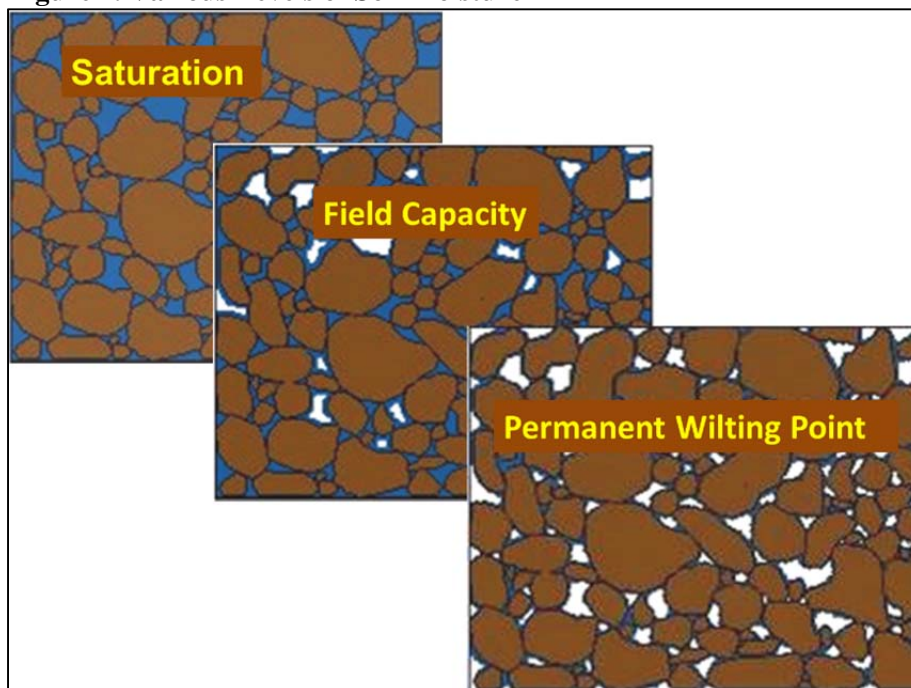
Field capacity can be measured in percentages, cubic feet of water per cubic foot of soil (m^3/m^3), or in inches of water that one foot of soil can hold. When irrigation applies more water to the soil than it can support, saturation occurs and the water must escape the matrix either by runoff or through deep percolation, each of which creates problems for the grower:

- Runoff causes erosion, which removes soil from the field and wastes water.
- Deep percolation occurs when water drains past (in other terms below) the root zone. In doing so, it drags soluble nutrients and fertilizer along with the water, away from the roots where they provide benefits, and into the groundwater, causing contamination to the environment. When deep percolation occurs the water is no longer available to the plant and is consider lost to the plant-soil system.

Saturation itself hinders crop development:

- It starves the roots of oxygen (the system becomes anaerobic, or without oxygen), which smothers beneficial bacteria, thus eliminating their natural process of generating nitrogen.
- It causes yellowing of plant leaves and hurts plant growth and crop yield.

Figure 1. Various Levels of Soil Moisture



Notes: In each image, blue signifies water; brown signifies the solid component of the soil; and white signifies air. These three components constitute the soil “matrix.”
Source: David Little/United Ag, LLC and Sentek Technologies

1.3. Evapotranspiration, Permanent Wilting Point, and Plant Available Water

Evapotranspiration – Water naturally leaves the soil through the processes of evaporation and transpiration; the simultaneous occurrence of the two processes is known as evapotranspiration (ET). The more water that leaves the soil, the harder it is for the plant to pull water from the soil matrix.

Permanent Wilting Point – As the soil becomes increasingly dry, the plant experiences greater difficulty pulling the remaining water from the soil, which gradually increases the amount of stress on the plant. This is analogous to wringing out the sponge mentioned earlier: the harder the wringing, the more water the sponge releases. At a certain point, however, although the sponge still contains moisture, it reaches a threshold at which no more water can be wrung from it.

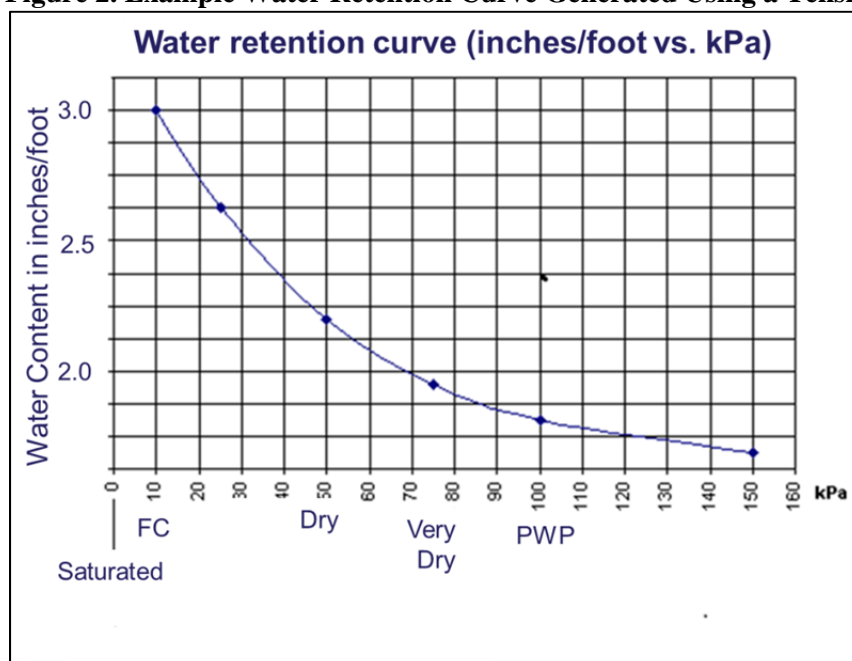
The analogous threshold for this overview – the point at which a plant can no longer pull water from the soil – is called the permanent wilting point (PWP). The PWP contains the term “permanent” because when the soil’s moisture declines to this level, the plant has wilted to the extent that it cannot recover. The PWP varies among different types of plants; olives or grapes have higher PWPs and row crops have lower PWPs. Growers’ irrigation decisions depend on their particular crops and their specific goals.

Researchers use a device called a tensiometer² that measures the force that water exerts on the soil. This force is called the matric potential, also sometimes called the “negative pressure response” of the soil. Its value indicates how hard the plant must work to extract water from the soil. The negative pressure response is measured in kilopascals (kPa)³ – the drier the soil, the more the plant has to exert its pull (at increasing kPa) to extract moisture from it. Tensiometer readings, when coupled with soil moisture content measurements, produce soil water retention curves that illustrate this phenomenon (Figure 2 shows an example).

² [http://en.wikipedia.org/wiki/Tensiometer_\(soil_science\)](http://en.wikipedia.org/wiki/Tensiometer_(soil_science))

³ The kilopascal is the most commonly-used unit of pressure in agronomy. 1 kPa = 0.145 pounds per square inch (PSI). Some manufacturers use centibar, which is equal to 1 kPa.

Figure 2. Example Water Retention Curve Generated Using a Tensiometer



Notes: At field capacity (FC on the x-axis), this soil sample can hold three inches of water per foot of soil at a pressure of 10 kPa. As the soil dries to about two inches of water, removing water from it becomes increasingly difficult and a plant would have to exert about 70 kPa to extract moisture. When the soil dries to about 1.75 inches of water, the plant would have to exert 100 kPa of pressure to extract moisture; this necessary level of suction exceeds this plant’s ability to extract moisture which usually causes the plant to die (at PWP on the x-axis).

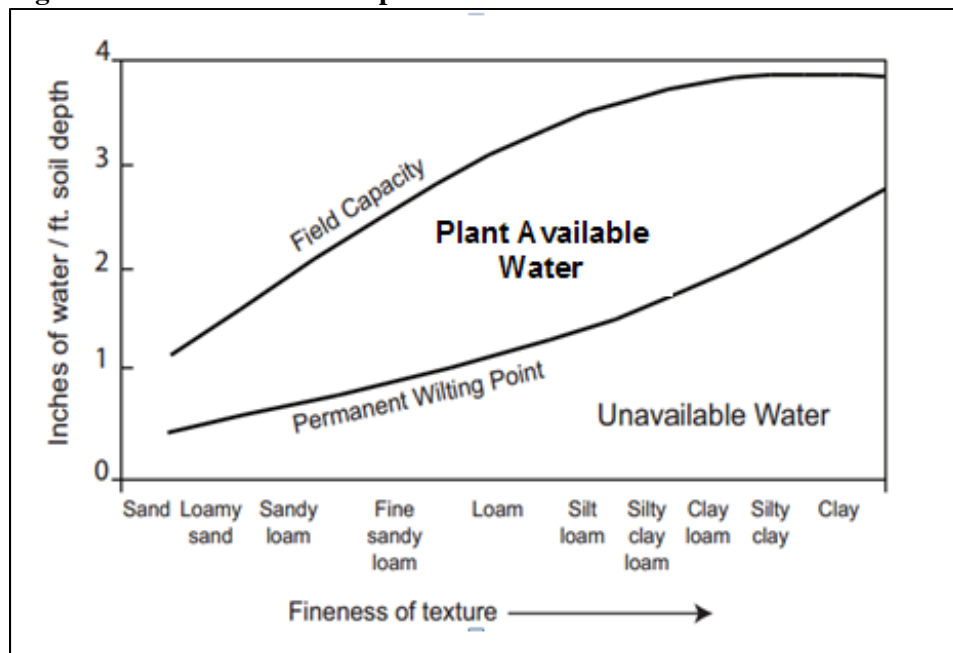
Soils are frequently somewhat drier than the FC level illustrated in Figure 2. The reports based on the findings of the NEEA studies in this Initiative express soil moisture in the two different ways described below (illustrated later in Figure 5).

1. Plant Available Water – Academics frequently report soil moisture in terms of current plant available water (PAW), which is the difference between the current soil moisture level and the PWP. This can cause some confusion since the formal definition of plant available water (PAW) is the difference between volumetric water content at FC and the PWP.
2. Total Moisture – Irrigation consultants report soil moisture in terms of total moisture (TM), which is the percent of current soil moisture between FC (100 percent) and completely dry (0 percent).

1.4. Impact of Soil Texture on Soil Water-Holding Capacity

The soil's texture significantly affects its water-holding characteristics, as Figure 4 and Figure 4 illustrate. For example, sand typically holds only about 1.0 inch of water per foot of soil, but its coarse texture allows plants to extract all but about 0.3 inches of that water (see Figure 3). On the opposite end of the texture continuum, clay can hold nearly 4.0 inches of water, but its fine particle size leads to the retention of much more water in the soil at the permanent wilting point. After determining the percentages of sand, silt, and clay in the soil, the grower can estimate values for FC, PWP, and PAW and use that knowledge to decide how much water to apply.

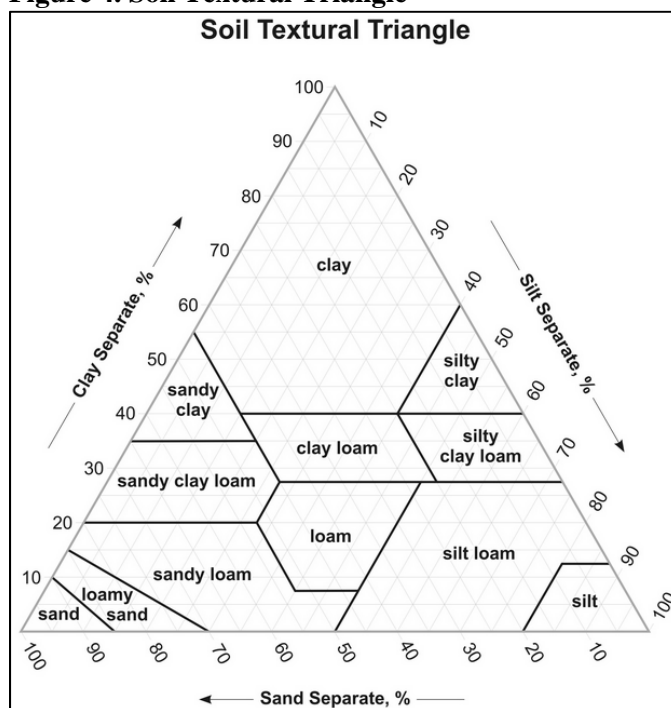
Figure 3. General Relationship between Soil Moisture and Texture



Note: From (NRCS 2008). Attributed to Ohio Agronomy Guide, 14th Edition, Bulletin 472-05

Figure 4 illustrates the soil textural triangle commonly used to describe the percentages of sand, silt, and clay in different types of soils. The various sections inside of the triangle (such as sandy clay and silt loam) represent the standard soil textural classes.

Figure 4. Soil Textural Triangle



Note: From (NRCS 2014)

1.5. Using a Bucket Analogy to Clarify Concepts in this Overview

As this overview shows, understanding irrigation management necessitates an understanding of many concepts and the manners in which each of them interacts with, or drives, the others. Figure 5 illustrates a useful analogy for understanding these concepts, in which the water level in a bucket with two holes represents the percentage of water held in the soil.

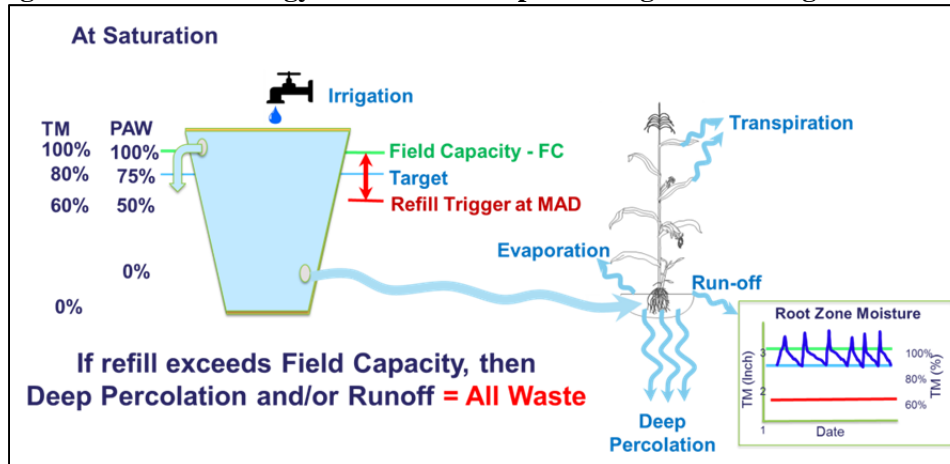
The first hole, the larger of the two, is close to the top of the bucket and the second, smaller hole is closer to the bucket's bottom. Water poured into the bucket will drain out of the holes. Water added quickly enough to fill the bucket completely will drain quickly to the level of the upper hole, because that hole is larger. The water will continue to drain, albeit more slowly, down to the level of the lower (smaller) hole. The level of water in the bucket will not drain any lower than the lower hole; some water will always remain. Water added more quickly than both of the holes can drain it will eventually cause the bucket to overflow.

This bucket analogy provides a number of parallels to concepts in irrigation:

- The bucket is analogous to the soil.
- Adding water to the bucket is equivalent to irrigating.
- The lower hole represents the water going to the plant (transpiration); a plant will consume water in the soil until it reaches some minimum level.
- The top hole represents deep percolation; when the soil moisture level is above field capacity, the excess moisture will drain below the root zone and will no longer be available to the plant.

- The distance between the upper and lower holes in the bucket is equivalent to plant available water.
- The top of the bucket is equivalent to saturation; when the bucket is filled beyond the top, water will run off, just as when the soil is filled to saturation, any additional water will run off the surface.

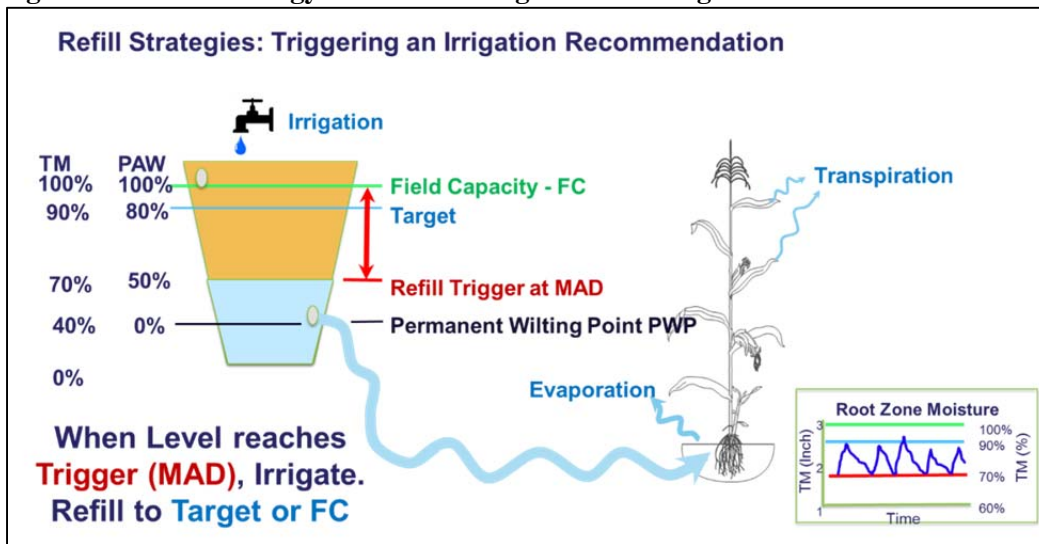
Figure 5. Bucket Analogy for Basic Concepts in Irrigation Strategies



Notes: TM = Total moisture; PAW = Plant available water; MAD = Management allowable depletion (described below)

The goal of irrigation management is to apply the right amount of water at the right time. Using the bucket analogy, irrigation management means adding water when the level is about halfway between the upper hole and the lower hole (see Figure 6), given that the midpoint between FC and PWP is generally when plants begin to experience stress. Using this level to indicate that irrigation is required is called management allowable depletion (MAD). An efficient irrigation management regime will start irrigating when the bucket is at the MAD level and stop when the water level is at or below the upper hole. This strategy results in very little plant stress and no crop losses. It is also a biological objective in that the MAD level is chosen to avoid *plant* stress. A strategy with an economic objective (such as maximizing profits) would use a different and usually larger MAD value.

Figure 6. Bucket Analogy for Determining When to Irrigate



Notes: TM = Total moisture; PAW = Plant available water; MAD = Management allowable depletion

2. References

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Natural Resources Conservation Service (NRCS). 2014. *Soil Textural Triangle* [graphic]. Retrieved from http://www.nrcs.usda.gov/Internet/FSE_MEDIA/nrcs142p2_050242.jpg.