13 IRRIGATION SCHEDULING

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INTRODUCTION

Proper irrigation scheduling is simply applying the appropriate amount of water at the correct time. Scheduling considers such physical factors as the water holding capacity of the soil, crop water use rate, and plant characteristics (e.g., root depth and sensitivity to water stress). But, scheduling also involves human factors, such as being able to irrigate only on certain days (e.g., even or odd days), labor constraints, water delivery constraints (e.g. canal system infrastructure), and a host of other human considerations.

Two reasons are often given for *irrigation scheduling* -- it saves water and it protects the environment. However, for farmers and landscape managers, the overall driving force for adopting irrigation scheduling is economic – scheduling is used because it makes or saves money. Nonetheless, even irrigators who find scheduling profitable will discontinue its use if it becomes too burdensome. Past experience shows that most irrigators, who try some form of scheduling, generally abandon using it after a few years. Currently, the actual number of farmers who schedule with either a computer or soil moisture/plant sensors is very low (Table 13.1 [USDA, 2004]). Therefore, successful irrigation scheduling methods must meld together <u>scientific</u>, <u>economic</u> and <u>social</u> considerations.

In agriculture, the percentage of irrigated farms using scientific irrigation scheduling methods[1] on a national basis is only about 15% (USDA, 2004). In those situations where the water resources are limited scheduling becomes a mute point and pumps run continuously as the farmer tries to play " catch up". Unless a water resource of about 3.0 to 4.0 gallons per minute (or higher in many arid climates) per irrigated acre exists, the water supply is marginal for full irrigation, and scheduling probably remains irrelevant. However, for those areas that have ample water, scheduling should be employed because it can increase yields. Table 13.2 shows the results of nine years of survey data from Missouri farmers; irrigators who used scheduling grossed about $40 per acre more than those irrigators who did not schedule (Henggeler, 2009b).

Table 13.1. Percentage of farms in 2003 using irrigation scheduling by either soil moisture or plant monitoring, computer program or media reports (USDA, 2004).

STATE	SOIL MOISTURE or PLANT SENSORS	IRRIGATION SCHEDULING by SELF, COMMERCIAL or GOV'T	MEDIA REPORTS	STATE	SOIL MOISTURE or PLANT SENSORS	IRRIGATION SCHEDULING by SELF, COMMERCIAL or GOV'T	MEDI REPOR
Alabama	6.1%	0.5%	3.1%	Nebraska	9.2%	14.0%	18.5%
Alaska	20.5%	11.0%	5.5%	Nevada	1.7%	5.9%	2.0%
Arizona	4.0%	3.2%	2.2%	New Hampshire	6.2%		3.7%
Arkansas	3.8%	9.7%	4.2%	New Jersey	13.0%	1.2%	3.7%
California	12.8%	6.1%	8.4%	New Mexico	2.7%	10.4%	0.7%
Colorado	4.6%	10.0%	8.5%	New York	9.0%	1.8%	2.4%
Delaware	8.0%	8.9%	2.8%	North Carolina	1.8%	3.5%	5.7%
Florida	10.4%	1.9%	2.3%	North Dakota	11.3%	11.1%	13.5%

[1] This includes: use of soil moisture sensors, use of plant sensors, daily ET reports, and computer simulation.

Georgia	4.8%	3.8%	6.5%	Ohio	5.5%		2.7%
Hawaii	3.1%	1.2%	2.3%	Oklahoma	3.0%	3.7%	2.1%
Idaho	3.0%	9.0%	3.3%	Oregon	3.0%	3.7%	1.4%
Illinois	3.3%	2.2%	5.7%	Pennsylvania	14.0%	6.5%	5.0%
Indiana	4.9%	2.0%	5.4%	Rhode Island	12.1%		
Iowa	4.7%	2.1%	6.8%	South Carolina	4.6%	2.6%	1.3%
Kansas	10.9%	20.7%	13.3%	South Dakota	11.4%	2.3%	5.4%
Kentucky	7.1%	0.2%	2.5%	Tennessee	9.0%	8.3%	2.6%
Louisiana	4.7%	4.8%	2.1%	Texas	14.4%	5.0%	9.7%
Maine	3.7%	7.5%	1.4%	Utah	6.2%	16.8%	3.4%
Maryland	10.2%	2.8%	2.8%	Vermont	2.9%		2.9%
Massachusetts	15.0%	9.3%	5.0%	Virginia	3.5%	0.9%	0.3%
Michigan	7.0%	5.9%	12.7%	Washington	8.4%	5.7%	10.6%
Minnesota	10.2%	7.0%	15.6%	West Virginia	9.0%	6.0%	6.0%
Mississippi	3.5%	2.2%	5.4%	Wisconsin	10.9%	3.0%	8.8%
Missouri	2.2%	4.9%	6.0%	Wyoming	3.2%	1.5%	1.1%
Montana	5.1%	2.6%	3.2%	**USA**	8.0%	7.0%	7.0%

In some instances high accuracy is required in irrigation scheduling, such as microirrigation of strawberries on sandy soil where managers might calculate hourly crop evapotranspiration. However, in most cases there is a certain amount of "cushion" in scheduling. Dogan et al. (2006), in a study that kept the irrigation intervals the same but varied the application amounts on corn grown under pivots in Kansas, reported that depths from 0.80 to 1.50 times the 100% ET replacement amount had close to the same yield levels. The same dataset used in Table 13.2 showed that schedulers who used historic weather (Woodruff charts, Henggeler, 2009a) actually experienced higher yields in all three of the crops surveyed as opposed to those using a real time weather computer program (***Arkansas Scheduler,*** Ferguson et al., 2000). Important aspects of scheduling are to ensure that irrigators apply the first irrigation in a timely fashion and that they irrigate late enough at the end of the season. Farmers frequently attribute their yield increases with adoption of scheduling to the fact that scheduling got them to irrigate earlier and/or continue later in the season.

Table 13.2. Comparison of yields and difference in gross returns for irrigators who scheduled versus those that did not schedule irrigation, SE Missouri, 2000-20008. Sample size in parenthesis (after Henggeler, 2009).

Crop	**Irrigators Who Scheduled** (bu. [or lbs.] /acre)	**Irrigators Who Did NOT Schedule** (bu. [or lbs.] /acre)	**Gross Return from Scheduling *** ($/acre)
Corn	188.7 (93)	175.5 (233)	$46.22
Cotton	1069.9 (39)	978.5 (129)	$54.87
Soybeans	51.8 (44)	44.8 (302)	$51.97

* Based on corn at $3.50/bu, cotton at $0.60/lb, and soybean at $7.50/bu.

The First Question: *Do I vary Time or do I vary Application Depth?*

Irrigation scheduling consists of two main parts: (1) applying the appropriate amount of water and (2) at the correct time. For these two variables, when one increases then the other automatically decreases, since they are inversely related. So a prime management choice that irrigators need to make is whether to key in on the amount of water per application or the time interval between irrigations.

For most methods of irrigation, a fixed amount of water is applied at each irrigation. The factor that does change is the length of the time period between irrigations (ultimately dictated by the crop water use rate and any precipitation that occurred since the last irrigation). Flood, sprinkler (e.g., side roll, hand move, permanent set, etc.), and center pivot/lateral move irrigation are generally managed this way (i.e., the irrigation amount applied remains constant). The alternative management option is to irrigate at a fixed time period, but change the amount of water applied based on the accumulative crop water use minus any rainfall that has occurred since the last irrigation. This management strategy might be used in turf, micro-irrigation, and where canal delivery is involved or where regional day of the week water restrictions are imposed.

Fixed Amount – Varying Time Period

In agricultural situations, the fixed amount approach is more common because it is simpler to manage. A center pivot, for example, merely has to be turned on/off and nothing new needs to be re-programmed into the control panel. In flood irrigation, a set application amount is already an inherent design component of the system. Irrigation scheduling using a fixed application amount is straightforward. First, determine what is the ideal irrigation amount based on the crop and soil in consideration and then apply this set amount every time the accumulative crop water use minus rainfall reaches that trigger amount of water.

A slight variation on the fixed-AMOUNT-varying-time method is when, early in the season, the fixed amount is initially smaller due to shallower root depths, later to be increased to the normal application amount. End of season application amounts may also be decreased, thus upping the frequency, as a means to fine-tune crop dry down and ensure the soil floor is dry for harvest.

Fixed Time Period – Varying Amount

A fixed-TIME-varying-amount philosophy might be ideal for landscape and turf irrigation because property owners may desire a regular irrigation schedule, or there may be day of week restrictions on irrigation. Under this scenario, run-times should increase with warmer weather as the plant grows faster and they decrease later in the season as the plant dies back or goes dormant, but the time period between irrigations stays constant. Many automatic timers used in turf applications have functions that allow all station runtimes to be increased or decreased set percentage amounts. This handy function can greatly reduce management time. For example, a timer can be programmed so that all the zones will run long enough to meet peak summer requirements (Jun, Jul and Aug). However, during the months of Apr, May, Sept and Oct a scale-back rate of 75% is used. In this example when the system is first turned on in late spring it is run at the 75% level. In June the rate is bumped to 100%, and later in September the rate is dialed back to 75%. Thus, the variations in seasonal water use requirements can be met with minimal labor input.

When microirrigation systems are used on horticultural and agronomic crops the fixed-TIME-varying-amount method is often employed. Irrigators who receive water from a canal system may be locked into a specific interval, and thus they must adjust the application amount applied irrigation by irrigation. Pivot operators who collect crop evapo-transpiration (ET_c) data from the Internet, may also use this method, summing up daily ET_c values and subtracting out any rainfall events since they last irrigated, and apply this amount on a fixed time schedule. Manufacturer–provided charts allow farmers to convert the percent run setting on the pivot panel to apply various application depths. In using the fixed time method, the operator must always be cognizant of that soil moisture deficit level at which yields and/or quality are impacted, and not exceed this depletion point. Also, variations in rainfall amounts during a set time interval period could be problematic. For example, enough rain may have been received since the last period that the soil moisture deficit needed to be replenished is smaller then what the irrigation method is capable of applying. A situation might be a flood-irrigated field that due to increased rainfall has only a two-inch deficit when it is time again to irrigate, and it at least three inches of water needs to be applied if the water is to get to the bottom of the field.

Note, when the fixed-TIME-varying-amount strategy is used and if soil moisture sensors, such as tensiometers or gypsum blocks are being used, their readings at the time of irrigation will likely differ. On the other hand, if the fixed-AMOUNT-varying-time method is being used, readings should be similar at the time of irrigation.

In this chapter the fixed-AMOUNT-varying-time irrigation scheduling methodology mentioned above will primarily be emphasized, especially for agronomic crops because it inherently brings a focus on applying the irrigation depth that leads to optimum yields. In either case, the desired application amount should be increased to account for efficiency losses (discussed later in this chapter). Some authors suggest that if salinity is a problem, an additional amount of water (called a leaching fraction) should also be added to the irrigation amount, but many times salt buildup can be controlled from off-season rainfall, or if that is not enough, applying off-season irrigation specifically dedicated to leaching. Chapter XX discusses salinity issues.

THE MAIN METHODS OF IRRIGATION SCHEDULING

There are three main methods of irrigation scheduling that will be discussed in this chapter:

1) Soil-based methods.
2) Plant-based methods.
3) Climate-based methods.

The climate-based method, along with its accompanying computer programs or fill-in charts, is usually what comes to mind when the term *irrigation scheduling* is mentioned. The other two methods are both *sensor-based methods,* employing sensors that make immediate contact with the plant/soil environment. Since they are a more direct approach to answering the question of *when to turn on the water*, fewer steps are required for scheduling with them than is required for the climate-based approach. For climate-based irrigation scheduling, seven main steps are involved. Sensor-based scheduling only needs three steps, as Steps 2 - 4 are not required. Table 13.3 lists the steps for the climate- and sensor-based methods of scheduling. Note that in Step 3 (Calculate daily crop water use) four sub-steps are presented. These are items are relegated to sub-step status since the regular irrigator generally will not need to be concerned with them, but are things that software developers may want to address as they construct the irrigation scheduling programs of the future.

Table 13.3. The main steps for climate- and sensor-based methods of irrigation scheduling.

Step	Climate-based Method	Sensor-based Methods
Step 1	Determine ideal irrigation depth	Determine ideal irrigation depth
Step 2	Collect ET_o data, or the required weather data to calculate ET_o yourself.	---------
Step 3	Collect K_c data.	
Step 4	Calculate daily crop water use (ET_c) by multiplying A and B above.	---------
Sub- Step 4a	Modify the rate of ET_c when soil moisture is limiting.	---------
Sub- Step 4b	Separately calculate the E and T of ET.	---------
Sub- Step 4c	Adjust the program's default K_c values to better fit local conditions.	---------
Sub- Step 4d	Modify the time-scale of the water use curve (e.g., days, Heat Units, etc.)	---------
Step 5	Subtract daily ET_c amounts (Step 3) and add effective rainfall amounts to soil moisture budget in checkbook fashion.	---------
Step 6	Apply the irrigation depth (Step 1) when deficit amount in Step 4 equals it.	Apply the irrigation depth (Step 1) when trigger value is reached.
Step 7	Validate performance with sensors or probing.	Validate performance. *

* Validation involves determining if the amount of soil moisture deficit in inches occurring at the time the sensor trigger value was reached is the same amount as in Step 1.

Since the first step of irrigation scheduling (*Determine Ideal Irrigation Depth*) is common to both climate-based and sensor-based methods of irrigation scheduling it is discussed first. However, discussion of the remaining five steps will be put on hold until soil- and plant-based methods of irrigation scheduling are presented. Note that since the Sub-steps in Step 3 are more of a more technical nature, discussion of them will be reserved for four appendices at the end of the chapter. Finally, some examples of climate-based scheduling programs and charts will be examined.

Step 1 of Irrigation Scheduling: *Determining Ideal Irrigation Depth*

Determining Depth of Irrigation: Traditional Equation Method.

The traditional method for determining the amount[2] of irrigation to apply involved gathering information from three distinct datasets, after which the three separate values were multiplied together. The needed values are: the soil's plant available water holding capacity (PAW) --the amount of water between field capacity and permanent wilting point (inches of water/foot of soil), the crop's rooting depth (Z_r) (feet), and the crop's allowable soil moisture depletion level, **p** (%). This last item, frequently referred to as MAD (manageable allowable depletion or maximum depletion amount), and represents the point at which crop yield loss begins to occur. Multiplying the three variables (Equation 13.1) yields the net inches of water to apply when irrigating:

$$d_{net} = PAW \times Z_r \times \mathbf{p} \qquad (13.1)$$

Where,

d_{net} = net irrigation depth, inches

PAW = plant available water holding capacity of the soil, inches/foot

Z_r = rooting depth of crop, feet

p = allowable depletion level for crop, (a fraction from ≈ 0.2 to 0.8)

This calculation procedure to obtain the net ideal irrigation depth seems fine, but has two flaws. First, even as straightforward as the involved math seems, it may induce those with "math anxiety" issues not to want to delve further into setting set up the parameters for irrigation scheduling. Second, and more importantly, that point at which yield begins to decline due to inadequate soil moisture conditions actually relates more to soil matric potential (or moisture tension), than to a set percentage value, which **p** in Eq. 13.1 represents. Figure 2 is illustrative of this and shows that a 50% water content level (often used as a guide to initiate irrigation) can have soil moisture tension levels ranging from 60 to 230 centibars depending on the soil involved (after USDA, 1970). Thus Equation 13.1 could be mathematically correct, but managerially wrong. To help ensure that proper soil matric potential values are maintained when using volumetric water content values, the results for courser soils should be increased 5-10%, and decreased 5-10% for fine textured soils (Allen et al., 1998). An easier method, bypassing Equation 13.1, is to simply use Table 13.4 to determine irrigation depth.

[2] Also referred to as "depth" and as "deficit".

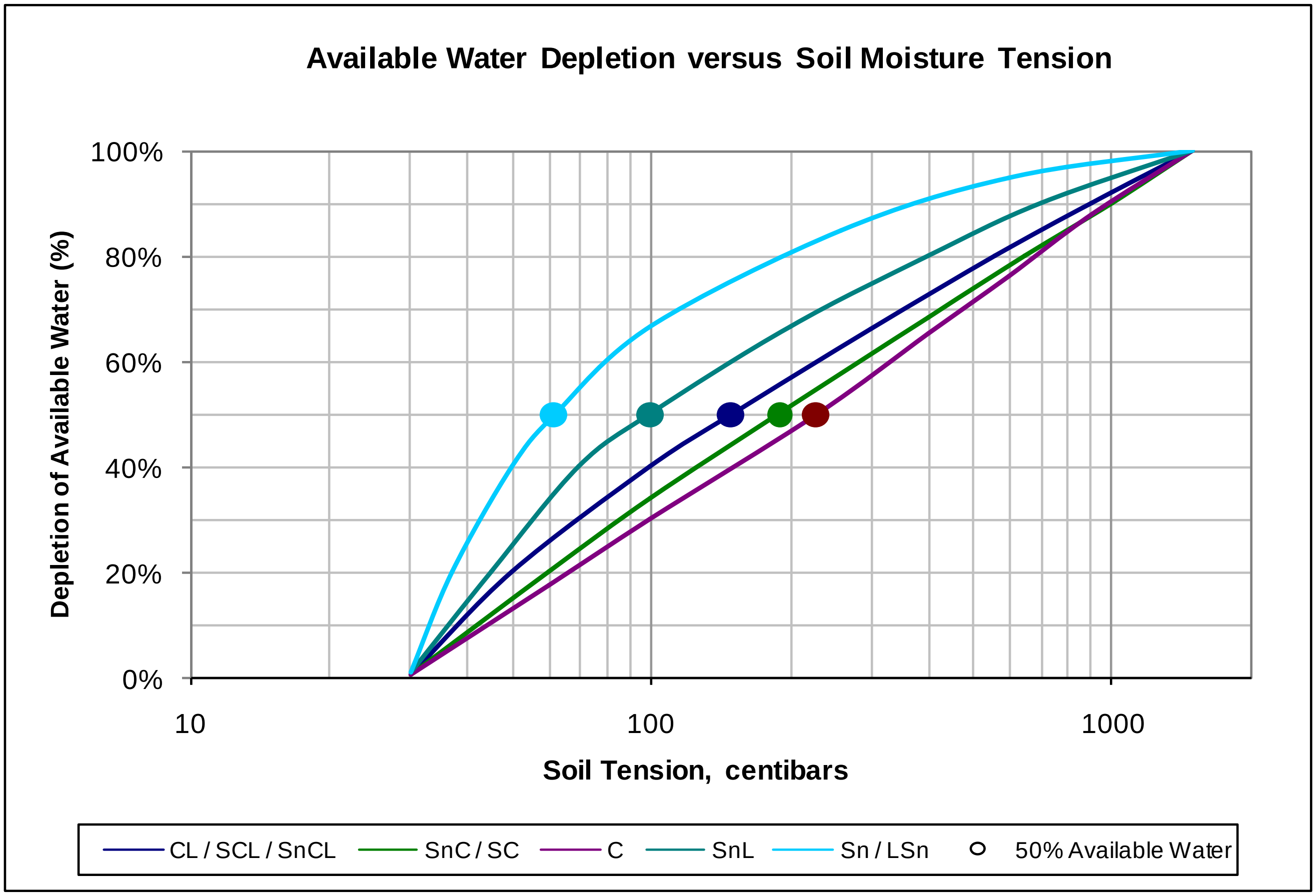


Figure 13.1. Percentage of water depletion versus soil moisture tension for various soil types at the 50% available water depletion level marked (after USDA, 1970).

Determining Depth of Irrigation: Table Method

As discussed, Equation 13.1 does not fully account for the fact that soil types have different soil water release curves. However, Table 13.4 accounts for tensiometric differences in soils and since it incorporates the typical rooting depths for various crops, can provide suggested net irrigation depths for a wide variety of crop/soil possibilities. As discussed earlier, the suggested irrigation depths in Table 13.4 are slightly modified upward for coarser soils and slightly downward for fine textured soils to adjust for soil matric potential influence (the scale of modification for each soil type is seen at the top of each column). The suggested irrigation depths derived from Table 13.4 should be considered as a starting point and values for PAW, root depth, and **p** in the table can be modified based on local conditions. Some other salient points to keep in mind are:

- In humid areas the crop rooting depths may be shallower then shown in Table 13.4 because of frequent rainfall. Reduce accordingly.[3]
- Soil factors, such as compaction pans, may reduce rooting depth. Reduce accordingly.
- For some crops, it may be wise to use varying **p** levels based on stage of growth. Various sources can be found to provide information regarding this. Also, queries to various discussion groups (e.g., TRICKLE-L, IRRIGATION-L, etc.) may again provide additional information on particular crops in question.

[3] One method of determining active root zone, is to apply gypsum blocks at various depths. Plotting the values of the blocks from different depths will help determine where active water depletion is occurring. It might be wise to use this procedure for more than a single season.

- During the early part of the season when full rooting depth has not been reached, irrigation amounts might need to be reduced.

Example 1 shows how to use Table 13.4 and modify results in light of local conditions.

Example 13.1
Calculating Net Irrigation (d_{net})

Crop: Field Corn

Soil: Sandy loam

Notes: Past experience of grower indicates that roots are only active to 18 inches.

Results:

Normal irrigation depth to apply	= 2.9 inches (Table 13.4)
Normal rooting depth (Z_r)	= 39 inches (Table 13.4)
Modified depth to apply	= (18 inches / 39 inches) = 1.3 inches

Table 13.4. Net Irrigation Depth to Apply for various Crops and Soils Based on Soil Moisture Holding Capacity, Rooting Depth, and p. Some soil textures adjusted by a factor to bring results closer to acceptable soil matric potential values. (After Allen et al., 1998) [a]

Factor to account for soil matric potential/soil water content levels →			(1.10)	(1.05)	(1.00)	(1.00)	(1.00)	(1.00)	(1.00)	(0.95)	(0.90)
Soil Type →			Sand	Loamy sand	Sandy loam	Loam	Silt loam	Silt	Silt clay loam	Silty clay	Clay
Water Content at Field Capacity, % →			11.0%	13.5%	17.0%	23.0%	26.5%	31.0%	30.0%	30.0%	33.5%
Water Content at PWP, % →			3.5%	5.0%	5.0%	10.0%	12.5%	16.0%	17.0%	17.0%	19.5%
Average Water Holding Capacity, % →			7.5%	8.5%	12.0%	13.0%	14.0%	15.0%	13.0%	13.0%	14.0%
Crop	**Z_r**	**p**	Net Irrigation to Apply (d_{net})								
	inches		**------ inches ------**								
Broccoli	16	0.45	0.6	0.7	0.9	1.0	1.1	1.2	1.0	1.0	1.1
Brussel Sprouts	16	0.45	0.6	0.7	0.9	1.0	1.1	1.2	1.0	1.0	1.1
Cabbage	20	0.45	0.7	0.8	1.2	1.3	1.4	1.5	1.3	1.3	1.4
Cauliflower	16	0.45	0.6	0.7	0.9	1.0	1.1	1.2	1.0	1.0	1.1
Carrots	20	0.35	0.6	0.6	0.9	1.0	1.1	1.1	1.0	1.0	1.1
Celery	12	0.20	0.2	0.2	0.3	0.3	0.4	0.4	0.3	0.3	0.4
Garlic	12	0.30	0.3	0.3	0.5	0.5	0.5	0.6	0.5	0.5	0.5
Lettuce	12	0.30	0.3	0.3	0.5	0.5	0.5	0.6	0.5	0.5	0.5
Onions: dry	12	0.30	0.3	0.3	0.5	0.5	0.5	0.6	0.5	0.5	0.5
Onions: green	12	0.30	0.3	0.3	0.5	0.5	0.5	0.6	0.5	0.5	0.5
Onions: seed	12	0.35	0.3	0.4	0.5	0.6	0.6	0.7	0.6	0.6	0.6
Spinach	12	0.20	0.2	0.2	0.3	0.3	0.4	0.4	0.3	0.3	0.4
Radishes	12	0.30	0.3	0.3	0.5	0.5	0.5	0.6	0.5	0.5	0.5
Egg Plant	28	0.45	1.0	1.2	1.6	1.8	1.9	2.0	1.8	1.8	1.9
Sweet Peppers (bell)	20	0.30	0.5	0.6	0.8	0.8	0.9	1.0	0.8	0.8	0.9
Tomato	28	0.40	0.9	1.0	1.5	1.6	1.7	1.8	1.6	1.6	1.7
Cantaloupe	35	0.45	1.3	1.5	2.1	2.3	2.5	2.6	2.3	2.3	2.5
Cucumbers	28	0.50	1.1	1.3	1.8	2.0	2.1	2.3	2.0	2.0	2.1
Pumpkin, Winter Squash	39	0.35	1.1	1.3	1.8	2.0	2.1	2.3	2.0	2.0	2.1
Squash, Zucchini	24	0.50	1.0	1.1	1.6	1.7	1.8	1.9	1.7	1.7	1.8
Sweet Melons	31	0.40	1.0	1.2	1.7	1.8	1.9	2.1	1.8	1.8	1.9
Watermelon	31	0.40	1.0	1.2	1.7	1.8	1.9	2.1	1.8	1.8	1.9
Beets, table	24	0.50	1.0	1.1	1.6	1.7	1.8	1.9	1.7	1.7	1.8
Cassava: year 1	20	0.35	0.6	0.6	0.9	1.0	1.1	1.1	1.0	1.0	1.1
Cassava: year 2	28	0.40	0.9	1.0	1.5	1.6	1.7	1.8	1.6	1.6	1.7
Parsnip	20	0.40	0.6	0.7	1.0	1.1	1.2	1.3	1.1	1.1	1.2
Potato	16	0.35	0.5	0.5	0.7	0.8	0.8	0.9	0.8	0.8	0.8
Sweet Potato	39	0.65	2.1	2.4	3.4	3.7	3.9	4.2	3.7	3.7	3.9
Turnip (and Rutabaga)	20	0.50	0.8	0.9	1.3	1.4	1.5	1.6	1.4	1.4	1.5
Sugar Beet	28	0.55	1.3	1.4	2.0	2.2	2.3	2.5	2.2	2.2	2.3
Beans, green	20	0.45	0.7	0.8	1.2	1.3	1.4	1.5	1.3	1.3	1.4
Beans, dry and Pulses	24	0.45	0.9	1.0	1.4	1.5	1.6	1.8	1.5	1.5	1.6
Chick pea	24	0.50	1.0	1.1	1.6	1.7	1.8	1.9	1.7	1.7	1.8
Fababean (broad bean)	20	0.45	0.7	0.8	1.2	1.3	1.4	1.5	1.3	1.3	1.4
Grabanzo	24	0.45	0.9	1.0	1.4	1.5	1.6	1.8	1.5	1.5	1.6
Green Gram and Cowpeas	24	0.45	0.9	1.0	1.4	1.5	1.6	1.8	1.5	1.5	1.6
Groundnut (Peanut)	20	0.50	0.8	0.9	1.3	1.4	1.5	1.6	1.4	1.4	1.5
Lentil	24	0.50	1.0	1.1	1.6	1.7	1.8	1.9	1.7	1.7	1.8
Peas: Fresh	24	0.35	0.7	0.8	1.1	1.2	1.3	1.4	1.2	1.2	1.3
Peas: Dry/seed	24	0.40	0.8	0.9	1.2	1.4	1.5	1.6	1.4	1.4	1.5
Soybeans	24	0.50	1.0	1.1	1.6	1.7	1.8	1.9	1.7	1.7	1.8
Artichokes	24	0.45	0.9	1.0	1.4	1.5	1.6	1.8	1.5	1.5	1.6
Asparagus	47	0.45	1.8	2.0	2.8	3.0	3.3	3.5	3.0	3.0	3.3
Mint	16	0.40	0.5	0.6	0.8	0.9	1.0	1.0	0.9	0.9	1.0
Strawberries	8	0.20	0.1	0.1	0.2	0.2	0.2	0.3	0.2	0.2	0.2
Cotton	39	0.65	2.1	2.4	3.4	3.7	3.9	4.2	3.7	3.7	3.9

Flax	39	0.50	1.6	1.8	2.6	2.8	3.0	3.2	2.8	2.8	3.0
Sisal	20	0.80	1.3	1.5	2.1	2.3	2.4	2.6	2.3	2.3	2.4
Castorbean (Ricinus)	39	0.50	1.6	1.8	2.6	2.8	3.0	3.2	2.8	2.8	3.0
Rapeseed, Canola	39	0.60	1.9	2.2	3.1	3.4	3.6	3.9	3.4	3.4	3.6
Safflower	39	0.60	1.9	2.2	3.1	3.4	3.6	3.9	3.4	3.4	3.6
Sesame	39	0.60	1.9	2.2	3.1	3.4	3.6	3.9	3.4	3.4	3.6
Sunflower	31	0.45	1.2	1.3	1.9	2.0	2.2	2.3	2.0	2.0	2.2
Barley	39	0.55	1.8	2.0	2.9	3.1	3.3	3.6	3.1	3.1	3.3
Oats	39	0.55	1.8	2.0	2.9	3.1	3.3	3.6	3.1	3.1	3.3
Spring Wheat	39	0.55	1.8	2.0	2.9	3.1	3.3	3.6	3.1	3.1	3.3
Winter Wheat	59	0.55	2.7	3.0	4.3	4.6	5.0	5.4	4.6	4.6	5.0
Field Corn	39	0.55	1.8	2.0	2.9	3.1	3.3	3.6	3.1	3.1	3.3
Sweet Corn	31	0.50	1.3	1.5	2.1	2.3	2.4	2.6	2.3	2.3	2.4
Millet	39	0.55	1.8	2.0	2.9	3.1	3.3	3.6	3.1	3.1	3.3
Sorghum	39	0.55	1.8	2.0	2.9	3.1	3.3	3.6	3.1	3.1	3.3
Sweet sorghum	39	0.50	1.6	1.8	2.6	2.8	3.0	3.2	2.8	2.8	3.0
Rice	20	0.20	0.3	0.4	0.5	0.6	0.6	0.6	0.6	0.6	0.6
Alfalfa: other cuttings	39	0.55	1.8	2.0	2.9	3.1	3.3	3.6	3.1	3.1	3.3
Alfafa: seed	39	0.60	1.9	2.2	3.1	3.4	3.6	3.9	3.4	3.4	3.6
Bermuda hay: avg. cutting effects	39	0.55	1.8	2.0	2.9	3.1	3.3	3.6	3.1	3.1	3.3
Bermuda hay: Spring crop for seed	39	0.60	1.9	2.2	3.1	3.4	3.6	3.9	3.4	3.4	3.6
Clover hay, Berseem - individual cutting periods	24	0.50	1.0	1.1	1.6	1.7	1.8	1.9	1.7	1.7	1.8
Rye Grass hay - averaged cutting effects	24	0.60	1.2	1.3	1.9	2.0	2.2	2.3	2.0	2.0	2.2
Sudan Grass hay (annual)	39	0.55	1.8	2.0	2.9	3.1	3.3	3.6	3.1	3.1	3.3
Grazing Pasture	20	0.60	1.0	1.1	1.6	1.7	1.8	1.9	1.7	1.7	1.8
Turf: cool season	20	0.40	0.6	0.7	1.0	1.1	1.2	1.3	1.1	1.1	1.2
Turf: warm season	20	0.50	0.8	0.9	1.3	1.4	1.5	1.6	1.4	1.4	1.5
Sugarcane, virgin	47	0.65	2.5	2.9	4.1	4.4	4.7	5.1	4.4	4.4	4.7
Bananas	20	0.35	0.6	0.6	0.9	1.0	1.1	1.1	1.0	1.0	1.1
Cacao	28	0.30	0.7	0.8	1.1	1.2	1.3	1.4	1.2	1.2	1.3
Coffee	35	0.40	1.2	1.3	1.9	2.0	2.2	2.3	2.0	2.0	2.2
Date Palms	59	0.50	2.4	2.8	3.9	4.2	4.5	4.9	4.2	4.2	4.5
Palm Trees	28	0.65	1.5	1.7	2.4	2.6	2.8	3.0	2.6	2.6	2.8
Pineapple (multiyear crop)	12	0.50	0.5	0.6	0.8	0.8	0.9	1.0	0.8	0.8	0.9
Rubber Trees	39	0.40	1.3	1.5	2.1	2.3	2.4	2.6	2.3	2.3	2.4
Tea: non-shaded	35	0.40	1.2	1.3	1.9	2.0	2.2	2.3	2.0	2.0	2.2
Tea: shaded	35	0.45	1.3	1.5	2.1	2.3	2.5	2.6	2.3	2.3	2.5
Berries (bushes)	24	0.50	1.0	1.1	1.6	1.7	1.8	1.9	1.7	1.7	1.8
Grapes: table/raisins	39	0.35	1.1	1.3	1.8	2.0	2.1	2.3	2.0	2.0	2.1
Grapes: wine	39	0.40	1.3	1.5	2.1	2.3	2.4	2.6	2.3	2.3	2.4
Hops	39	0.50	1.6	1.8	2.6	2.8	3.0	3.2	2.8	2.8	3.0
Almonds, no ground cover	39	0.40	1.3	1.5	2.1	2.3	2.4	2.6	2.3	2.3	2.4
Apples, Cherries, Pears	39	0.50	1.6	1.8	2.6	2.8	3.0	3.2	2.8	2.8	3.0
Apricots, Peaches, Stone Fruit	39	0.50	1.6	1.8	2.6	2.8	3.0	3.2	2.8	2.8	3.0
Avocado, no ground cover	20	0.70	1.1	1.3	1.8	2.0	2.1	2.3	2.0	2.0	2.1
Citrus: 70% canopy	47	0.50	1.9	2.2	3.1	3.4	3.6	3.9	3.4	3.4	3.6
Citrus: 50% canopy	43	0.50	1.8	2.0	2.9	3.1	3.3	3.6	3.1	3.1	3.3

Citrus: 20% canopy	31	0.50	1.3	1.5	2.1	2.3	2.4	2.6	2.3	2.3	2.4
Conifer Trees	39	0.70	2.3	2.6	3.6	3.9	4.2	4.5	3.9	3.9	4.2
Kiwi	28	0.35	0.8	0.9	1.3	1.4	1.5	1.6	1.4	1.4	1.5
Olives (40 to 60% ground coverage by canopy)	47	0.65	2.5	2.9	4.1	4.4	4.7	5.1	4.4	4.4	4.7
Pistachios, no ground cover	39	0.40	1.3	1.5	2.1	2.3	2.4	2.6	2.3	2.3	2.4
Walnut Orchard	67	0.50	2.8	3.1	4.4	4.8	5.2	5.5	4.8	4.8	5.2

[a] The rooting depth of a crop (highlighted grey column) can vary greatly based on climate conditions, irrigation method, and soil factors.

Determining Depth of Irrigation: Empirical Studies

The often used method for determining the ideal irrigation depth for a (1) crop, (2) soil type, and (3) method of irrigation for local conditions is with local irrigation depletion/frequency studies. The University of Arkansas actively promoted this concept by making recommendations on irrigation amounts (which they referred to as *deficits*) for various soil types and crops based on empirical irrigation depletion studies. These deficit values were used as defaults in their popular irrigation scheduling program, ***Arkansas Scheduler*** (Ferguson et al., 2000) which was probably one of the most widely used scheduling programs in the 1980s and 1990s. One of the reasons it was so widely used probably was the ease at which farmers could input data. Just by indicating crop and soil type, the suggested irrigation depth was proffered without any math or additional input tables.

The University of Missouri has done similar, more recent empirical studies (Figure 13.2). The Arkansas and Missouri results indicate that crops grown in semi-humid areas may need to be irrigated at smaller depletion levels then Table 13.4 would indicate, probably because the rooting depths are not as great in these semi-humid regions as traditionally held. For example, empirical studies seen in Figure 13.2 show that the best yields for corn came from depletion levels of about 1.0 and 1.5 inch for a sandy and a silty soil, respectively. In contrast, Table 13.3 results (when not modifying the rooting depth) suggest applying 3.3 inches for sands and 4.8 inches for silty soils. Thus, there is no substitute for local, multi-year irrigation deficit studies. (Note: by using the modification procedure for shallower rooting depths shown in Example 1, the suggested result of 4.8 inches is reduced to 2.0 inches, which is in close agreement to Figure 13.2).

The method of irrigation used is important in localized empirical studies of ideal irrigation depths. The depth that is ideal for regular center pivot sprinkler irrigation will probably differ from that for microirrigation, LEPA, or flood irrigation.

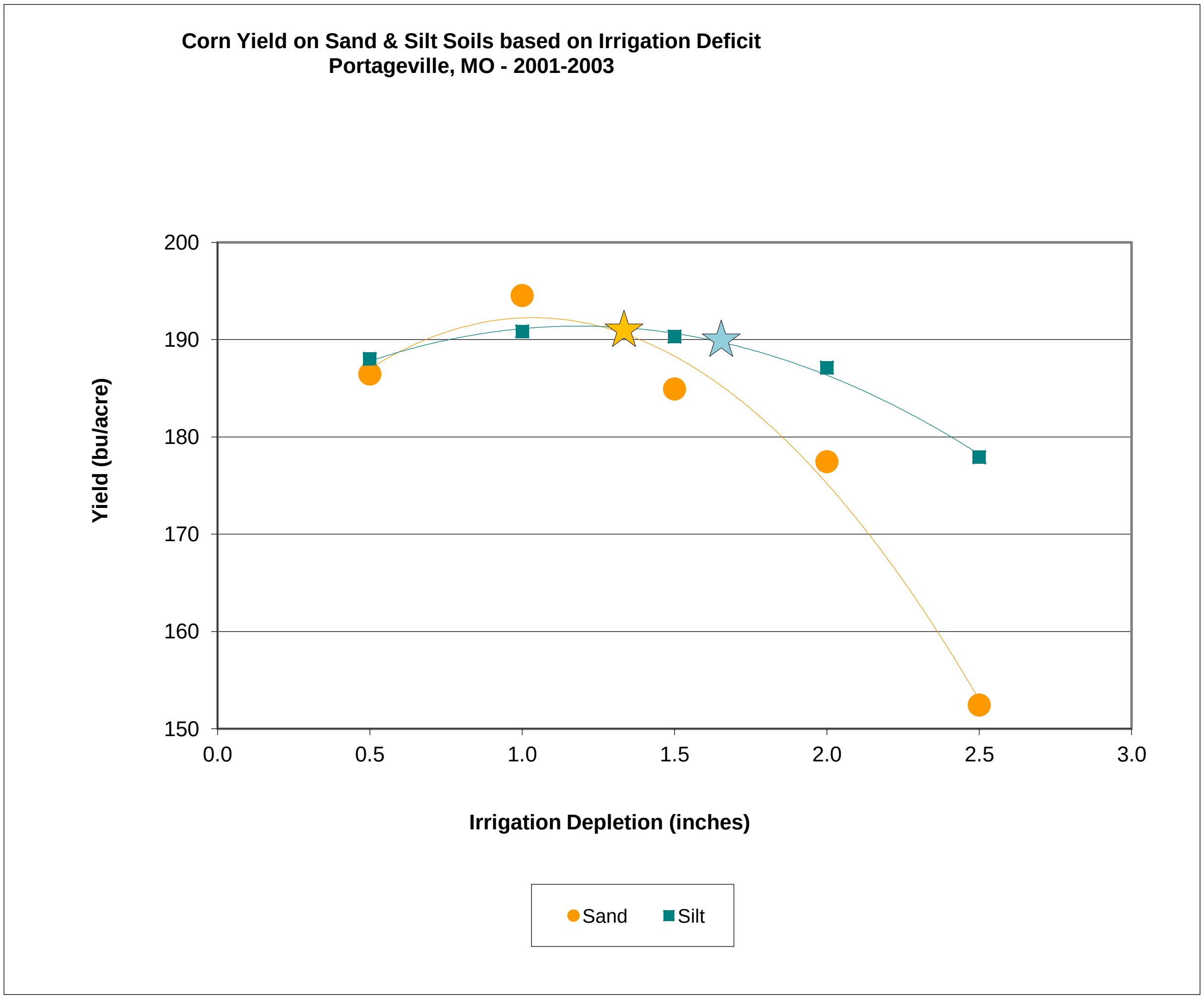


Fig. 13.2. Irrigated corn yields for two soil types based on the irrigation depletion study (After Henggeler, 2004. Stars indicate the ideal calculated depletion amount using Table 13.4 as seen in Example 13.1).

Ideal irrigation depletion amount studies are closely related to water use studies, which are much more plentiful in the literature. Therefore, finding local empirical water use studies and then extrapolating the ideal application amounts from them is a viable option to use to garner data on ideal irrigation depletion levels. Again, remember to look at soil type and irrigation method to see if it is applicable for you.

As previously mentioned, there are three main means of irrigation scheduling: soil-based, plant-based and climate-based methods. The first two methods involve taking a physical measurement of either a soil or plant attribute. The soil-based and, especially, plant-based methods of irrigation scheduling are rational approaches to determining when a plant needs water since they directly measure the effects of inadequate water in the soil profile. The third method, the climate-based method, uses weather data to estimate crop water use over time and calculate when to replace it through irrigation. This approach is generally what people think of when the term *irrigation scheduling* is used. The climate-based method is much easier to use and less expensive than soil- and plant-based methods, especially in light of today's ready availability of computers and Internet sites where current weather data can be found. Since this method estimates water use, as opposed to actually measuring a physical aspect of it, it is important to periodically perform validity checks by measuring a tangible parameter, such as the soil moisture. Once the irrigator becomes satisfied that the climate-based scheduling method is accurate, the time-consuming validation measurements can be curtailed or eliminated.

SOIL-BASED METHODS OF IRRIGATION SCHEDULING

Soil-based scheduling methods rely on sensors that monitor the moisture level in the soil at appropriate locations and depths. As a plant uses water, the root zone soil moisture reservoir is depleted. Many devices are available that can measure the amount of remaining water in the soil. When sensors indicate that remaining soil moisture level reaches a critically low value, irrigation is applied. To a lesser degree, sensors can also indicate when irrigation has restored the moisture to the desired level, in which case, the irrigation system is shut off.

The procedures often used to employ soil moisture sensing devices for irrigation scheduling include:

1. Determine the irrigation application amount to apply (already discussed).
2. Determine which type of sensor to use.
3. Decide whether to collect sensor data manually or involve automation. There are two levels of automation. One, the sensors automatically turn the irrigation system on (and possibly off) and two, only data is collected automatically (through hard-wiring or telemetric signal) but the irrigation is turned on/off independently of sensor readings.
4. Decide at what depths to install the sensors and at how many locations in the field.
5. Determine the sensor value which will serve as the "trigger point" to start irrigation.
6. Decide how often sensor measurements will be taken.
7. Convert numerical data into graphical representations.

SMS devices are generally used to tell WHEN to irrigate, as opposed to HOW MUCH irrigation to apply, since only the neutron probe and some of the dielectric SMS methods provide volumetric measurements of water. For these other types of SMS devices, Table 13.4 and the discussion of ideal irrigation depths can help provide a starting point on the quantity that will be applied.

Types of Soil Moisture Measuring Devices

A great variety of SMS devices are currently available. Only those that are suitable for irrigation scheduling (as opposed to research) are discussed here. These devices include tensiometers, resistance devices (gypsum and granular matrix blocks), neutron probes, and sensors that measure dielectric constant. In addition, many irrigators still rely on the "feel" of root zone soil samples to determine its moisture characteristics. Generally these sensors, including the human hand used in the feel method, do not measure soil moisture itself but some other factor related to soil moisture, which can then be translated into units of moisture. For example, a tensiometer measures the soil suction (also herein called soil moisture tension or soil matric potential) and a gypsum block measures electrical resistance of a porous block buried in the soil. Most manufacturers provide information relating their sensor's data output into units an irrigator can use in irrigation management. Hanson et al. (2000) describes some excellent cases studies that demonstrated the pros and cons of various SMS devices used under different crops and soil type situations; they concluded that in some instances SMS devices reporting tensiometric values were better, while under other conditions SMS sensors having volumetric water content output seemed best.

Tensiometers

A tensiometer is a water-filled plastic tube having a porous tip on one end and a vacuum gauge on the other. Tensiometers are installed in the plant zone with their porous end in contact with surrounding soil. As the root zone soil moisture dries out, the suction or negative pressure, draws out water from the plastic column via the porous tip into the soil, thus creating a vacuum in the tube equal to that of the soil moisture tension. This value is registered on the vacuum gauge.

This negative pressure (i.e., "tension" or "matric potential") is a fundamental aspect of soil physics. The English units of measurement for tensiometric values are *bars* or *centibars* (1/100th of a bar). The corresponding SI unit is the *kilopascal* (1 kilopascal = 1 centibar). Water moves through the soil, and into the plant, and ultimately into the atmosphere, following a negative energy gradient, i.e., more suction exists at each step. The volumetric water content corresponding to soil suction has been determined for the various soil types. Thus, if one knows the tensiometric value , then the corresponding soil moisture value can be estimated. Figure 13.3 shows soil moisture tension versus the percentage of remaining available water for various soil types. Another excellent resource for making cross calculations is the web-based calculator, *Soil Water Characteristics Hydraulic Properties Calculator* (Saxton and Rawls, 2006).

A problem with tensiometers is that their range of measurement is fairly limited, covering from just 0 to 80 centibars. They are influenced by altitude and at elevations of 3000 feet they break suction at 60 centibars. While this range is adequate for medium and courser soil textures, it is inadequate for clay soils. A second problem is that tensiometers require continual maintenance. Also, tensiometers only measure the moisture suction/tension at the depth they are set at, thus multiple units are needed to evaluate soil moisture conditions over the whole plant root zone.

On the positive side, once tensiometers are installed, information on moisture conditions is obtained quickly with a mere glance at their gauge, and they cause minimal soil profile disturbance. Tensiometers can be readily hooked up to data loggers, or automated for controlling irrigation systems, as is frequently done in greenhouses.

Another significant benefit of tensiometers is that they directly measure a basic soil moisture property fundamental to plant water use: *soil suction* (i.e., matric potential). Since plant water uptake responds to the amount of soil tension, and not per se to the percentage depletion of plant available soil moisture, it makes sense to key on soil tension in determining when to irrigate. Using soil tension as an irrigation guide also bridges over the management problems in dealing with various soil types. For example, if it is determined that, for a particular crop, soil tension should not exceed 60 centibars, then for all soil types this value should hold. If, however, one schedules on an available water depletion, say 40%, this might work well on a loam, but would be too wet on coarser soils and too dry on fine textured soils (see Fig. 13.1).

It is important to also note that not only is the value of the tensiometric measurement of importance, but the depth at which it was taken has great bearing. For example, a plant may be experiencing little stress with a tensiometric value of 55 centibars at the six-inch depth; however, if the same value is registered at 18 inches, the plant might be undergoing severe stress. Thus, both the SMS value and the depth of measurement must be known, and are key to properly interpreting and using SMS devices. If an information resource lists only a SMS value without an indicated depth (as in Table 13.5 from Taylor, 1965) assume it is for the top third of the rooting zone.

Table 13.5. Recommended soil moisture tensions for various crops (after Taylor, 1965)

Crop	Tension (centibars) *	Crop	Tension (centibars) *
Alfalfa	80–150	Corn (sweet)	50–80
Alfalfa seed		Deciduous tree	50–80
Pre-bloom	200	Grain (small)	
Bloom	400–800	Vegetative	40–50
Ripening	800–600	Ripening	70–80
Broccoli		Grapes	
Early	45–55	Early	40–50
Post-bud	60–70	Mature	100
Cabbage	60–70	Lettuce	40–60
Cantaloupe	35–40	Onion	45–65
Carrot	55–65	Potato	30–50
Cauliflower	60–70	Strawberry	20-30
Celery	20–30	Tomato	60-150
Citrus	50–70		

* The smaller values are recommended for a warm, dry climate and the larger values for a cool, humid climate. Intermediate climate should use intermediate values.

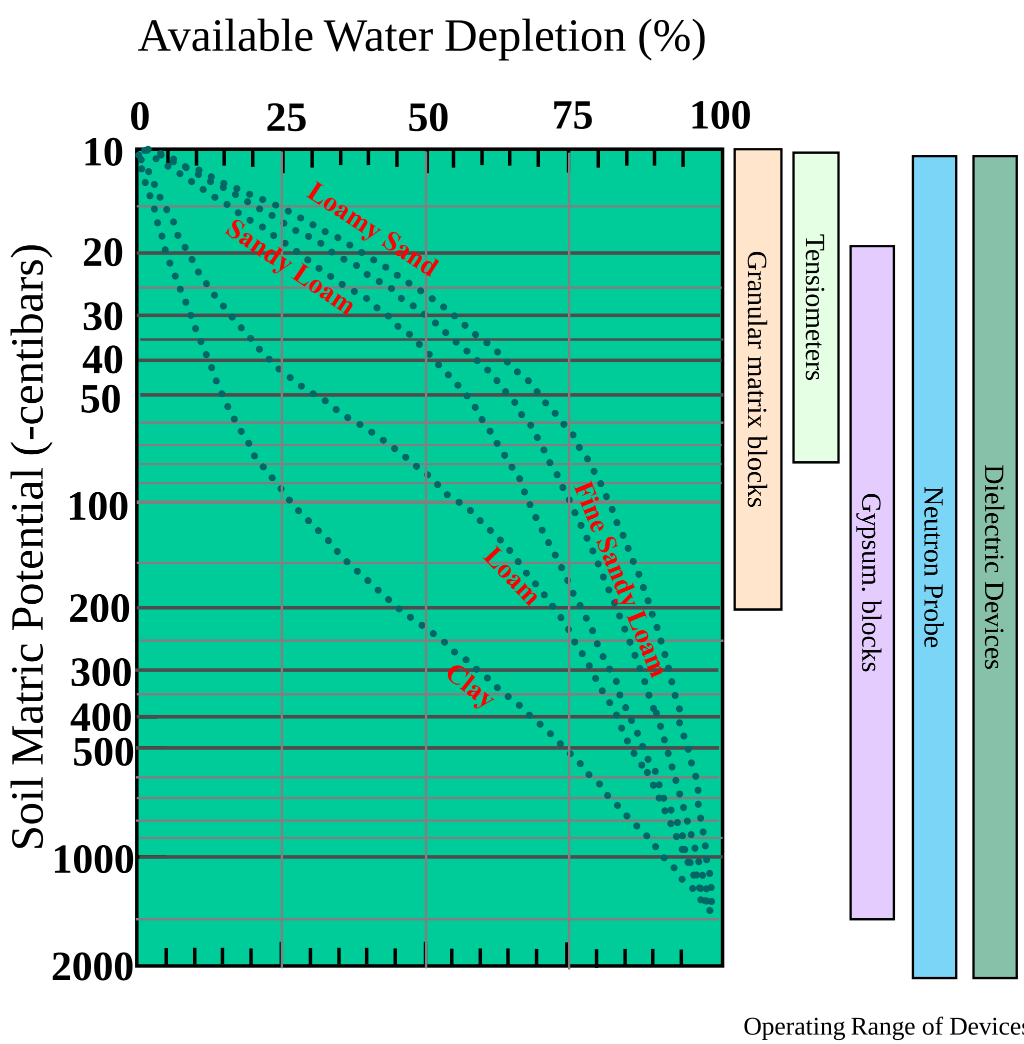


Fig. 13.3. Soil matric potential versus available plant water depletion for various soil types within the range of measurement of various sensors (after Taylor, 1965).

Resistance Devices

Gypsum blocks. Gypsum blocks have a long history in irrigation scheduling that started before WW II and are electrical resistance-based sensors. They are constructed of porous material into which are embedded two wires or two concentric wire screens attached to wire leads. A single block is buried in the soil to the root zone depth at which the water content will be monitored, with the leads brought to the surface. Additional blocks are used for additional depths and locations. A modified ohmmeter is used to read the resistance in the block by clipping onto the wire leads. The output units have been converted from resistance units to a numerical scale, generally from 0 to 100. Information is normally available from the manufacture to estimate the percent water content by weight corresponding to either the output value and/or actual electrical resistance. Irrigators who make use of these manufacturer-provided aids should keep in mind that percent water content by weight is not the same as percent water by volume, which is the form used in calculating soil water content and irrigation deficits. Since soil tension is a fundamental measurement in determining a plant's ability to obtain water, some of the newer generations of gypsum blocks now convert resistance readings to estimates of soil tension.

The two greatest benefits of gypsum blocks are that they are inexpensive and they cause only minor disturbance of the soil profile. The low cost allows irrigators to monitor soil moisture in more locations and depths, compared to tensiometers. Where fields are cultivated annually, gypsum blocks essentially have a one-year life. Although they might operate well for up to two years in acidic soils, and three to five years in neutral or alkaline soils, their low cost does not warrant digging them up. The disadvantages of gypsum blocks are that they are fairly unresponsive at the higher levels of moisture content, affected by the presence of salt, dissolve over time creating a poor soil surface contact, and are slow in response time. Regular gypsum blocks can be tied to a data-logger to automatically record data, but generally are not used for this purpose, as most who wish such a system normally opt for granular matric blocks.

Granular matrix blocks. Granular matrix blocks (GMB) are a special type of resistance device that uses a material other than then gypsum for the main part of the resistance block. A small wafer of gypsum still remains inside the GMB to help buffer out the effects of salinity on readings, but the non-gypsiferous outside keeps them from dissolving. These blocks may cost two or three times more than the normal gypsum blocks, but they last longer, respond quicker, and have a larger range of sensitivity. These blocks have been extensively used by researchers and can be readily hooked up to inexpensive data loggers. They, likewise, can be installed with minimal soil profile disturbance.

Neutron probe

The neutron probe is a very accurate method of determining volumetric water content (e.g., inches/foot, % by volume, etc.) when properly calibrated. It would probably be the unchallenged champion of water measurement devices except for three drawbacks, the first being its initial high cost. Secondly, since the neutron probe contains a small amount of radioactive material, its use is highly regulated. And lastly, they have accuracy problems at shallow depths (e.g., less than 6 inches).

The neutron probe works by emitting neutrons into the soil and reading how many neutron bounce back. When a neutron strikes a molecule of hydrogen in the soil it ricochets off the hydrogen in a new direction. Some of the deflected neutrons bounce back in the direction that they came from and are then detected by a reader on the neutron probe. The number of hydrogen molecules, and thus the number of deflections bouncing back to the reader, increases with the amount of water in the soil.

The probe is used by inserting the probe tip, with the neutron emission device, into the ground through an access hole, lined with an aluminum or plastic tube to allow for repeated measurements to be made. Readings are taken by lowering the probe tip down the access tube to successive desired depths. The probe is portable and can be carried to multiple locations for moisture measurements. The sphere of influence being read depends on soil type and moisture conditions, i.e. varying from about 6 inches in wet soil (Van Bavel et al., 1961) to about two feet in diameter in dry soil (e.g., beach ball size). This constitutes a relatively large sample volume when contrasted to the volume that other sensors read. Larger areas of influence reduce the likelihood of errors.

Instruments sensing dielectric properties

All materials possess a measurable property called dielectric constant, which is related to electrical capacitance and how the molecule behaves in any electric field. For instance, air has a dielectric constant of 1.0 and quartz 3.8. Water has a very high value of 80.0. A composite medium like soil has an overall dielectric constant value based on the constituent amounts of air, solid particles, and water. Because the dielectric constant of water is especially high, compared to the other soil components, it is a good reference to the amount of moisture present. Once the dielectric constant of a mixed medium is measured and is known, the water content can be calculated.

The dielectric properties of a soil can be measured through using time domain reflectometry (TDR) and frequency domain reflectometry (FDR). TDR measures the time it takes for an electric pulse to travel through the soil (e.g. propagation velocity). FDR measurements involve the frequency of the pulse, and for those devices that specifically employ capacitors to measure the frequency, the term *capacitance system* is used.

A wide range of sensors can measure water based on dielectric properties. The cost of dielectric systems varies from fairly inexpensive to quite expensive. Some systems involve installing access tubes in the ground into which the sensor is inserted. Other systems use probes that are installed directly into the soil to take repeat readings throughout the season. Some equipment has probes that are portable and allow spot-checking of moisture in the top six to nine inches of the soil. Many of these systems can be hooked up to data loggers and come with powerful water management software. Unlike the neutron probe, these devices have a very small sphere of influence. The presence of air gaps between the probes and the soil cause erroneous readings, thus installation becomes difficult and critical. Also, very high levels of organic matter can reduce their accuracy. Some TDR, FDR, and capacitance systems show great promise in irrigation management, but many types are beyond the needs of most irrigators. However, the portable capacitance meters with prongs that can be inserted six to nine inches into the soil, may help schedule irrigations for shallow-rooted crops like turf and some vegetables. Such a device is the Aquaterr probe (Aquaterr Instruments & Automation, Costa Mesa, CA) which costs about $600. Dielectric sensors are, however, mostly used by researchers and the advanced manager who wishes to intensely monitor soil moisture at a few locations and then make universal projections on moisture conditions and plant water uptake over larger irrigated areas.

The reason dielectric systems can be pricey is that a single sensor device costs over $100, higher than other buried SMS devices (gypsum blocks at $10, GMBs at $35, and tensiometers at $75). If only a few depths/locations are needed, the units stay somewhat competitive. But if many sites are to be monitored they quickly become prohibitive. An exception for these capacitance sensors being on the high end of the cost scale exists when monitoring is done telemetrically. In these instances, the unit cost of sensors is overshadowed by other costs (data loggers, transmitters, receivers, cell phone charges, etc.). Also, several companies have developed excellent, low cost data loggers/transmitters to support these capacitance probes, like the Echo-5 (Decagon Devices, Inc., Pullman, WA). The exciting and promising field of soil moisture sensing and telemetry will be discussed later.

An Internet discussion group, SOWACS, is an excellent resource for those wishing to learn more about all the sensors above.

The feel method

Many competent consultants continue to determine soil moisture by the "feel method" – the manipulation of a sample of soil in one's hand. It is fast and affords the freedom to check moisture conditions at any place in the field, not being tied down to just where devices have been previously installed. The accuracy of a competent user is said to be as high as 5 percent. The moisture content is determined from handling a small handful of the soil, and then comparing the physical "feel" to corresponding moisture units (typically using inches of available water per foot), such as seen in Table 13.6. The soil can be gathered with a slotted soil probe, an auger, or shovel. Ideally, a sample from the active root zone at several locations will be tested. If only a single depth is used, the depth should correspond to the depth of the most active roots.

The moisture status is determined by firmly squeezing the sample in one's hand to form a potato-shaped ball and then by "ribboning out" some of the sample between thumb and forefinger. An estimate of available soil moisture can be made using Table 13.6 keyed to observable results, such as to how well a ball was made, how far it could "ribbon" before breaking off, how particles broke off, and other traits. Since use of Table 13.6 requires classifying the soil sample into its textural classification, this determination must be made. NRCS maintains an Internet site with photographs of various soil texture families at different moisture levels and how they look in performing this test (http://www.wy.nrcs.usda.gov/technical/soilmoisture/soilmoisture.html).

The feel method and Table 13.6 deal with the entire range of soil appearances over the available soil moisture spectrum for common soil textures. In reality, what is of <u>singular importance</u> regarding a soil's appearance and feel is just exactly how does it appear/feel at the time when irrigation should be applied? Since crops have different thresholds at which they should be irrigated, both soil type/depth and crop concerned are important in deciding what the water content, and thus the "feel" of the soil, should be at irrigation. In a study Phipps (2004), who had ascertained from the literature that 55 centibars was the ideal tension at which to irrigate cotton, memorized the feel and appearance of the clay soil at this point. He then used this "feel reference" as one of the treatments in a study evaluating three irrigation scheduling methods for cotton. The results were that this simplified feel method out-yielded a scheduling method that used historic-weather and another scheduling method employing a computer program and real-time-weather.

The simplicity and the positive results of the Phipps method indicate its potential utility when used by an experienced irrigator, particularly as a backup to other scheduling methods. In 2003 40% of irrigators in the USA were examining the soil to determine when to irrigate (USDA, 2004). The Phipps method is rudimentarily simple and involves (1) determining the ideal soil moisture tension at which to irrigate a crop (e.g., using Table 13.5), (2) installing a tensiometer in the active root depth, (3) after an irrigation or rain waiting until your soil dries out to the desired trigger tensiometric value, (4) then pulling up a soil sample from that depth and memorizing how it feels, and (5) periodically pulling soil samples to see if at the trigger point has been reached. Figure 13.4 shows the Phipps method being used.

Figure 13.4. The Phipps method entails memorizing the appearance and feel of the soil for <u>only the single point</u> which corresponds to the ideal soil tension/ matric potential at which to re-irrigate based on crop and soil type/depth. In hiss case it was cotton, grown on a clay soil, and a potential of 55 centibars. If the soil sample felt/appeared like this or seemed drier, he irrigated, otherwise he waited.

Table 13.6 Soil Moisture Deficits (SMD) in inches/foot based on described soil appearance. Color code shows an estimate for soil tension levels. After NRCS,				
Available Soil Moisture Percent (%)	**Soil Moisture Deficits ---------- Descriptions & SMD in inches per foot ----------**			
	Coarse Texture Fine Sand and Loamy Fine Sand	**Moderately Coarse Texture- Sandy Loam and Fine Sandy Loam**	**Medium Texture - Sandy Clay Loam, Loam, and Silt Loam**	**Fine Texture-Clay, Clay Loam, or Silty Clay Loam**
0 - 25	Dry, loose, will hold together if not disturbed, loose sand grains on fingers with applied pressure. SMD 1.2-0.5	Dry, forms a very weak ball‡, aggregated soil grains break away easily from ball. SMD 1.7 -1.0	Dry. Soil aggregations break away easily, no moisture staining on fingers, clods crumble with applied pressure. SMD 2.1-1.1	Dry, soil aggregations easily separate, clods are hard to crumble with applied pressure SMD 2.4-1.2
25 - 50	Slightly moist, forms a very weak ball‡ with well-defined finger marks, light coating of loose and aggregated sand grains remain on fingers. SMD O.9-0.3	Slightly moist, forms a weak ball† with defined finger marks, darkened color, no water staining on fingers, grains break away. SMD 1.3-0.7	Slightly moist, forms a weak ball† with rough surfaces, no water staining on fingers, few aggregated soil grains break away. SMD1.6-0.8	Slightly moist, forms a weak ball†, very few soil aggregations break away, no water stains, clods flatten with applied pressure SMD 1.8-0.8
50 - 75	Moist, forms a weak ball† with loose and aggregated sand grains on fingers, darkened color, moderate water staining on fingers, will not ribbon. SMD O.6-0.2	Moist, forms a ball with defined finger marks, very light soil/water staining on fingers, darkened color, will not slick. SMD O.9-0.3	Moist, forms a ball, very light water staining on fingers, darkened color, pliable, forms a weak ribbon between thumb and forefinger. SMD 1.1- 0.4	Moist, forms a smooth ball with defined finger marks, light soil/water staining on fingers, ribbons between thumb and forefinger. SMD l.2-0.4
75 - 100	Wet, forms a weak ball†, loose and aggregated sand grains remain on fingers, darkened color, heavy water staining on fingers, will not ribbon. SMD O.3-0.0	Wet, forms a ball with wet outline left on hand, light to medium water staining on fingers, makes a weak ribbon between thumb and forefinger. SMD O.4-0.0	Wet, forms a ball with well-defined finger marks, light to heavy soil/water coating on fingers, ribbons between, thumb and forefinger. SMD O.5 -0.0	Wet, forms a ball, uneven medium to heavy soil/water coating on fingers, ribbons easily between thumb and forefinger. SMD O.6-0.0
Field Capacity (100%)	Wet, forms a weak ball†, moderate to heavy soil/water coating on fingers, wet outline of soft ball remains on hand. SMD 0.0	Wet, forms a soft ball, free water appears briefly on soil surface after squeezing or shaking, medium to heavy soil/water coating on fingers. SMD 0.0	Wet, forms a soft ball, free water appears briefly on soil surface after squeezing or shaking, medium to heavy soil/water coating on fingers. SMD 0.0	Wet, forms a soft ball, free water appears on soil surface after squeezing or shaking, thick soil/water coating on fingers, slick and sticky. SMD 0.0

† A weak ball disintegrates with two to three bounces;

‡ A very weak ball will disintegrate with one bounce of the hand.

Color code for Table 13.6	
0 – 25 centibars	100 – 200 centibars
25 – 50 centibars	200 – 500 centibars
50 – 75 centibars	500 – 850 centibars
75 – 100 centibars	> 850 centibars

Comparing Soil Moisture Sensors

The annual cost for various soil moisture sensors based on the number of measurement points involved is seen in Figure 13.5. No additional costs, such as, installation costs, operating costs, and, in the case of the neutron probe, regulatory costs are included. The cost of soil moisture sensors is strongly influenced by the number of measurement points to be monitored. For example, the neutron probe, which is generally considered expensive, becomes cost effective when a large number of measurement points are monitored. It becomes the least expensive method with more than 64 monitoring points (e.g., 16 locations of 4 depths each), except where gypsum blocks' useful life can be extended to two years.

The advantages, disadvantages, cost, and expected product life of the various soil-based methods are listed in Table 13.7. Other factors to consider in comparing soil moisture-sensing devices include:

- The device should be sensitive at important soil moisture content levels (e.g., a crop like celery with a **p** value of 0.20 [≈ 0.4 to 0.6 bars] needs sensitivity in the higher moisture levels)
- Installation and maintenance should not be burdensome
- Returning repeatedly to take readings does not disturb/influence the plant's normal growth
- Do your needs call for quicker responding SMS devices (e.g., desiring to cutoff irrigation at a set level)?
- Will SMS devices that disturb the surrounding soil structure (e.g., some dielectric SMS devices) destroy the integrity of future readings? A case in point is where hard pans exist in the field and installation of the SMS can break the pan and alter normal rooting and percolation patterns.

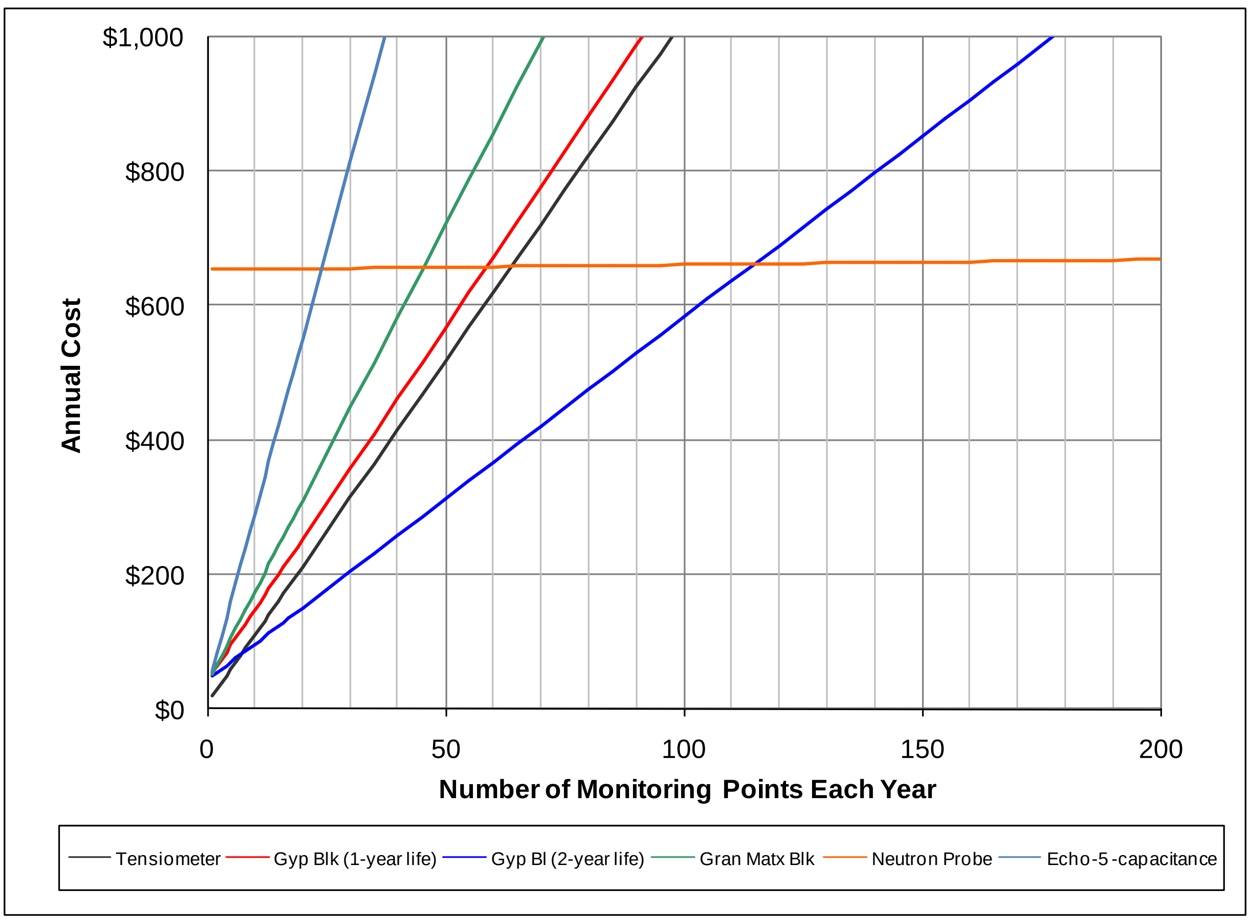


Figure 13.5. The annual cost in 2009 dollars of various soil moisture sensing devices versus the number of monitoring points each year (see Table 13.7 for unit cost data).

Table 13.7. Advantages and disadvantages of various soil moisture monitoring devices.

SMS Method (initial cost/life)	**Advantages**	**Disadvantages**
Tensiometer ea. unit: $75/10 yrs vacuum pump: $82/10 yrs	• fairly inexpensive if just a few locations are involved • "home-made" units possible • can be tied to system automation • can be tied into data-logger • not effected by salinity • disturbs little soil • soil tension values are less subject to field spatial variability then are water content values • the output, soil tension, is the driving force in plant water uptake • very fast response time	• range is limited (0 – 80 centibars) • can break suction and require re-setting • needs to be removed over winter • only measures a limited soil volume
Gypsum blocks ea. unit: $10/1 or 2 yrs meter: $315/10 yrs	• very inexpensive • disturbs little soil	• requires separate, moderately priced meter • effected by salinity • effected by temperature • slow response time • insensitivity in wetter ranges of soil moisture and then values drop quickly – it is as if they go from HIGH to MEDIUM LOW readings, skipping over MEDIUM values. • subject to hysteresis • short life (1 to 3 years) • only measures a limited soil volume
Matrix granular blocks ea. unit: $37/3 yrs meter: $280/10 yrs	• moderately inexpensive if just a few locations are involved • disturbs little soil • has a larger range of sensitivity (0 to 200 centibars) • can be tied to system automation • can be tied into data-loggers temperature effects can be compensated for	• requires separate, moderately priced meter • effected by higher levels of salinity • moderately slow response time • subject to hysteresis • only measures a limited soil volume
Neutron Probe	• moderately inexpensive when many locations are involved • disturbs little soil • has a very larger range of sensitivity (0 to >1500	• cannot be tied to system automation • cannot be tied into data-logger • poor readings at shallow depths • regulatory red tape • tends to cause trampling of measured

tubes: $1.50/ft/15 yrs meter: $7,500/20 yrs	centibars) • out put can be “inches of water” • very accurate • not effected by temperature or salinity	crop
Capacitance (Echo-5) ea. unit: $110/5 yrs meter: $280/10 yrs	• disturbs little soil • has a very larger range of sensitivity (0 to >1500 centibars) • output is in “inches of water” • very accurate • not effected by salinity • excellent compatibility with telemetric equipment	• high cost when multiple locations need to be monitored • only measures a limited soil volume

Placement of Moisture Sensing Devices

Other then the sensors that use access tubes, the SMS devices described above only measure water content at their specific location and. It is important that enough sensors are installed in the irrigated area and at enough soil depths to determine overall water status. Furthermore, it is important that installation of the sensors and future collecting of data does not influence subsequent measurements.

In the first year, a general strategy is to that install SMS devices in ample numbers (both in the number of monitoring locations and in the depths to be monitored). The number of locations and depths per location can then be reduced in subsequent seasons.

Before burying and using the sensors it is helpful to have a picture of how water moves into a soil (as from rain or irrigation), and how it leaves the soil (as evapotranspiration). Plants use stored soil moisture (transpiration) from the top of the soil profile downwards (Figure 13.6). Surface evaporation primarily affects the top part of the soil profile. Thus, the moisture status changes more rapidly in the top 6 inches then it does in mid-depths (i.e., 12 to 15 inches). At still deeper levels, soil moisture status changes slowly and does not begin to noticeably decrease until the plant is running out of readily extractable water in the layers above.[4] Thus, the sensor depth placement is particularly important when using values to make irrigation management decisions. For example, a 60-centibar reading on a tensiometer at 12 inches depth might not pose a problem, but the same reading at 24 inches could be harmful. One of the reasons that plants preferentially abstract water closer to the surface is that roots growing at deeper depths require more suction to draw water up to the plant’s leaves. More importantly, there is a reduced root mass in deeper depths. When the root mass is small, little water can be extracted, even under conditions when the soil moisture content is high. Thus, both <u>sensor reading</u> plus its installed <u>depth</u> are to be interpreted together.

Following water application, again it is the 6-inch level that changes most rapidly (except in situations of sub irrigation or where a high water table exists). As the top layer receives water exceeding the field capacity level, water moves downward to the 12-inch depth, and then to the 18-inch depth and so on. This wetting edge, or wetting front, is where salts (including nitrates) are concentrated.

[4] In humid areas where frequent rains occur and hard pans often exist, the rooting depth of row crops is shallower then in arid areas. Thus the terms “top”, “middle”, and “deep” roots might refer to 6, 12, and 18 inches, respectively, in humid areas. An arid area might have corresponding depths of 12, 24, and 36 inches. Also, the type of crop obviously effects rooting depth.

How many depths to monitor

Irrigation managers need to have enough depths monitored to allow good irrigation decisions be made. Researchers may wish to monitor more depths in the soil profile, but schedulers need not over burden themselves by installing sensors at too many depths. Usually scheduling objectives can be met with three, two, or even one depth per location. (Devices using access tubes, like a neutron probe, can collect readings at numerous depths and are only limited by how deep the access hole/tube is). However, for the first year it may be useful to "read" a fourth, fifth or sixth depth per site. This added data enlightens the irrigator on crop/water/soil facets specific to his farm that he is likely not aware of. Information learned can include insights on how deep rainfall penetrates, where the active depth of roots is, and many other things. In the second and subsequent years the number of monitored depths can be reduced as the irrigator/farmer becomes more familiar with the soil types and the performances of the irrigation systems on his farm.

Using three monitoring depths. Information from three depths can give the grower adequate information for field crops. The readings at the **depth closest to the surface** (6 to 12 inches) gives results that are very responsive and "bounce" a lot, but they do record the nuances of moisture change. It is normally difficult to make irrigation decisions on SMS devices at just this depth due to the bounce. They will almost always show drier readings then the deeper depths. However, if regular gypsum blocks are being used and since they are very sluggish in the higher soil moisture levels, locating additional blocks close to the surface may provide more of a "heads up" on moisture status. The **mid-depths** (e.g., 12 to 15 inches) give readings that are more stable, and also focus on where the greatest root mass is located, so are important in triggering an irrigation application. The **deeper level** devices (depths >18 or 36 inches) show changes slowly, and indicate if your application strategy is on an "even keel". The general directional trend of these devices show if over-irrigating is occurring (lines trend up) or if under-irrigation is occurring (lines trend down). For many crops, one manages so that the deeper level devices are flat during the first part of the season and later course upward as the crop is finished out.[5] These deeper located devices are also good beacons for determining if deep percolation is occurring.

When three depths are used to characterize a plant root zone, averaging the data values and plotting one comprehensive curve is very helpful, but one should also evaluate readings of the individual depths as well.

[5] SMS devices that record tension have negative values. Thus, as data trends upward the plot is drying out. It is intuitive to the casual user to interpret plotted SMS values that are declining downward as drying out; this can be confusing. For this purpose, using the absolute value to plot tension readings can make a graph easier to interpret.

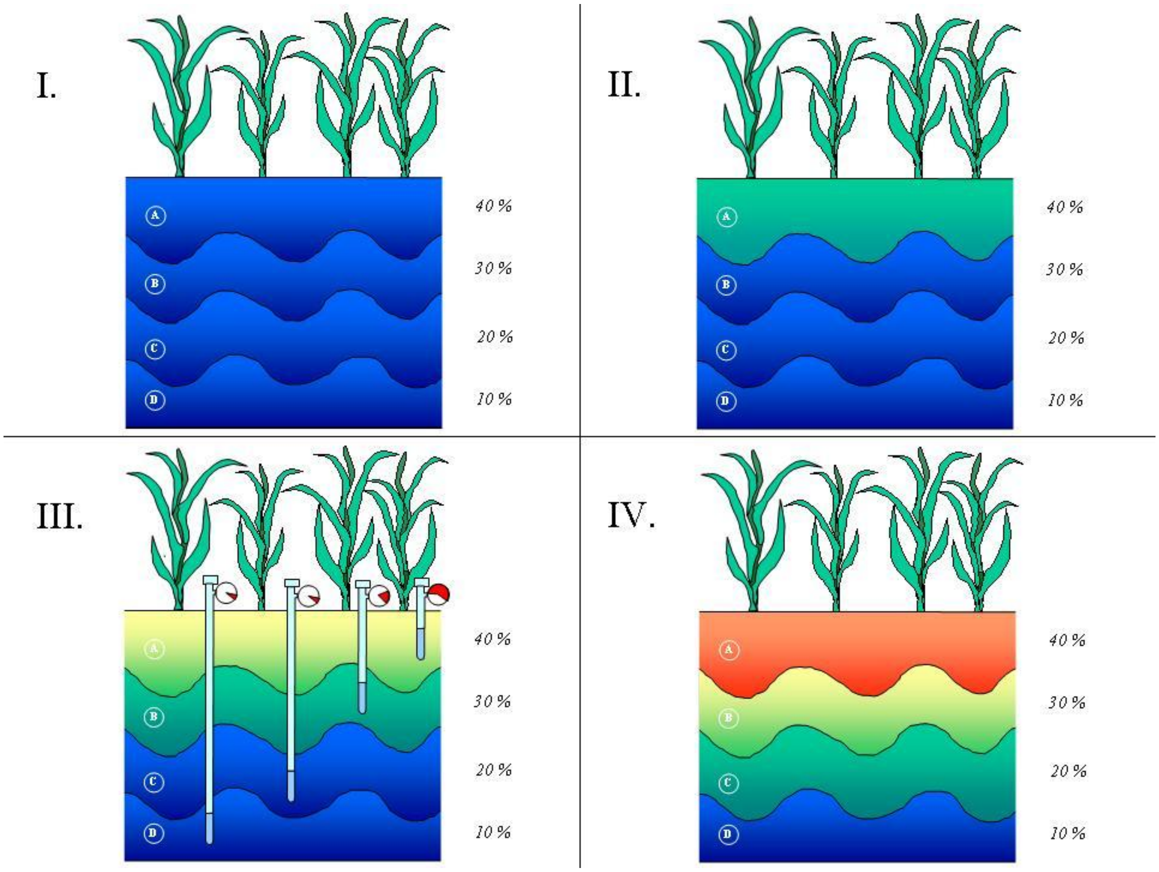


Figure 13.6. Plants use water from the top downward as illustrated here in a soil profile where A = shallow layer (top 25% of root area), B = medium layer (next 25% of root area), C = a deeper layer (next 25% of root area), and D is deepest layer (bottom 25% of root area). A rule of thumb is that A has 40% of the roots, B has 30% of the roots, C has 20% of the roots, and D has 10% of the roots. The soil profile is all full in (I), as after irrigation or good rain. The plant will then take up water and surface evaporation will occur depleting part of the top layer, as seen in (II). The plant will then start extracting water from the middle layer once the top layer as been markedly reduced as seen in (III). The bottom layer will then begin to be drawn upon as the top and middle layers are used up, as seen in (IV). The depth that SMS devices are placed is very important as seen in (III), which is nearing the stage that irrigation should be applied. The SMS devices register different values based on their insertion depth, therefore, the SMS value plus the depth installed need to be considered together. The actual depths of A, B, C, and D depend on crop, soil type, and frequency of rain/irrigation.

Using two monitoring depths. A second management philosophy of soil moisture monitoring, often recommended by experts, involves installing sensors at just two depths. The first sensor is in the primary root zone (i.e., 9-12 inches) and the second at a deeper level where there are fewer roots (e.g., 18 or 30 inches). The locations of the first sensor might be at a depth equal to about 25% of the normal rooting zone. The bottom sensor is placed at about 60% of the root zone depth. The top sensor is monitored to trigger irrigation. The bottom sensor is monitored to help determine when to (a) cut off the irrigation (a fast responding SMS device must be used), or (b) to detect deep percolation, or (c) to observe if overall under- or over-irrigation is occurring by the direction of the trend line of the plotted data. This concept of using SMS to cut-off irrigation has merit, but one or two irrigations may be required before the irrigator/manager determines what setting to use. If two sensors are employed per site, their averaged vales could provide a clearer picture of overall trending, rather than interpreting two separate soil moisture curves.

Using one monitoring depth. Caveats are in order if just a single depth is being monitored, especially for novice users of SMS devices. To help offset the risk factor additional locations in the field should be monitored. However, those irrigators who have previously monitored at multiple depths, and have learned how their soil/crop behaves, probably could successfully phase into single depth monitoring. When using just a single monitoring depth, it is best to install the sensor where the majority of roots are found, but deep enough so that "bouncing" does not occur. A depth of around 9 to 12 inches might be appropriate. Near the surface, readings modulate considerably plus temperature-sensitive units are affected by diurnal changes in soil temperature When a standard gypsum block is used, it is important to be aware that they have a flat response at the higher water content levels, and not to be caught off-guard. It may be wise to install these slow-responding devices closer to the soil surface since moisture levels there are quicker to go down.

What locations to monitor

Multiple sensors at various depths, but at a single location is termed here a “station". Every field, no matter what size, should have at least two stations to account for possible irrigation system non-uniformity. And due to the poor distribution uniformity often found in flood irrigation, at least three or four stations may be called for. Hanson and Orloff (1998) recommend two stations for each 40 acres.

Having several stations in a field also increases the overall “sensitivity” by allowing multiple sensor values to be averaged into a single response curve. Use common sense in locating stations. Major variations in soil types in a field may influence the location and number of station sites. The lighter soils that hold less water should be given special consideration in locating station sites, since an irrigator will want to manage the field based on the areas most sensitive to stress; of course, the relative amounts of the various soil types should play a factor in determining station location. Obviously, having more than one type of crop in the field influences station number. Areas with different crops (and significantly different planting dates) should be managed as separate fields.

The locations should be easy to access at the time of installation (as well as when the crops are fully grown—it is easier to walk down rows then across them). Sites should be marked clearly with stakes or marking flags or the GPS location recorded (many sensor sites have been lost through the course of a season!). Small flags located at the field edge help to mark where to enter the field. A map should be made showing the location of the sensor stations.

In surface irrigated fields, one should place sensor batteries at locations that represent average soil moisture conditions in the entire of the field. For instance, sensors should not be located 100 or 150 feet from either end. Under furrow irrigation one should be aware of whether the row that the sensor is being installed in is a “wheel row” where tractor tires travel down, as these rows soak up less water than non-wheel rows. If a farmer is using 8-, 12-, 16-row, etc. equipment then the preponderance of rows will be non-packed, so that is where sensors should be placed. Large surface-irrigated fields may have sets that are watered days before the last set is irrigated. In these instances, the irrigator may be tempted to install stations somewhere in first, middle, and last part of his irrigation rotation to collect background information on the whole field, but in reality, only SMS values from the first irrigated set are needed. Since irrigation starts off here, it will always be the driest area of the field. Having SMS data from various parts of the field, some of which was watered 14 days ago, some 7 days ago, and some 3 days ago would only muddle trying to interpret SMS readings. Also, if water supplies are inadequate (generally 3 or 4 GPM/acre) there may be no need to install SMS devices as irrigation is never caught up with, and deciding when to start irrigating becomes a moot point.

Similarly, with center pivot irrigation, avoid placing sensor stations in locations that may not receive the average application of water, including the area under the first and second spans and the area outside the last tower (i.e., the area watered by the end gun and the dry area in the pivot corner). For a typical pivot, the end gun generally waters another 10% of surface area, but the application rate to this area is often quite different from the application rate beneath the pivot spans, and so SMS devices should not be installed in that area. A pivot, likewise, has a normal starting point and an ending point, with the application period typically lasting from two to four days. Just after irrigation has begun sensor batteries located in the portion of the field where irrigation begins show very wet conditions, while dry conditions will be found in the sensors located in that portion of field not yet watered. Remember, the prime purpose of sensors is to tell you when to start irrigating, so concentrate batteries in the area where irrigations begin. Figure 13.7 shows site location for SMS stations under pivots.

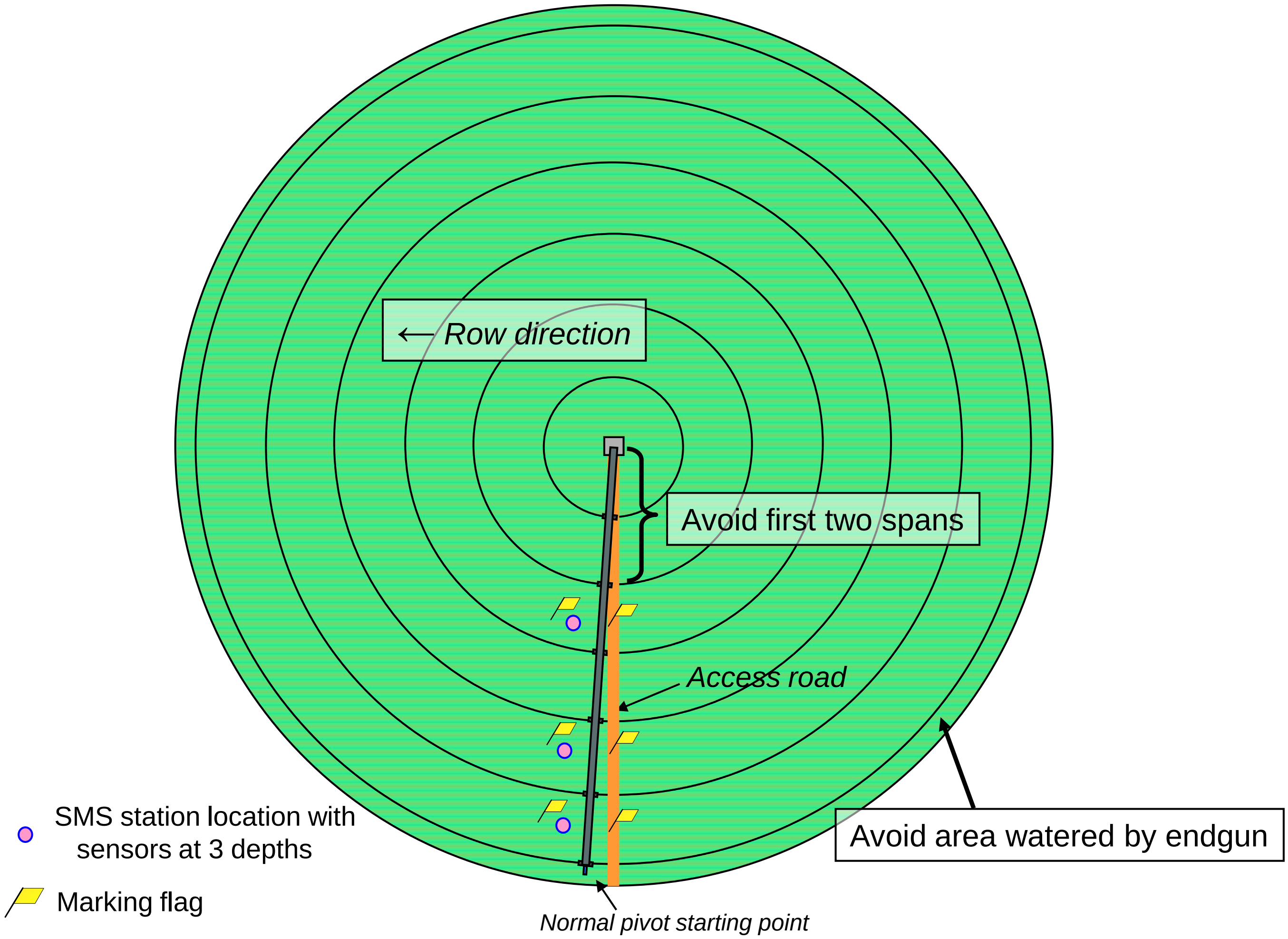


Figure 13.7. Location for SMS stations under a center pivot. Each station might contain three sensors located at different depths.

In microirrigated fields, proximity to the emitter influences SMS readings greatly, so sensors should be placed within the wetted area, but at least 12 inches away from the emitter. Keep in mind that the size of the wetting area beneath the surface is greater than what is seen on top of the surface. A dripping emitter creates a wetted "bulb" beneath itself in the soil (carrot-shaped for light soils and onion-shaped for heavier soils). A tile probe can help determine the three dimensional shape of the wetted area. The wettest portion of this "onion" is at the emitting point and decreases radially from there out towards the wetted edge. The changes in water content can be thought of as the layers in an onion. Because of this gradient, soil tension at the same depth can change several centibars just several inches away as seen in Figure 13.8. Even when emitter/sensor distances are carefully observed variability in readings can occur (Meron et al, 2001). Thus, it is difficult to irrigate, say at 15 centibars, since the location of the SMS is so critical. Also, keep in mind that emitter location can change over the season due to shrinkage/expansion of surface lateral lines and movement during farming practices. In this situation, the operator needs to install the SMS in a common sense manner and choose an appropriate trigger value to irrigate at, knowing that he may need to increase or decrease the trigger value based on the response of his crop. Averaging the values from multiple SMS stations will help provide assurance to the grower. Tile probing periodically through the season can serve the drip user as a means to evaluate his irrigation scheduling. A correctly irrigated field will maintain a constant size of wetted bulb. If the bulb decreases in size, not enough irrigation is being applied and, similarly, if the bulb increases in size over the season then too much water is being applied. Since resistance-type SMS are often not sensitive at higher levels of water content, they should be avoided or used with care. One SMS option is the Aquaflex (Streat Instruments, New Zeeland) which is a SMS 10 feet in length. Since it integrates moisture values over a large area it may be useful for microirrigation users.

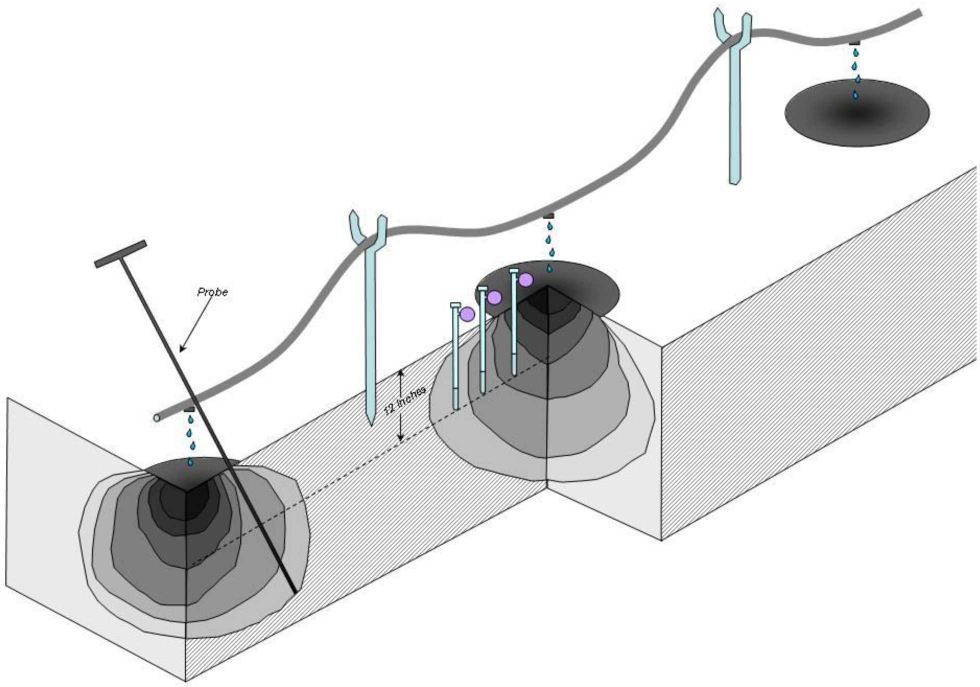


Figure13. 8. The wetted profile from microirrigation showing that soil water content changes radially from the center beneath the emitter and that three SMS devices at the same depth, though just a few inches from each other, will give different readings. A tile probe can be used to determine the shape of the wetted ball. If the wetted ball stays the same size over time it indicates that irrigation application and crop water uptake are matched.

Sensor placement should take into consideration cultivation practices. They should not be placed where plowing, weeding, mowing, or other operations might destroy them. If cultivation practices are changed to avoid SMS devices, such as raising a mower over the tensiometer locations, their moisture readings may no longer be representative. Sensors in mowed crops, like alfalfa or turf, can be installed to protect their components by excavating a hole and sinking a container to surround the sensor (e.g. a coffee can with the bottom and top cut out). The top of the device or wire leads can thus be kept below grade and covered up with a plastic lid.

Installation of Soil Moisture Sensors

The installation of sensors should not drastically disturb the surrounding soil. If so, it may affect normal rooting and/or water movement, especially if a hardpan exists and the installation process were to break through the pan. When possible, it is best to install soil moisture sensors in undisturbed soil. For example, a pit could be excavated and TDR sensors could be installed in the undisturbed pit walls. Sometimes a steel rod is used to pound out the access hole for the installation of tensiometers or resistance blocks. However, this would compact the soil surrounding the sensor and perhaps affect readings. Soil probes or screw augers are better instruments to use for installation. Follow manufacturers' instructions on installation.

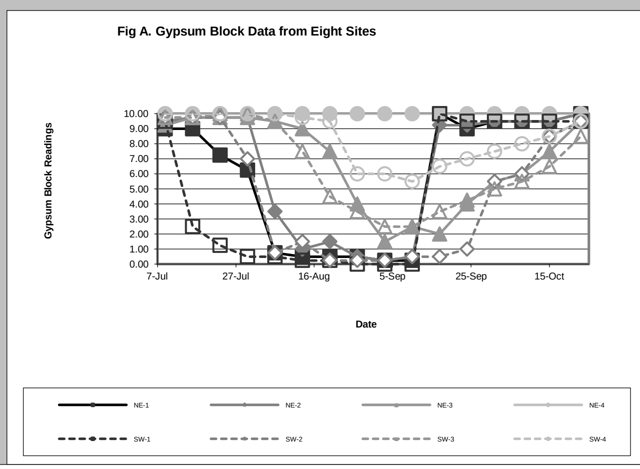
Using Soil Moisture Data

The neutron probe and some TDR devices are capable of giving moisture readings in volumetric water units (for example a reading of 20% by volume = 0.20 inches of water/inch of soil depth). Thus, the irrigation application depth needed to be applied can readily be determined by subtracting the current root zone moisture status from the corresponding status at field capacity, a soil moisture condition occurring one to three days after a substantial irrigation or rain event. However, many SMS devices use units of measurement other than water volume, such as soil tension or an arbitrary numeric scale. These sensor manufacturers may provide literature to help convert their sensor values to another form of soil water content. For example, some gypsum block companies provide charts to relate their readings to percent moisture by weight. Those values, which are gravimetric percentages, need to be multiplied by the bulk density of the soil to obtain a volumetric value

Almost more important than the numerical values of the soil moisture sensors, is the graphical trend depicted in the data. The weakest utilization of information gathered from sensors is just looking at the numeric values, neglecting to record and track them. The fullest benefits from monitoring occur when readings are recorded on a periodic basis --such as once or twice a week (or better yet, continuously so with automated equipment)-- and then graphically plotted.

Figure 13.9 illustrates how the presentation method for the same soil moisture data affects the usability of the data as an irrigation decision tool. Table A, Figure A and Figure B in Figure 13.9 all represent the same data set of SMS values from a field with two stations each of four depths presented in different formats. The table of data does not capture the drift of what is happening, and the graph with multiple lines for each sensor (Fig. A) is also very confusing. The salient information that needs to be gleaned is readily seen in Figure B, where all values were averaged. Combining sensor values from four depths and two sites into a single mean value projected a good picture of what was happening in the field regarding soil moisture.

Table A. Gypsum block data from four depths and two sites on cotton irrigated with drip-irrigation with limited water in west Texas.								
	NE-1	NE-2	NE-3	NE-4	SW-1	SW-2	SW-3	SW-4
9-Jul	9.00	9.50	9.25	10.00	9.50	9.75	9.75	10.00
16-Jul	9.00	9.75	9.75	10.00	2.50	9.75	9.75	10.00
23-Jul	7.25	9.75	9.75	10.00	1.25	9.75	10.00	10.00
30-Jul	6.25	9.75	9.75	10.00	0.50	7.00	10.00	10.00
6-Aug	0.75	3.50	9.50	10.00	0.50	0.75	9.50	10.00
13-Aug	0.50	1.00	9.00	10.00	0.25	1.50	7.50	9.75
20-Aug	0.50	1.50	7.50	10.00	0.25	0.25	4.50	9.50
27-Aug	0.50	0.50	4.00	10.00	0.00	0.25	3.50	6.00
3-Sep	0.25	0.25	1.50	10.00	0.00	0.25	2.50	6.00
10-Sep	0.25	0.50	2.50	10.00	0.00	0.50	2.50	5.50
17-Sep	10.00	9.25	2.00	10.00	10.00	0.50	3.50	6.50
24-Sep	9.00	9.25	4.00	10.00	9.50	1.00	4.25	7.00
1-Oct	9.50	9.50	5.50	10.00	9.50	5.50	5.00	7.50
8-Oct	9.50	9.50	6.00	10.00	9.50	6.00	5.50	8.00
15-Oct	9.50	9.50	7.50	10.00	9.50	8.50	6.50	8.50
23-Oct	10.00	10.00	9.50	10.00	9.50	9.50	8.50	9.50



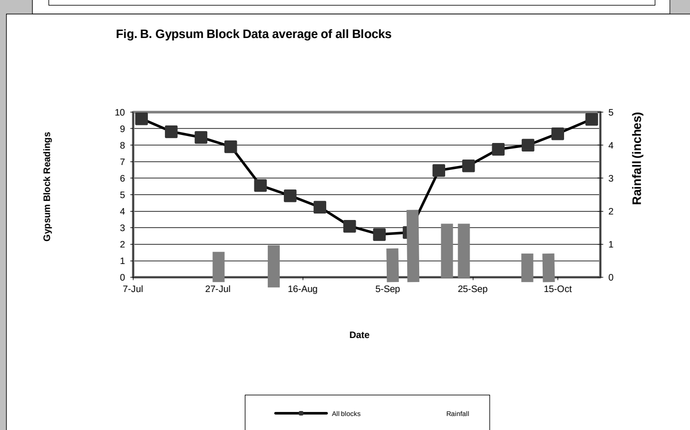


Figure 13.9. Table A, Fig. A and Fig. B all represent the same data set of eight gypsum block readings from a cotton field, but Fig. B, which averages and graphs the data from several blocks in the field is easier to use for irrigation management decisions.

Points of Interest for the Irrigator. The advent of automatic SMS data logging has given the irrigation world new insights into the soil/plant/water environment. There are three key points of interest to irrigators in graphically presented soil moisture data that has been automatically collected. All three are characterized by the graphed values beginning to change shape in some way or other. Figure 13.10 shows seasonal soil moisture readings that exhibit some of these points of interest.

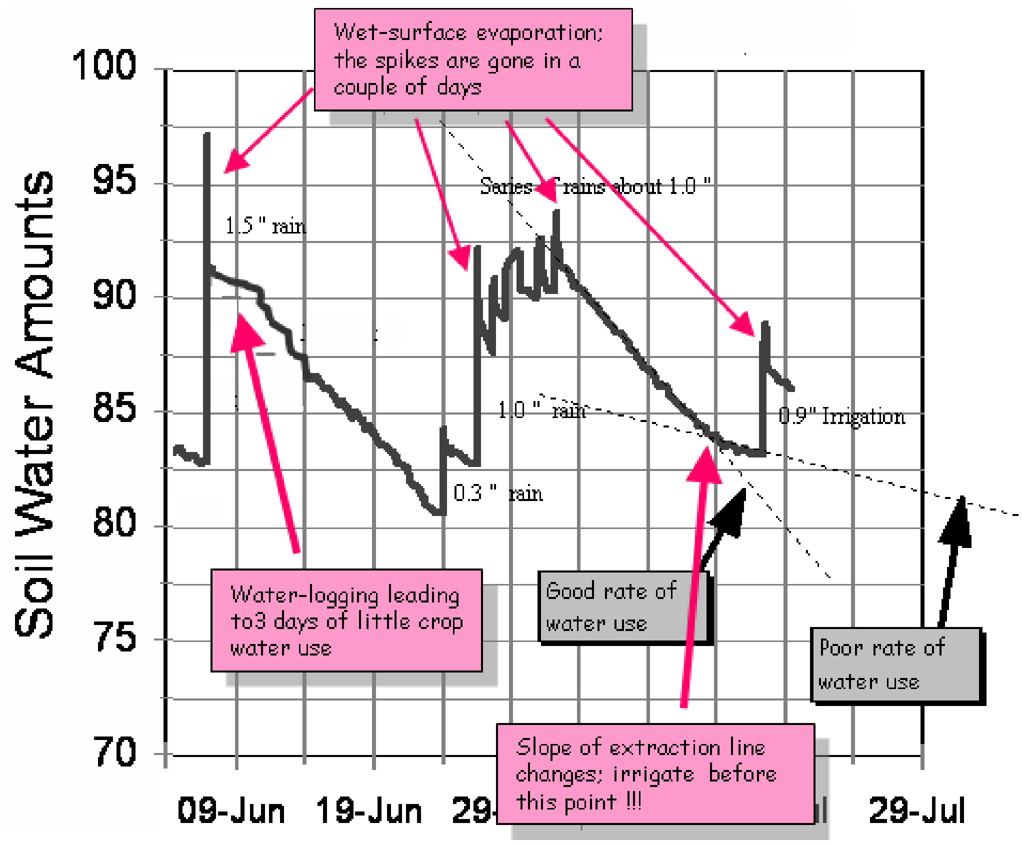


Figure 13.10. Graphical data of the average values of the 6-, 12-, and 18-inch readings on soybeans using data-logged capacitance sensors. For the period of Jul 5 to Jul 15 the extraction rate is constant indicating healthy plant-soil-environment conditions. After Jul 15 the rate of extraction has declined, indicating that the plants are being water stressed. The decline began at about a reading of 83, so future irrigations should occur before this point. The data set also shows wet-surface evaporation peaks. Note, that after the 1.5-inch rain on July 7 extraction rates declined for about four days, indicating water logging problems.

The first, and most important, one is at the point when plant stress begins to show up. After irrigation, and once the soil moisture has stabilized by draining down to field capacity, the water extraction rate is linear for a period of time. However, once the moisture content reaches a critical depletion level, the water extraction rate begins to slow down and the curve starts to flatten out. It is at this point that moisture stress beginnings to occur. The numerical value of the plotted sensor data is not nearly as important as is this shape change in the water extraction curve. When an irrigator observes that the linear extraction rate has slowed and begins to flatten (and apart from something like a cold front, herbicide burn, or other anomaly taking place), this numerical value should be noted, and in the future irrigation should be initiated prior to this point being reached. Such a trend change occurred in mid-July. An item to remember in using the visual method to trigger irrigations is that some sensors (e.g., the regular gypsum blocks and some dielectric SMS devices) are sensitive to temperature. As soil temperature increases, these sensors tend to register increases in water content. This situation would be especially prevalent in the early part of the season as the soil begins to warm up rapidly. In this case, the record of water actually being extracted is masked by the sensor registering higher values due to the soil warming up, and the timing of the first irrigation (which is very important in many crops) could be thrown off.

The second important visualizing point comes right after irrigation or a good rain. If, after rain/irrigation events, the extraction rate remains flat for a period of two or three days or more, then the field is probably subject to water logging, a case of which is seen around June 7. If s\this occurs, smaller applications may be needed for subsequent irrigations. In the next growing season, the problem can be alleviated by alternative remedies, such as deep ripping, or planting on higher beds, or using plant varieties tolerant to water logging. This decreased level in water extraction was hard to identify with hand-read sensors because by the time the field is dry enough to enter and collect the readings, the phenomenon had disappeared. Therefore, detecting it usually requires that the sensors are hooked to a data logger.

A third point of interest involves *wet surface evaporation*. This phenomenon occurs after a rain or irrigation when the soil's color is darkened (resulting in more sunlight being absorbed) and the water is standing free on the surface or only lightly held by the soil particles. Only under these conditions does the concept of *potential evapotranspiration* truly take place. The water content in the top layers of the soil drops rapidly during the next two or three days following a rain due to high levels of evaporation taking place, leaving spikes on the water content graph. As the season progresses and the canopy becomes fully established, these spikes decline in size. Being able to visualize this surface evaporation loss taking place from graphically-presented data can educate irrigators about not applying too many smaller irrigations. Again, detecting this condition requires data logging.

Remote Data Collection.

Continuous SMS data collection with data loggers can provide new insight into crop water use patterns. Another technology that has emerged over the last few years involves incorporating telemetry into automatic data logging. This technology will continue to grow as the costs for it declines. Using the guideline that a center pivot of 135 acres would have three stations of SMS sensors at three, quality telemetric systems can be installed for as little as $7-10 per acre per year! These investment costs are affordable compared to the potential benefits.

There are two main approaches to telemetrically gathered SMS data. First, the data can be sent to the users own PC. The alternative methodology is to use cell phones to send the data to a web-hosting site. In this latter instance, the farmer and anyone he designates (like a crop consultant) can have access to the data. There have been cases of time-strapped farmers being called by his consultant asking him if certain fields are not being watered. Satellite data hosting generally costs more then collecting to your own computer.

One area of cost that the new user should not scrimp on when venturing into remote sensing is on the telemetry equipment offered by the sensor company. The communication distance quoted by a manufacturer that a device can send/receive might be theoretical maximum with totally unobstructed line-of-sight, which may not exist at your location. Data communication is accomplished with senders and receivers that use either a 900 MHz or a 2.4 GHz frequency. The former cost more, but are capable of transmitting 2 or 3 times further. Also, some companies sell repeaters that help relay the data. An investment in a few additional repeaters early on may be worthwhile.

PLANT-BASED METHODS OF IRRIGATION SCHEDULING

Many measurable plant physiological traits can provide excellent insight into the plant moisture status and consequently, irrigation timing. These traits include sap flow, stem shrinkage, leaf water potential, and canopy temperature among others. Irrigators primarily use the last two methods, so discussion will be limited to them. Some discussion of stem diameter will also occur since it is a method that shows potential for the future. An important aspect concerning plant-based sensors is that all components of the plant-soil-weather complex are integrated together. For example, it is not only the ET rate that plays a role in plant water extraction, but factors, such as the presence of nematodes, salinity, herbicide burn, and compacted soil layers can all affect the extent of water transpired; this is the benefit of plant-based sensors as these other factors readily show up.

Leaf Water Potential/Pressure chamber

Leaf water potential (LWP) is the negative pressure or tension found in plant leaves. The LWP of well-watered plants is higher (i.e., less negative in value) than that of plants under water stress, thus LWP values (English units are *bars* and SI units are *megapascals* [MPa]) provide information on the moisture status of a plant. The pressure chamber, or pressure bomb as it is sometimes referred to, is a device that measures the leaf water potential of a plant. This measurement is done by detaching a leaf from the plant and inserting into a chamber with its petiole sticking out of a small hole. Gaseous nitrogen is allowed to enter the chamber increasing the pressure within the chamber. When the internal pressure of the chamber is as positive in value as the leaf and petiole are negative in tension, small water bubbles can be seen on the incised edge of the petiole, and this equilibrium pressure is recorded as the LWP value.

There is a natural diurnal change in the LWP values throughout the day as stomata open and close and the microclimate surrounding the plant changes. Values are at their most negative around solar noon, and they are least negative late in the night extending to pre-dawn. For example, stressed cotton may have LWP values of -9 bars before sunrise and -35 bars at solar noon, nearly a fourfold change in values in six hours. Thus, one problem associated with using LWP values for irrigation scheduling is that the diurnal swings could mask day-to-day changes. Therefore, only measurements during temporal baseline periods are useable. The two periods used are <u>pre-dawn</u> and <u>solar noon</u>. Additionally, if the conditions during the solar noon period are not totally cloud-free, this period becomes unreliable, leaving only pre-dawn readings.

In California, which often has cloudless summer days, researchers/irrigators have pioneered the use of the pressure chamber using solar noon measurements as the baseline period for evaluating plant water status and making irrigation decisions. The California recommendation for cotton is to initiate the first irrigation when solar noon LWP values are –15 bar and subsequent irrigations at –18 bars (Hake et al., 1996). Many fruit and nut crops have been studied to determine ideal LWP levels for irrigation initiation. Internet web sites are available that provide LWP levels to initiate irrigation for several crops. The PMS Instrument Company of Albany, OR maintains a list of simple guidelines for LWP values for various crops plus a small literature bibliography of LWP studies (http://pmsinstrument.com/).

The procedure usually involves taking readings on two separate sun-lit leaves. The leaves should be young, but fully-expanded leaves. If there is close agreement between the two values then the average value is used. If there is more than about 20% difference a third leaf is measured to get a larger sample for computing the mean. The location in the field where measurements are made should be typical. Since the pressure chamber is somewhat bulky the plants need to be close to an area that can be driven up to. Once leaves are incised, the LWP measurement must be made within 20 seconds. The time of day needs to be recorded. If pre-dawn values are used, they need to be taken before first light, as they rapidly change after the sun rises. Solar noon values can be taken in about a three-hour window starting at solar noon. The pre-dawn values are more stable since passing clouds do not affect readings, however, the draw-back with pre-dawn values are that they are infrequently used in the literature. Solar noon values are affected by many things, especially changers in solar radiation. Measurements should be made at least twice a week and results plotted. The change in values over time will be linear, so the projected date when the critical LWP value will be reached can be estimated from the shape of the plotted values.

One major drawback is that the pressure chambers are fairly expensive (about $3000 to $4000). Another problem is that chambers can only be used during certain parts of the day. LWP values from plants having odd shaped leaves, like corn, can still be taken, but the correct grommet must be used.

Canopy temperature

As plants transpire, they cool themselves and thus generally remain cooler then ambient air during the day time. If there is plenty of soil moisture, cooling readily takes place; as the soil moisture decreases transpiration also decreases, leaving the plants less able to cool themselves. This phenomenon has and continues to be researched as an irrigation scheduling tool by using fixed-place infrared (IR) thermometer sensors that continuously measure the canopy temperature. Hand-held IR sensors are available today at reasonable prices. These devices can be taken to different locations and used to spot-check canopy temperature to draw some conclusions about soil moisture conditions. However, in order to make reasonable decisions based on hand-help equipment, a large number of values, shot at the same height, angle, location with respect to the sun, etc., would be needed to obtain a good average value. Some IR devices have built-in relative humidity sensors to allow the user to develop Crop Water Stress Index (CWSI) values. CWSI values bring together differences between canopy and air temperature and vapor pressure deficit and are influenced by the moisture conditions in a plant.

While CWSI values are accurate quantifications of plant soil moisture status, the complexity involved in the procedure makes it impractical for most producers. Recent research on cardinal plant temperature thresholds at which to irrigate plants has some merit (e.g., Wanjura et al., 1992). However, many current IR instruments are simply not robust enough for on-farm use, since they require more maintenance and calibration then most farmers would be able to provide. A second problem is that full canopy has to be achieved before they can be employed, and thus early season irrigations cannot be scheduled effectively by this method. Finally, this method is dependent on cloud free conditions and will not work well for much of the Eastern U.S. and other humid regions. However, there is much research and promise in this field of study and it merits that irrigators keep abreast of improvements in this field.

Stem diameter change

As the LWP in a plant increases in suction over the course of the day, the plant stem, behaves like a soda straw sucking up a drink, and decreases in diameter as walls are pulled radially inward. Although the human eye can't detect this slight deflection, it can be measured with instrumentation. Well-watered plants will have more amounts of diurnal stem diameter change than will stressed plants. The instruments to measure this change are much simpler in nature than IR instruments, making future stem diameter sensors rugged enough for on-farm use. One problem with using stem diameter is that stems naturally increase in size during the growing season, partially obfuscating the interpretation of diurnal diameter changes. Academic research needs to be done in the future on a various crops to develop indices to use in scheduling irrigation based on stem diameter change.

CLIMATE-BASED METHODS OF IRRIGATION SCHEDULING

Climate-based methods of irrigation scheduling rely on weather information to estimate the amount of water depleted from the plant/soil system. Inevitably, during periods of the growing season, the water depleted, primarily due to plant evapotranspiration, outpaces the additions from precipitation causing soil moisture to decline. When a critical amount of water has been depleted, but prior to the plants becoming stressed, the area is irrigated to replace depleted water and the soil water reservoir is filled back up.

The general approach to climate-based methods is to maintain a running balance of current soil moisture available (or depletion/deficit relative to field capacity) to the plant by keeping track of the evapotranspiration losses and the additions from irrigation and precipitation. This procedure is analogous to maintaining the balance in a bank checking account, it is therefore commonly referred to as the "checkbook" method of scheduling. However, in lieu of currency, the checkbook is kept in units of water volume, usually inches. Climatic data serve to estimate water uptake, one of the needed entries for the checkbook.

The three important components of balancing the checkbook are (1) the water withdrawals (evapotranspiration and, to a lesser extent, deep percolation), (2) water deposits (rain and irrigation), and (3) the critical water balance level (the point at which to irrigate), referred to variously as *application amount*, *irrigation trigger point*, *irrigation deficit*[6], etc.. This amount is equivalent to the net irrigation depth of Eq. 13.1. Of these three main components, water deposits are the most straightforward to deal with. They are simply the amount of usable water added by precipitation and irrigation. Nonetheless, even this basic accounting entry may require some amount of adjustment to account for that portion of water not usable because it runs off or is lost to various irrigation inefficiencies. The water withdrawals occur via crop evapotranspiration (ET_c [estimated from current weather and growth stage of the plant]) and deep percolation. ET_c is the most dynamic part of the accounting system, changing with the weather and stage of crop growth (see Chapter 5). This changing crop water use rate is generally characterized by a seasonal crop coefficient curve, traditionally constructed using just three cardinal crop coefficient values (K_c), located at strategic junctures in the plant growth cycle. The critical amount of water left in the soil (perhaps analogous to the point where a check bounces) stays relatively constant, though it may change with rooting depth and stage of crop growth.

Today, climate-based scheduling is generally, but not always, done with a computer. It was mentioned earlier that there are seven basic steps involved in climate-based irrigation scheduling:

[6] The term *deficit* in this context should not be confused with *deficit irrigation*, which implies situations where crop water needs are not fully met with the amount of irrigation applied.

Step 1. Determine net irrigation depth at which the crop is to be irrigated at (previously discussed).

Step 2. Collect reference evapotranspiration (ET_o) data (or, alternatively, the appropriate weather data and calculate ET_o yourself).

Step 3. Determine K_c values based on crop and stage of growth (Table 5.2).

Sub-Step 3a (Optional): Modify the amount of ET_c if soil moisture is limited.

Sub-Step 3b (Optional): Separate the calculations of evaporation (E) and transpiration (T) to obtain more accuracy.

Sub-Step 3c (Optional): Adjust default K_c values to better fit local conditions.

Sub-Step 3d (Optional): Modify the time scale used.

Step 4. Calculate daily crop water use (ET_c) by multiplying ET_o and K_c data together.

Step 5. Balance the checkbook by subtracting out daily ET_c and adding effective rainfall.

Step 6. Irrigate when the soil checkbook balance equals Step 1.

Step 7. Validate irrigation scheduling with soil moisture sensors or by probing.

Steps 2 through 6 (but not Sub-Steps) are done in loop fashion throughout the season with Step 7 being done occasionally. Using local irrigation scheduling software or charts "right out of the box", the irrigator will apply water amounts closely matching crop needs. Utilizing the four mentioned Sub-Steps make the overall performance of the scheduling tool a bit more accurate or easier to use. One of the beauties of climate-based irrigation scheduling is that even if some error is present, it does not accumulate for long. Once irrigation or a big rain occurs then the slate is wiped clean and the checkbook balance starts back at zero deficit.

The first Sub-Step involves a procedure that tamps down the amount of predicted crop water use in cases where the soil moisture is limiting. Many computer programs already have this feature built in, plus, the purpose of irrigation scheduling is actually to avoid getting the soil too dry in the first place. The second Sub-Step makes water use more accurate by separating the E and T terms of ET. Few computer programs use this procedure. The third Sub-Step adjusts the default crop coefficients to better fit actual conditions by modifying K_c values and/or modifying the time involved in the crop's four main growth periods. The last Sub-Step modifies the time-scale of the seasonal crop coefficient curve (e.g., days after planting, or Heat Units, or growth stage, or percentage of season, etc.) that is used. Since the four Sub-Steps may bee helpful, but generally are not needed, further discussion of them is not included here. However, more on them can be found in four Appendices at the end of this chapter.

The definitive work on predicting crop water use with climatic data is found in the 1998 publication: *FAO Irrigation and Drainage Paper No. 56. Crop evapotranspiration (guidelines for computing crop water requirements)* (Allen et al., 1998), commonly referred to as FAO-56. It is the prime source for Chapter 5, plus a major resource for this chapter.

Climate-Based Scheduling: Overview

In basic terms, the essence of climatic-based irrigation scheduling is contained in a two-part process which involves (A) obtaining a <u>baseline measurement of the weather's energy</u> to drive evapotranspiration and (B) choosing an adjusting factor; the product of the two is equal to the water use of the crop in question. It can be mathematically expressed as:

Crop water use = Climatic baseline X Adjustment factor (13.2)

In the past, predicting crop water use was confusing since there were many ways to quantify the baseline weather energy. For each and every type of climate baseline used in Equation 13.1, a separate and distinct set of adjustment factors were needed. An analogous situation would exist if a decorator wanted to hang a series of wall lights at a specific height (crop water use amount). The carpenter set a blue chalk line on the wall 3 feet above the floor (baseline #1), while the electrician made a yellow chalk line at 4 feet (baseline #2). Since the actual desired height is 6 feet, instructions of: "blue line x 2" or "yellow line x 1.5" would both come up with the desired result of wall lights being at 6 feet. However, mixing instructions up, as in: "blue line x 1.5" or "yellow line x 2.0", would give erroneous heights.

Some of the earliest used "chalk lines" relating to weather's energy was the amount of water evaporated from a small dish, a pan , or a lake. Later methods of baseline quantification involved predicting the amount of water consumed by a full-cover crop, like alfalfa or a grass, which were referred to as "reference crops" (ET_{ref}). Researchers using reference crop ET did not actually measure the reference crop's consumption of water each day, but would instead estimate what it would be on any particular day based on the local weather conditions that day. Thus reference crops ultimately were *virtual* crops. In short, during the last half of the 20th-century, many researchers worked independently in quantifying the evaporative energy in the environment leading to a myriad of energy-quantifying baselines being developed (all needing their own specific crop coefficient chalk line). However, as the millennium came to a close, leaders in the irrigation industry sought to standardize the environmental evaporative energy component in Equation 13.2 by resorting to a single equation to estimate evapotranspiration (ET). The estimated water use rate of a well watered grass surface was chosen as the energy quantifier and has become today's standard energy reference. It is known as the *standardized ASCE-EWRI Penman-Monteith Equation* (ET_o) or sometimes as the standardized FAO Penman-Monteith Equation or just the FAO-56 Penman-Monteith (Eq. 5.3).

The water use of crops is termed *crop evapotranspiration* (ET_c) and is predicted by multiplying an adjustment factor known as a *crop coefficient* value times the ET_o, and thus the generalized Eq. 13.2 takes the form of Equation 5.41 of Chapter 5:

$$ET_c = ET_o \times K_c \qquad (5.41)$$

Step 2 of Irrigation Scheduling: *Providing ET_o Data*

In this step of irrigation scheduling the computer program (or irrigation chart) must input a daily ET_o value, or alternatively, daily weather data from which the ET_o value can be calculated. Differences in current weather conditions, such as temperature, relative humidity, sunshine, and wind speed, will effect how much water a crop uses. There are several methods to quantify the climatic energy factor.

Penman-Monteith equation

As mentioned previously, the method of choice today for calculating the weather energy baseline value is the *standardized ASCE-EWRI Penman-Monteith Equation* (Eq. 5.3. It predicts grass water use and is symbolized as ET_o. This type of equation has been referred to as a *combination equation* because it separately calculates water uptake stemming from solar radiation from that uptake stemming from advective energy (a function of temperature, wind, and the vapor pressure deficit) and combines the two values to obtain one water uptake value. It is interesting to note that Penman was a physicist by training and the equation is primarily based on physical laws of nature. The equation actually has near perfect dimensional integrity, that is, if the terms of Eq. 5.3 were multiplied out and the dimensions factored out then the resultant would be mm of water/day. In contrast, most other approaches to calculating reference ET are empirical, and were developed by numerically correlating sets of weather data to sets of reference crop water use.

The Penman-Monteith equation performs well under both humid and arid conditions. It also has the benefit of being able to calculate ET down to time intervals as small as one hour. Many other ET methods work satisfactorily only over large periods of time, such as the case of the Blaney-Criddle equation, where a month is the suggested interval.

To remove any ambiguity from the original Penman-Monteith procedure, agreed upon values have been established for certain of the crop traits that have bearing on the equation, such as crop height, the amount of light reflected from its surface (albedo), and how readily it allows crop transpiration to the air (surface resistance), thus providing the equation with the moniker *standardized*.

Previously, the complicated nature of Equation 5.3 may have dissuaded some irrigators from attempting to use climate-based irrigation scheduling. Today, however, there are many free computer programs that automatically calculate ET_o from supplied weather data. In addition, many states and agencies now post the daily calculated ET_o values obtained from weather data collected from the station networks they operate. Barring major elevation differences, ET_o data from any site within 50 or 75 miles will be sufficiently accurate enough for use. In reality, knowing the exact values of ET_o and K_c are superfluous information for the scheduler; only their product, ET_c, is required by the user. Indeed, many of the more successfully adopted irrigation scheduling programs have purposely left items like ET_o and K_c invisible within the program to keep things simple; the irrigator only deals with raw weather data, ET_c, and the current soil moisture balance.

Penman-Monteith equation (alfalfa reference*)*. The standardized FAO Penman-Monteith equation normally calculates grass reference evapotranspiration, ET_o. However, a secondary form of the Penman-Monteith methodology is also available to calculate ET using alfalfa as the reference crop (ET_r). Both reference crop procedures exist in standardized form. Much of the early work on ET came from Kimberly, Idaho which had used alfalfa as the reference for many years Because of this pioneer work, many agencies and consultants historically chose to use the alfalfa reference in their computer programs and educational work and, consequently, alfalfa based crop coefficients are often found in the literature. The daily water use rates of alfalfa are about 20-25% higher than grass rates, therefore, ET_r crop coefficient values should be about that much smaller then ET_o coefficient values. **Caveat: Be sure the reference crop coefficient values you are using are specific to your form of the reference ET equation.**

At the time of this writing, about half of the state-supported irrigation scheduling programs use alfalfa-based evapotranspiration (ET_r), and thus employ alfalfa-based coefficient values. There is no problem estimating actual crop water use employing either method, as long as the ET method and its concomitant coefficient values are employed in unison. ET_r-based coefficients may be converted to ET_o-based coefficients, and vice versa. One rule of thumb estimates alfalfa reference ET (ET_r) to be equivalent to 1.2 the grass reference ET (ET_o) value. A better estimate for this ratio (and thus a truer crop coefficient value) can be obtained with the following equation (Allen et al., 1998) that mathematically describes the ratio between alfalfa and grass reference crop coefficients:

$$K_{ratio} = 1.2 + [0.023(u_2 - 2) - 0.0023(RH_{min} - 45)] \qquad (13.3)$$

Where,

K_{ratio} = ET_r/ET_o.

u_2 = mean value for daily wind speed at 2 m height for the period in question[m/s]

RH_{min} = mean value for daily relative humidity for the period in question [%]

An example of how to convert from alfalfa-based coefficient value to a grass-based coefficient value is seen in Example 13.2.

Example 13.2
Changing Crop Coefficient Values to fit a Different Reference ET

Given:

u_2 = 1.5 m/s

RH_{min} = 58 %

Alfalfa based K_c for cotton = 0.85

What is the grass-based K_c value?

Results:

K_{ratio} = 1.2 + [0.023(1.5 -2) - 0.0023(58 -45)] = 1.2 - 0.012 - 0.030 = 1.16

Since ET_r/ET_o = 1.16 then inversely the ratio for $K_{c\text{-grass}}/K_{c\text{-alfalfa}}$ is also 1.16, and the grass-based coefficient value is 0.85 x 1.16 = 0.98.

Note: 1 mph = 0.447 m/s

When Other ET Equations May be Appropriate

Missing weather variables.

While the *standardized ASCE-EWRI Penman-Monteith Equation* (ET_o) is method of choice for calculating ET, several other methods should be discussed as they can be useful at times. One of the reasons for using alternative methods is when one or more of the four needed weather variables are missing. However, FAO-56 (Allen et al., 1998) does contain procedures for estimating missing parameters such as when humidity data is missing and minimum temperature data can be used to estimate dew point temperature from which the relative humidity can be derived or when solar data is missing and minimum and maximum temperature can be used to estimate solar radiation values. These estimated values can then be substituted in lieu of the actual data points thus allowing the *standardized ASCE-EWRI Penman-Monteith Equation* to still be calculated. It is felt by some experts that it is still better to use the *standardized ASCE-EWRI Penman-Monteith* method to calculate ET, albeit with estimated weather parameters, then other non-Penman-Monteith forms of the ET equation.

However, when weather variable substitution is not desired, several other options remain open to calculate ET. Only temperature data are required for the Hargreaves-Samani (H-S) (Hargreaves and Samani, 1982) and the Blaney-Criddle (B-C) (Blaney and Criddle, 1950) equations to be calculated. Thus, in situations where the full complement of weather data is not available, these equations can be used as reasonable substitutes. The H-S is the more accurate of the two and requires both maximum and minimum daily air temperature, whereas, the B-C requires only average daily temperature. Both the H-S and the B-C equations can be increased in their accuracy relative to the FAO Penman-Monteith equation through local calibration. Figure 13.11 shows a comparison of the H-S and B-C procedures versus the FAO Penman-Monteith method for southeast Missouri, using 5-day running averages for the growing season period (1 April to 30 September). In Missouri the Penman-Monteith values are approximately equal to 1.05 and 0.83 of ET_o calculated by the Hargreaves-Samani and the Blaney-Criddle equations, respectively. Since neither of these equations have a wind term, correlating their ET values with a wind measurement, if available, should give an even closer approximation to Penman-Monteith. When wind data is not available, and since wind run is often related to periods in the year, simply correlating results of either equation over the time scale of interest (e.g., monthly or quarterly) also increases their accuracy in approaching FAO Penman-Monteith values, as done for the California delta areas (Orang et al., 1995).

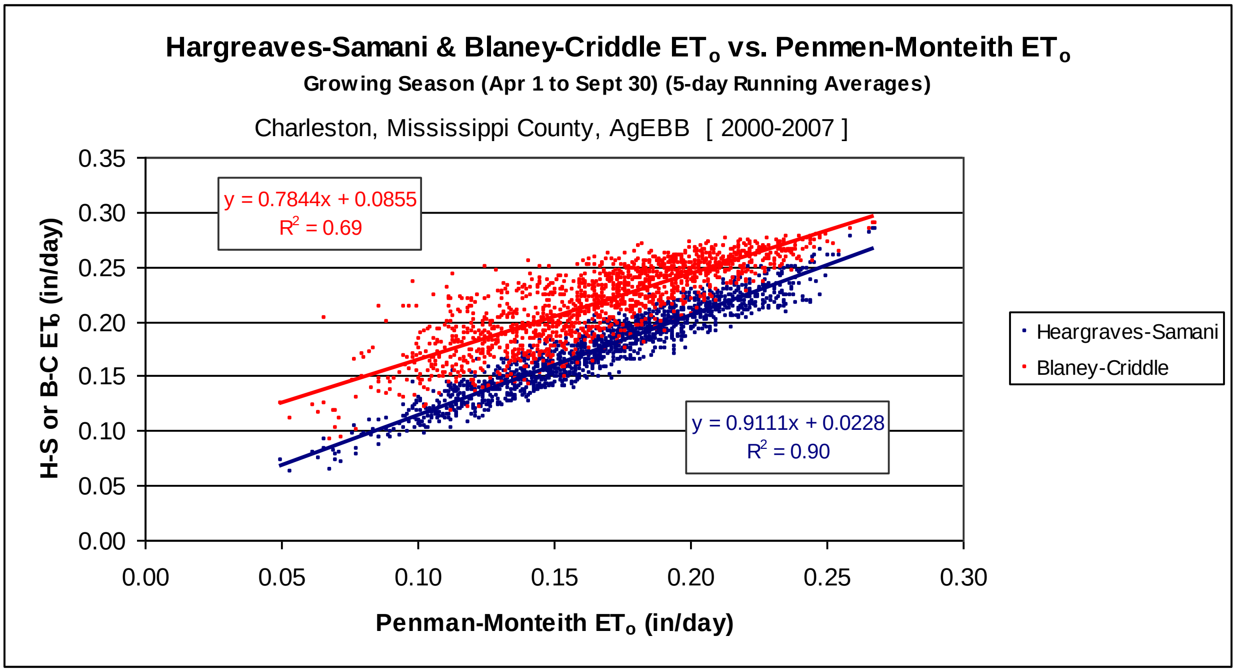


Figure 13.11. A comparison of Hargreaves-Samani and Blaney-Criddle ET equations to the FAO Penman-Monteith equation for 5-day running averages for Charleston, MO 2000-2007 for the period of 1 April to 30 September.

Several modifications to the Blaney-Criddle equation have been offered, but the original equation is:

$$u = k * t * p / 100 \qquad (13.4)$$

Where

u = water use of a warm season grass [inches/ time period]

k = crop coefficient

p = percent daylight hours for the period [%]

t = average temperature for the period [°F]

Two interesting side notes concerning the (often maligned) Blaney-Criddle equation are that the value **p**, which represents the percentage of the daylight hours in the period, becomes 1.0 for the full year making the value of the annual grass ET in inches ≈ the annual average temperature in °F. Secondly, since for any given crop (plus its location and planting date) only a single variable is missing (average temperature) tables of water use can be constructed with average temperature as the lookup variable as shown in Table 13.8.[7]

A related field of study that could benefit from temperature-based ET calculations are global warming or other climate change studies. The record of temperature goes back centuries in some locales.

[7] An additional positive aspect for arid areas concerning the B-C method is the existence of an excellent resource, *Consumptive use of water by major crops in the Southwestern United States* (Erie et al., 1982) that list B-C crop coefficient values for many crops on a bi-weekly basis.

Predicting Future Crop Water Use.

An extremely important component of any good irrigation scheduling software is the ability to estimate future water use so that target dates for the next irrigation can be given. Forecasting ten days out seems a reasonable timeframe. The irrigator can then begin laying out out the plans so that he is ready to irrigate on that predicted day. Of course, as each day passes toward the target date real weather supplants predicted weather so the accuracy gets better and better as the date approaches. Traditionally, this important prediction function was based on historic weather files. However, during periods of non-typical weather the historic data will be off in its predictions of future water use. Today, a better way to estimate upcoming water use is to use forecasted weather data from web sources, such as the National Oceanic and Atmospheric Organization and others. One of most accurately predicted of all the forecasted weather variables, plus one that has a relative long forecast window, is **temperature**. In contrast, some of the other weather variables used in ET equations are difficult to garner and/or have small windows of prediction. For example, the National Weather Service (NWS) indicates a 6-step process is required to obtain relative humidity data and the forecast window is just 48 hours (Werth, 2009). Perez et al. (2007) uses NWS predictions of cloud cover to estimate solar radiation but goes no further than a 76-hour forecast.

Since NWS includes predictions for both maximum and minimum temperature, either the H-S or the B-C method can be used to estimate future water use. Again, short-term forecasting of water use and predicted irrigation dates is pivotal in irrigation management and these temperature-based ET methods are excellent means to allow this to be done. Figure 13.12 is an irrigation work order for upcoming fields that need to be irrigated and is taken from the Arkansas Scheduler computer program.

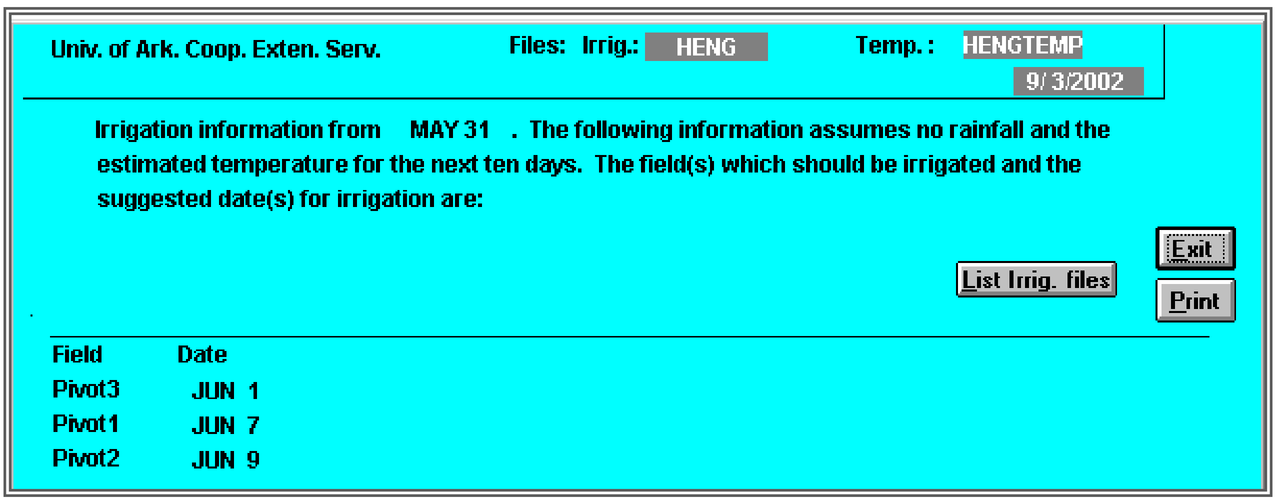


Figure 13.12. The irrigation work order page from the *Arkansas Scheduler* computer program. A key component of scheduling software is to provide the user ample forewarning of future irrigation dates.

Table 13.8. An Example Water Use Chart (in/day) Using Average Daily Temperature as the Lookup Variable and the Blaney-Criddle Equation constructed for Corn with 115 RM planted in Scott Co, MO on March 15.

	Crop:	Corn	RM:	115	County:	Scott	Plant:	15-Mar	Est. Term:	14-Aug	B-C Adjuster:	80%	
Date	15-Mar	27-Mar	9-Apr	22-Apr	4-May	17-May	30-May	11-Jun	24-Jun	7-Jul	19-Jul	1-Aug	14-Aug
% Sunlight/day	0.26%	0.28%	0.29%	0.30%	0.31%	0.31%	0.32%	0.33%	0.33%	0.33%	0.32%	0.31%	0.30%
Kc	0.730	0.781	0.836	0.926	1.029	1.131	1.170	1.170	1.170	1.170	0.961	0.688	0.500
Avg. Temp	---------- inches / day ----------												
60	0.09	0.10	0.12	0.13	0.15	0.17	0.18	0.19	0.19	0.18	0.15	0.10	0.07
61	0.09	0.11	0.12	0.14	0.15	0.17	0.18	0.19	0.19	0.19	0.15	0.10	0.07
62	0.10	0.11	0.12	0.14	0.16	0.18	0.19	0.19	0.19	0.19	0.15	0.11	0.07
63	0.10	0.11	0.12	0.14	0.16	0.18	0.19	0.20	0.20	0.19	0.15	0.11	0.08
64	0.10	0.11	0.13	0.14	0.16	0.18	0.19	0.20	0.20	0.20	0.16	0.11	0.08
65	0.10	0.11	0.13	0.15	0.16	0.18	0.20	0.20	0.20	0.20	0.16	0.11	0.08
66	0.10	0.11	0.13	0.15	0.17	0.19	0.20	0.21	0.21	0.20	0.16	0.11	0.08
67	0.10	0.12	0.13	0.15	0.17	0.19	0.20	0.21	0.21	0.20	0.16	0.11	0.08
68	0.10	0.12	0.13	0.15	0.17	0.19	0.21	0.21	0.21	0.21	0.17	0.12	0.08
69	0.11	0.12	0.14	0.15	0.18	0.20	0.21	0.22	0.21	0.21	0.17	0.12	0.08
70	0.11	0.12	0.14	0.16	0.18	0.20	0.21	0.22	0.22	0.21	0.17	0.12	0.08
71	0.11	0.12	0.14	0.16	0.18	0.20	0.22	0.22	0.22	0.22	0.17	0.12	0.09
72	0.11	0.12	0.14	0.16	0.18	0.20	0.22	0.22	0.22	0.22	0.18	0.12	0.09
73	0.11	0.13	0.14	0.16	0.19	0.21	0.22	0.23	0.23	0.22	0.18	0.12	0.09
74	0.11	0.13	0.14	0.17	0.19	0.21	0.22	0.23	0.23	0.23	0.18	0.13	0.09
75	0.11	0.13	0.15	0.17	0.19	0.21	0.23	0.23	0.23	0.23	0.18	0.13	0.09
76	0.12	0.13	0.15	0.17	0.19	0.22	0.23	0.24	0.24	0.23	0.19	0.13	0.09
77	0.12	0.13	0.15	0.17	0.20	0.22	0.23	0.24	0.24	0.23	0.19	0.13	0.09
78	0.12	0.14	0.15	0.17	0.20	0.22	0.24	0.24	0.24	0.24	0.19	0.13	0.09
79	0.12	0.14	0.15	0.18	0.20	0.22	0.24	0.25	0.25	0.24	0.19	0.14	0.10
80	0.12	0.14	0.16	0.18	0.20	0.23	0.24	0.25	0.25	0.24	0.20	0.14	0.10
81	0.12	0.14	0.16	0.18	0.21	0.23	0.25	0.25	0.25	0.25	0.20	0.14	0.10
82	0.13	0.14	0.16	0.18	0.21	0.23	0.25	0.26	0.25	0.25	0.20	0.14	0.10
83	0.13	0.14	0.16	0.19	0.21	0.24	0.25	0.26	0.26	0.25	0.20	0.14	0.10
84	0.13	0.15	0.16	0.19	0.21	0.24	0.25	0.26	0.26	0.26	0.21	0.14	0.10
85	0.13	0.15	0.17	0.19	0.22	0.24	0.26	0.26	0.26	0.26	0.21	0.15	0.10
86	0.13	0.15	0.17	0.19	0.22	0.24	0.26	0.27	0.27	0.26	0.21	0.15	0.10
87	0.13	0.15	0.17	0.19	0.22	0.25	0.26	0.27	0.27	0.27	0.21	0.15	0.11
88	0.13	0.15	0.17	0.20	0.22	0.25	0.27	0.27	0.27	0.27	0.22	0.15	0.11
89	0.14	0.15	0.17	0.20	0.23	0.25	0.27	0.28	0.28	0.27	0.22	0.15	0.11
90	0.14	0.16	0.18	0.20	0.23	0.26	0.27	0.28	0.28	0.27	0.22	0.15	0.11

(ET estimates are based on Based on of Blaney-Criddle Equation)

User's Disposition to Alternative Methods

In some locales, irrigators have become "married" to other non Penman-Monteith methods that have served them well in the past. An example are the potato growers of Wisconsin who have adopted the WISP (Wisconsin Irrigation Scheduling Program) (Curwen and Massie, 1984). The program is in both chart and spreadsheet format. The ET values used are monthly values based on the cloud cover that day (Table 13.9). Users now can get daily ET data from state-wide ET graphical maps constructed from satellite-derived measurements (a sample graphic can be seen in Example 13.4).

Table 13.9 Values for estimating evapotranspiration (after Curwen and Massie, 1984)

	----------- Evapotranspiration (inches/day) ------------------				
Climate	**May**	**June**	**July**	**Aug.**	**Sept.**
Dull, cloudy	0.12	0.15	0.15	0.12	0.09
Normal	0.15	0.20	0.20	0.15	0.12
Bright, hot	0.20	0.25	0.25	0.20	0.15

Another group that has strong roots to an alternative measure of climatic energy is the pan evaporation users.

Pan evaporation

The evaporation rate from a free water surface has been used as a weather energy baseline for many years. Examples of evaporation include pan evaporation (many types of pans exist), lake evaporation, evaporation from special dishes, and evaporation from atmometers. However, the rate of evaporation from these various sources can greatly differ. For example, the rate of lake evaporation is only about 0.75 of a Class A pan. After World War II there were many studies relating pan evaporation to crop water use, but different types of pans, installed in various ways, had been used. Therefore, the derived coefficient values from individual studies applied only to that type of pan installed in that same method. Later, the acceptance of the Class A pan as the standard helped reduce this confusion. FAO-56 (Allen et al., 1998) does provide information on converting pan evaporation data directly into ET_o data. The benefit of going to the trouble and making this conversion is that there are many more sources of ET_o-based crop coefficients then there are pan coefficients

The concept of evaporation from a pan to predict crop water use, while rainfall at the same time replenishes the same pan as it does the soil moisture reserve, is basically intuitive in nature and logical to many growers. Researchers in Georgia developed a pan with a floating pointer, which they called the UGA EASY (Evaporation-based Accumulator for Sprinkler-enhanced Yield) pan, which visually indicates when to irrigate (Thomas et al., 2009) (Fig. 13.13). The use of pan evaporation is strongest in the Midwest and Southeast regions of North America, as well as in some developing countries, and many horticulturists use pan, also.

Figure 13.13. The University of GA EASY Pan that uses a pointer (white stick) to indicate when to irrigate (red line).

Step 2 of Irrigation Scheduling: *Collecting Proper Crop Coefficients Values*

In this step of irrigation scheduling the proper crop coefficient value for the day is determined. Computer programs are set up to automatically extract this value. Charts allow a K_c value to be chosen based on stage of growth, canopy coverage, days after planting, crop appearance, etc.

The crop coefficient remains the ultimate lynchpin in accurately predicting crop water use from weather data. Crop water use, ET_c, is determined by adjusting the known/predicted value of ET_o with the proper crop coefficient value (K_c). Sometimes, $ET_c > ET_o$, which indicates that the crop in question uses more water than does the reference crop, thus the crop coefficient exceeds 1.0. When $ET_c < ET_o$, the crop coefficient value <is less than 1.0.

In consumptive use research the studied crop's rate of water use, ET_c, is empirically determined (using lysimeters, Bowen ratio studies, neutron probes, etc.). From these data, crop coefficient values are then developed by rearranging Eq. 5.41 to the form of Eq. 13.5, which is valid for periods that have not received rainfall or irrigation.

$$K_c = ET_c \div ET_o \tag{13.5}$$

Table 5.2 provides suggested K_c (used when crop transpiration and wet surface evaporation are lumped together) and K_{cb} values (used when transpiration and evaporation calculated separately) for a great number of crops.

Over the growing season, crop coefficient values for a season start out low, then increase as the canopy fills in, and then plateau out until they begin to decline with the onset of crop senescence. When plotted over the season, the changing crop coefficient values have the shape of an upside-down sauce pan. A best fit curve of the K_c values plotted over time is referred to as a *crop coefficient curve* or K_c *curve*. The actual day-to-day K_c values along the K_c curve can exhibit much bounce (as seen in Figure 5.6).

The FAO-56 procedure for using crop coefficients is outlined in Chapter 5 and it is surprisingly simple. This procedure uses three cardinal crop coefficient values centered at important growth stage junctures. These three values (plus information on length in days for the plant's four growth stages) serve as a framework over which the user is expected to develop a season-long crop coefficient curve. Computer programs have already internalized the day-by-day changes in K_c value throughout the crop coefficient curves, so the irrigator need not be concerned.

Most of the detailed discussion of "tweaking" crop coefficient values which make up the Sub-Steps is reserved for the appendices at the back of this chapter. However, brief mention will be made of regarding two points . First, the default K_c values of Table 5.2 were developed for a moderate climate that had minimum relative humidity (RH_{min}) values of 45% and wind speed values of 2 m/s (4 ½ mph) during the crop growth period in question. If your locale's humidity level and amount of wind deviate much from these amounts then the default K_c values of Table 5.2 may no longer apply. If RH_{min} values are smaller than 45% then the actual K_c value is expected to be higher. If the average wind speed values are greater than 4 ½ mph then, likewise, K_c value are expected to be higher. Also, the amount of deviation from the default K_c values increases with taller crops. Equation 5.46 can be used adjust K_c values. It can be seen that states have a variety of climatic zones, but provide just a single set of crop coefficient values for the entire state may have some under- or over-irrigation occurring.

Secondly, the most likely point for deviation to exist between FAO-56 default K_c values (Table 5.2) and adjusted values will be in the case of the initial K_c value ($K_{c\ ini}$) when the single coefficient procedure is used.[8] The reason for the possible deviation is due in large part to the *frequency of wetting events* during this period. As listed, most FAO-56 $K_{c\ ini}$ values reflect a wetting frequency of about 10 days. If wetting interval was, instead, 7 days then the $K_{c\ ini}$ values would be about 30% too low; if it were about 3 or 4 days it would be 50% too low. Figure 5.3 is a graphical solution for determining $K_{c\ ini}$ values based on soil type, ET_o, and frequency of wetting, and is an important resource. Appendix III contains monthly ET_o and rainfall intervals for several hundred cities in the US and its possessions.

Step 4 of Irrigation Scheduling: *Calculate Daily Water Use*

After obtaining each day's ET_o, and K_c values they are multiplied together to obtain ET_c for that day. In many programs a soil moisture limiting coefficient, Ks, is multiplied also. There are a variety of other types of coefficients that could be used to delimit the actual crop evaporation, such as vegetation coefficient, density factor coefficient, microclimate coefficient, etc. Most of these specialized coefficients apply to landscape irrigation (see Chapter 5 for more information).

Step 5 of Irrigation Scheduling: *Balance Checkbook*

The previously calculated daily water use values are subtracted from the current soil moisture content in checkbook fashion. The effective rainfall amounts are added to the profile amount. When the summation of daily ET_c values minus all effective rainfall amounts is equal to the ideal irrigation application amount then it is time to irrigate.

Effective Rainfall

Required irrigation can be reduced by any rainfall that soaks into the soil, called *effective rainfall*. Soil factors (e.g., texture of soil, surface conditions, and slope), farming practices (e.g., row direction, tillage, etc.), the type and stage of crop being grown, antecedent moisture conditions, and rainfall intensity all affect how much runoff will occur following a rainfall event, and thus the effectiveness of the rain. Any rainfall that percolates beneath the root zone is still considered effective rain, but is accounted for as a deep percolation loss. Note, effective rainfall has two connotations. The SCS effective rainfall equation (USDA, 1970) is a procedure meant to estimate the amount of monthly effective precipitation from historic data to design and size irrigation systems; it is a design tool, and might be better termed *reliable* or *dependable rainfall*. It was not meant as a tool to convert daily gross precipitation amounts into net precipitation amounts for use in checkbook (i.e., root zone water balance)irrigation scheduling. Historically, runoff, and thus effective

[8] The dual coefficient value K_{cb_ini} won't have this error because both E and T are calculated separately.

precipitation, has been partially neglected in irrigation scheduling protocols. The University of Nebraska's *Estimating Effective Rainfall*; (Cahoon et al., 1992) is a good management tool (as opposed to a design tool) for calculating effective rainfall. Their procedure uses SCS Soil Runoff Curves (a name whose similarity to the 1970 procedure adds to the confusion on whether it is the design tool or the management tool). The amount of error associated with inputing correct net rainfall (by not having nearby rain gages or by not correctly estimating what part was effective) may well be the weakest link in computer-based irrigation scheduling today. When irrigation scheduling is based on soil or plant sensors, estimating the effectiveness of rainfall events becomes a moot point. In the future the use of Doppler radar rain storm event reports available from the 230 or so NEXRAD facilities run by the National Weather Service may solve the problem of rain gages not being at field sites. Each pixel of a Doppler image (as currently seen on TV weather reports) represents and averages the rainfall on 1000 acres. Resolution will probably be increased and accuracy of the data will be increased as more of the NEXRAD sites convert over to phased-array radar in the future.

One very practical method to estimate the amount of effective rainfall is to just ask the local manager how much rainfall is needed to cause ditches at the field bottoms to run. Rainfall events smaller then this can be considered effective. That portion of larger rains that exceed this runoff trigger will need to be reduced using common sense. Rainfall events of less than ½ inch generally have little run off, so the majority of the rain is effective.

Step 6 of Irrigation Scheduling: *Apply the Irrigation*

Step 1 of Irrigation Scheduling (Determining Ideal Irrigation Depth) has been previously discussed and provides the net irrigation amount to be applied. If the checkbook indicates that the amount of current moisture deficit equals or exceed D_{net} then irrigation should take place. However, it is likely that this amount may need to be adjusted due to efficiency losses. Also, management concerns may exist. For example, the calculated amount of net irrigation in Step 1 may be too high and many pivot owners may not wish to apply more then 1.5 to 2.0 inches due to excessive wheel rutting and the sticking of pivots. In cases like this, two back-to-back circles could be made. For example, if 2.2 inches is the desired application amount, then two circles of 1.1 inches could be used. The net irrigation amount should be adjusted upward to account for system inefficiencies.

Accounting for System Efficiencies

Since part of the water applied by irrigation systems will be lost to inefficiencies, the net application amount (d_{net}) must be increased offsetting losses. The average application efficiency (AE) for various types of irrigation system is given in Table 13.10. These efficiency values are used to determine the gross application amount (d_{gross}), which is what should be applied. The actual application efficiency of any given irrigation system or irrigation event can vary beyond the ranges shown in Table 13.4. Environmental factors of wind and vapor pressure deficit will greatly affect the efficiencies of sprinkler and spray systems, as will sprinkler height and droplet size. For these sprinkler systems, putting out a series of catch cans and running the system over them provides information on net depth irrigation getting to the ground. On center pivot systems, caught values in cans towards the outside of the pivot have more significance since they water more area. Avoid putting cans under the first and second span as they represent only a small percentage of area (< 10%) and these spans often times have poorly matched output due to the small orifice sizes required. Chapter XX has more information about system testing. Since sprinkler application efficiencies can vary between daytime and nighttime operation, it is a good idea to perform this quick test during both periods.

The equation for calculating gross irrigation depth/amount is:

$$d_{gross} = d_{net} / AE \qquad (13.6)$$

Where,

d_{gross} = gross amount to apply, inches
AE = irrigation application system efficiency, decimal

Table 13.10. Irrigation System Application Efficiencies (after Burt et al., 2000 and Kansas CC, 2005)

Method	Efficiency Range
Surface Irrigation	
Basin	75 – 80%
Border Strip	
Sloping w/ runoff	75 – 85% [a]
Low Gradient/Blocked	80 – 90% [a]
Contour Border	70 – 80% [a]
Contour Ditch	40 – 50%
Continuous Flood	80 – 85%
Ponding	75 – 80%
Furrow	
Traditional Sloping	70 – 75% [a]
Mechanized (surge flow or cablegation)	75 – 85% [a]
Contour	65 – 75%
Corrugation	65 – 75%
Sprinkler Irrigation	
Hand-move, End-tow, Side Roll	65 – 85%
Traveling gun, boom	60 – 75%
Center pivot, linear move	75 – 90%
Impact Nozzles [b]	75%
Spray Nozzles (9 ft. above surface) [b]	85%
Spray Nozzles (4 ft. above surface) [b]	90%
Spray Nozzles (2 ft. above surface) [b]	95%
End gun [b]	55%
Solid set, side move	70 – 80%
LEPA	80 – 93%
Undertree orchard (non-overlap)	80 – 93%
Microirrigation	
Sub-surface microirrigation [b]	95 -98%

[a] with irrigation runoff recovery systems, increase by 10 - 15%
[b] data from Kansas CC (2005), all else from Burt et al. (2000).

Example 13.3 shows how gross irrigation is calculated.

Example 13.3
Calculating Gross Irrigation Depth

Net Irrigation, d_{net} : 2.0 inches

System Type: Center pivot with spray nozzles 9 ft above surface (Table 13.4)

Results:

Gross Irrigation, d_{gross} = 2.0 inches / 0.85 = 2.4 inches

Step 7 of Irrigation Scheduling: *Check the "Checkbook"*

Since the checkbook method of scheduling only estimates crop water uptake, the "balance" in the checkbook should be periodically verified by using one of the soil moisture sensors described earlier. Verification is especially important in the first year of irrigation scheduling. As time goes by, the level of verification can be decreased as the user gets more experience.

A simple alternative to installing sensors involves probing the soil with a metal rod. The act of irrigation refills the soil moisture that had previously been depleted by the crop water uptake. If the correct amount was re-applied then the wetting front of the applied water should have reached the target root depth. A metal rod (sometimes called a push rod or tile probe) can be pushed into the soil to determine the depth to which the soil is wetted to. To construct a push rod, weld a handle of about 10 inches to the end of a steel rod, 3/8ths to 5/8ths inch in diameter and about 3 or 4 feet long. The rod easily penetrates the moist soil but stops abruptly at the point where the soil becomes dry – the extent of the "wetted front." If pans are present in the soil profile, they will offer some resistance, but the rod will penetrate them, only stopping at the wet/dry interface. If the objective of irrigation scheduling is to wet down to a rooting depth of 24 inches, then a rod should easily penetrate approximately 24 inches about a day or two after irrigation is applied. If the rod probes to 24 inches, the scheduling job is well done (i.e., you have just reapplied the amount of water your crop had previously consumed.) If the depth of penetration is less then this amount, irrigation is insufficient. If the probe moves deeper then the designed depth, over-irrigation is occurring. Figure 13.14 illustrates how this simple method is used.

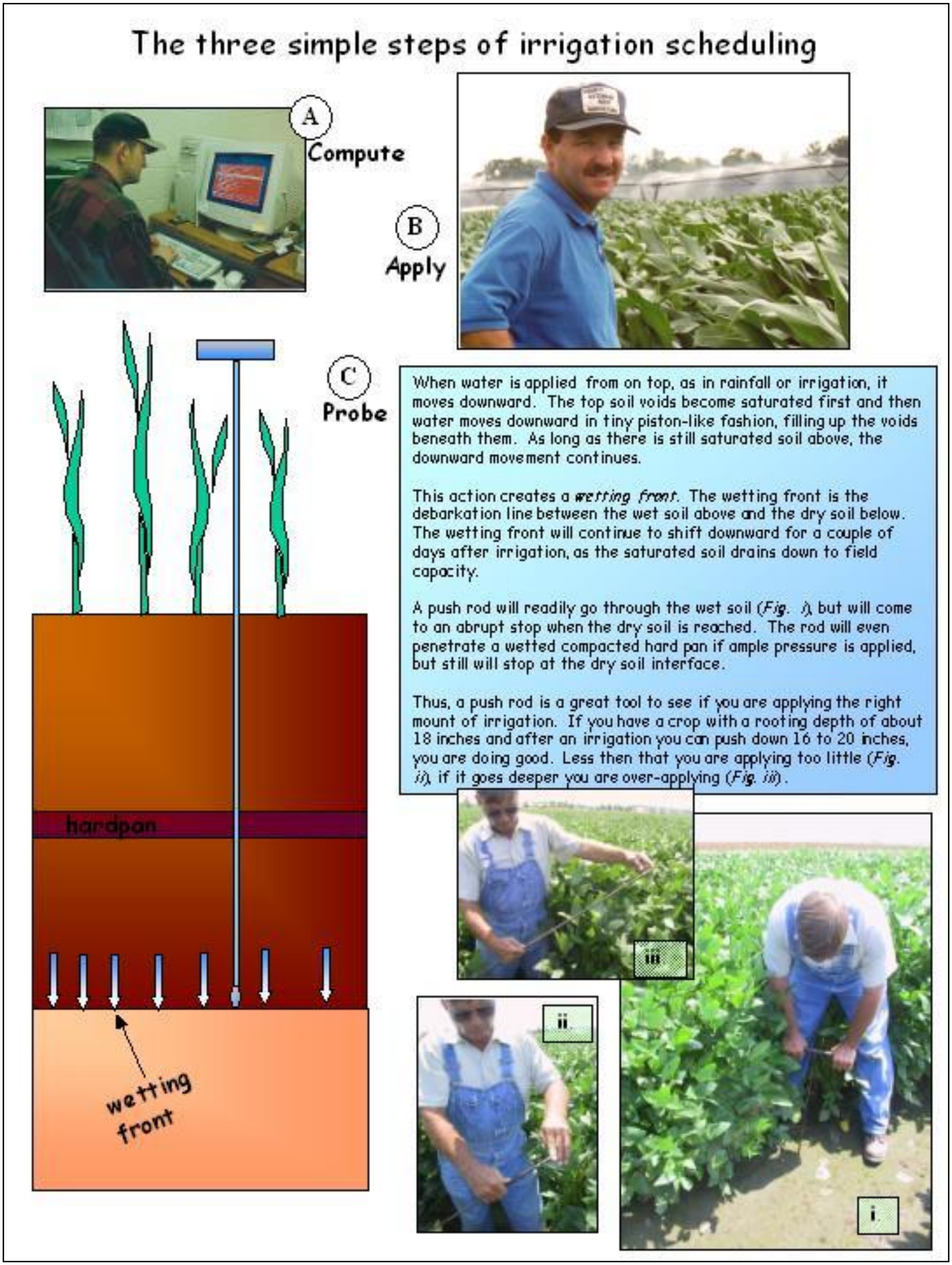


Figure 13.14. Irrigation scheduling based on weather data involves estimates of what is happening. Therefore, irrigators should verify the predicted results with the actual results. A push rod is an excellent tool to do this with.

Putting All The Steps Together

As already mentioned, many irrigation computer programs perform some of the seven steps of climate-based irrigation scheduling internally, and it is difficult to step back and get a view of how all things come together. However, a good way to view the seven steps coming together is to examine a hand-input irrigation scheduling form as shown in Example 13.4.

Example 13.4
Performing the Steps of Irrigation Scheduling

Given:
Crop: Field Corn
Location: SE Wisconsin
Date of Planting: May 1
Net Irrigation Amount = 2.0 inches (Table 13.5)

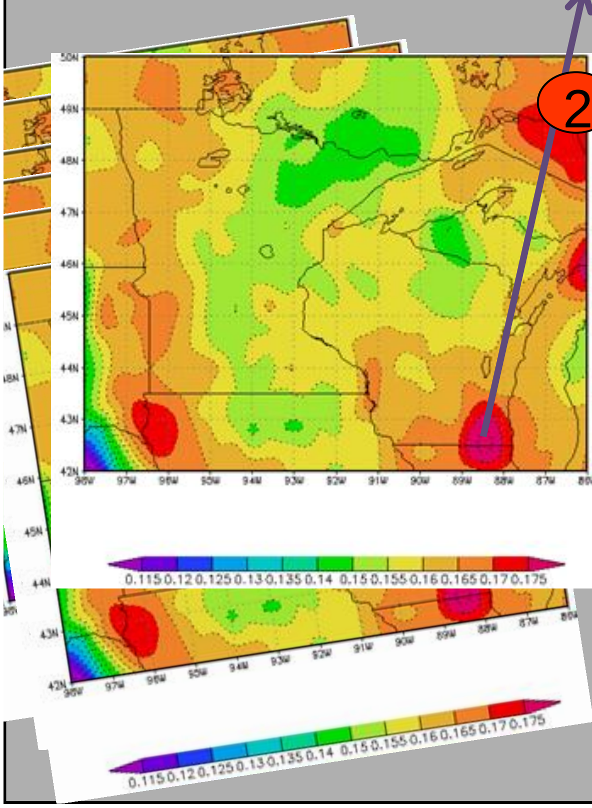
1 Decide d_{net}

4 Calculate ET_c

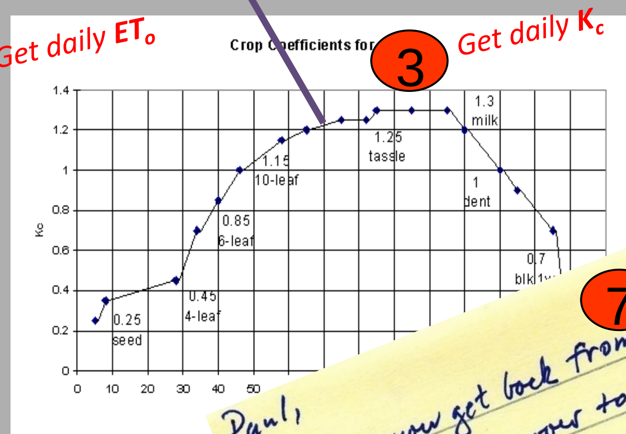
Date	DAP	Effective Rainfall	Irrigation	ET_o	Crop Stage	K_c	ET_c	Daily Balance	Soil Moisture Balance
14-Jul	74			0.24	12-leaf	1.20	0.29	-0.29	-0.87
15-Jul	75			0.25	-do-	1.20	0.30	-0.30	-1.17
16-Jul	76			0.24	-do-	1.21	0.29	-0.29	-1.46
17-Jul	77	0.23		0.18	13-leaf	1.21	0.22	0.01	-1.45
18-Jul	78			0.34	-do-	1.22	0.41	-0.41	-1.86
19-Jul	79		2.00	0.22	-do-	1.22	0.27	1.73	-0.13
20-Jul	80			0.26	14-leaf	1.22	0.32	-0.32	-0.45
21-Jul	81			0.24	-do-	1.22	0.29	-0.29	-0.74
22-Jul	82			0.23	-do-	1.23	0.28	-0.28	-1.02
23-Jul	83	0.85		0.16	-do-	1.23	0.20	0.65	-0.37
24-Jul	84			0.19	15-leaf	1.23	0.23	-0.23	-0.60
25-Jul	85			0.20	-do-	1.23	0.25	-0.25	-0.85
26-Jul	86			0.25	-do-	1.23	0.31	-0.31	-1.16
27-Jul	87			0.26	16-leaf	1.24	0.32	-0.32	-1.48
28-Jul	88			0.27	-do-	1.24	0.33	-0.33	-1.81
29-Jul	88		2.00	0.18	-do-	1.24	0.30	1.70	-0.11

6 Irrigate

5 Balance the "checkbook"

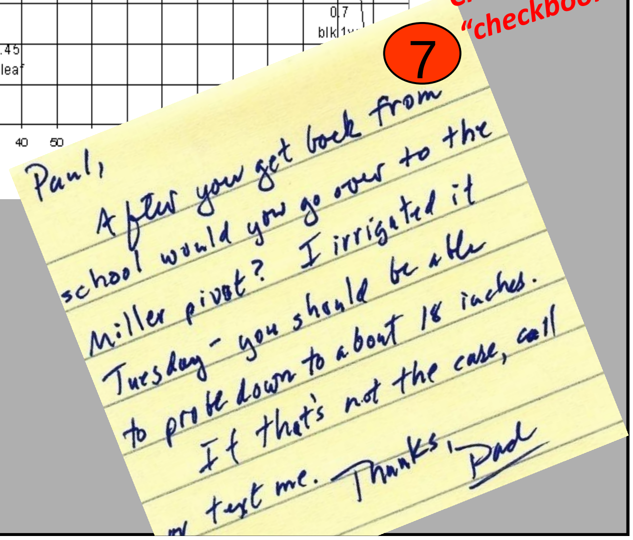


2 Get daily ET_o



3 Get daily K_c

7 Check the "checkbook"



Types of Irrigation Scheduling Tools

The Internet and other sources can be used to secure a variety of scheduling aids for the irrigator, ranging from real time weather data to full "checkbook" irrigation scheduling programs that can be downloaded to your computer. Irrigation schedule aids include:

← Fewer additional steps   More additional steps →

- DATA
  - Real-time and historic weather data (generally, in the form of tables)
  - Real-time and historic ET_o and ET_r reports (generally, in the form of tables or graphics)
  - In-season water use reports (generally, in the form of tables, graphics or radio public service announcements (PSAs)
- MANAGEMENT TOOLS
  - Computer irrigation scheduling aids (incomplete "checkbook" -water use can be calculated, but date to irrigate not determined)
  - Full-scale computer irrigation scheduling programs (full "checkbook" function) using either historic or real time weather data.

Part of human nature is that the likelihood that a product or idea will be employed diminishes as the number of steps involved in performing it increases. This altruism applies to irrigation scheduling as well. The list of scheduling aids above starts with those tools requiring more subsequent steps down to those that can schedule "right out of the box." Thus, while all these aids increase the awareness of irrigation scheduling, it is probably only those tools towards the bottom part of the list that will regularly be used by irrigators.

Weather Data

The most basic irrigation scheduling component is raw weather data. These data will be used to calculate ET_o. However, even if ET_o data are available, weather data are still important in determining other things, such as Growing Degree Days. Oftentimes growers will have more interest in using weather data in pest and disease models then they do in irrigation scheduling programs. Talking to administrators at the PAWs program in Washington State I found that it was other weather-related tools, such as frost protection, that growers wanted. However, once using those products, growers would often expand out to using their irrigation scheduling products. System administrators should keep other useful agronomic models in mind as they develop irrigation scheduling products.

ET_o and ET_r reports

One level up, but still only a basic irrigation scheduling component is the ET report. Reference ET amounts for daily, and longer periods of time, are provided on many Internet sites, both as real-time and historic averages. Maps of plotted ET estimates (seen in Example 13.4) can be a source for this information. To facilitate using reports like these for scheduling, some states provide the forms for irrigators to fill out with the appropriate coefficient values to assist in making calculations. This scheduling tool has limits in that it requires additional effort before an irrigation management decision can be made; as it stands it is not a "checkbook". Also, without accompanying documentation a user might mistake the ET form (grass or alfalfa reference) being used, and make use of the wrong set of coefficient values.

Water use reports

A still more useful tool is the water use report. In this case, the product of ET_o and K_c values is already calculated and crop water use data (ET_c) are supplied . As a program has already calculated ET_c, there is no chance of mismatching ET method with type of coefficient. Since K_c values change with stage of growth, the planting date must be inherent in the report. Thus a range of several realistic planting dates should be available for the irrigator to choose from. The time period in the report is another important parameter inherent in a water use report. One-, three-, seven-, and ten-day accumulations are typically available. Many states and water conservation districts provide this ET_c data to irrigators. Rainfall must be compensated for separately. An ET_c report in tabular form and one in graphical form is shown in figures 13.15a and 13.15b. It is interesting to note that the URL Internet site containing North Dakota's handsome graphical presentation (Fig.13.15b) has fewer "hits" than its companion URL site with the equivalent tabular data that can be cut-and-pasted into a spreadsheet. This indicates that the more the product is user-friendly, albeit more bland, the more demand it will have.

Computer irrigation scheduling aids (incomplete "checkbook")

In some cases, local public agencies have been reluctant to develop full-scale irrigation "'checkbook" computer programs for dissemination to the general public to avoid competition with private companies and crop consultants. The alternative end result from this are some very high quality water-use calculators developed as education tools, but which fall short of being a full checkbook or water budget program. The one basic component generally missing in these education tools is that a predicted date to irrigate is not provided.

Commercial Agriculture Automated Weather Station Network

Jun 16, 2001 Estimates of Evapotranspiration
(All estimates in inches or fractions of an inch)

Location: Portageville, Pemiscot County

Crop: Corn

Planting Date	Yesterday	Last 3 Days	Last 7 Days
April 1	0.31	0.83	2.07
April 7	0.31	0.82	2.07
April 21	0.30	0.81	1.98
April 30	0.30	0.80	1.94
May 7	0.28	0.78	1.88
May 15	0.26	0.76	1.80
May 21	0.24	0.70	1.77
May 30	0.22	0.65	1.57

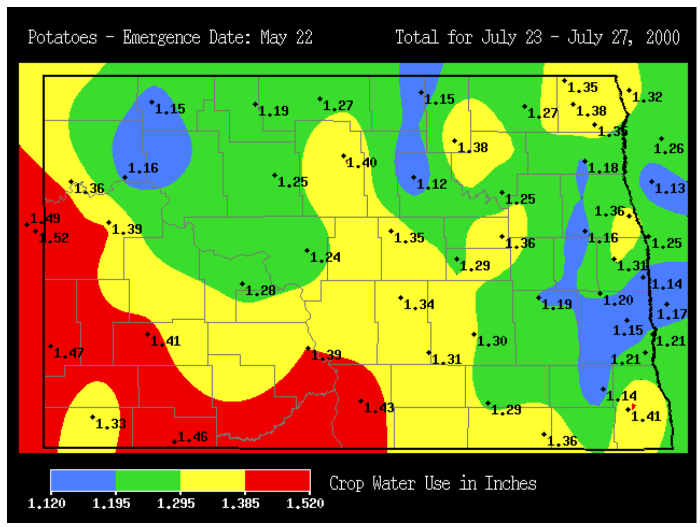


Fig. 13.15a. (left) - A water use report for corn generated daily from one of the 21 automatic weather stations operated in Missouri and Fig. 13.15b. (right) a water use report for 4-day period for potatoes that emerged May 22 for the State of North Dakota.

Computer irrigation scheduling programs (historic weather)

Using historic weather data to calculate ET_o, but allowing real time data for the one climatic variable that changes the most (i.e., rainfall), is an option for scheduling that is possible. A unique tool for scheduling is the Woodruff chart. It is different from what we generally think of as computer irrigation scheduling since the computer is only employed once at the beginning of the season when an irrigation chart is generated. After that the grower uses a pencil to plot accumulated rainfall and irrigation. The web-based program from the University of Missouri uses historical weather data to develop an accumulative water use curve for the crop based on emergence date and the weather file chosen. As the chart is being developed, the program queries the user for information on crop, soil type, and county. Choosing the county loads the 30-year average weather data for that county

The objective of the Woodruff program is to keep requirements simple. Growers do not have to enter root depth, water holding capacity or **p** to develop an irrigation depth per application. The program chooses this based on the crop and soil chosen. The Internet site constructs the appropriate graph and the user prints it off. From then on scheduling is done with a pencil. When irrigators use shallow application depths (< 1.0 inch) this method becomes impractical. Figure 13.16 shows a generated Woodruff graph. The web site at: http://agebb.missouri.edu/irrigate/woodruff/

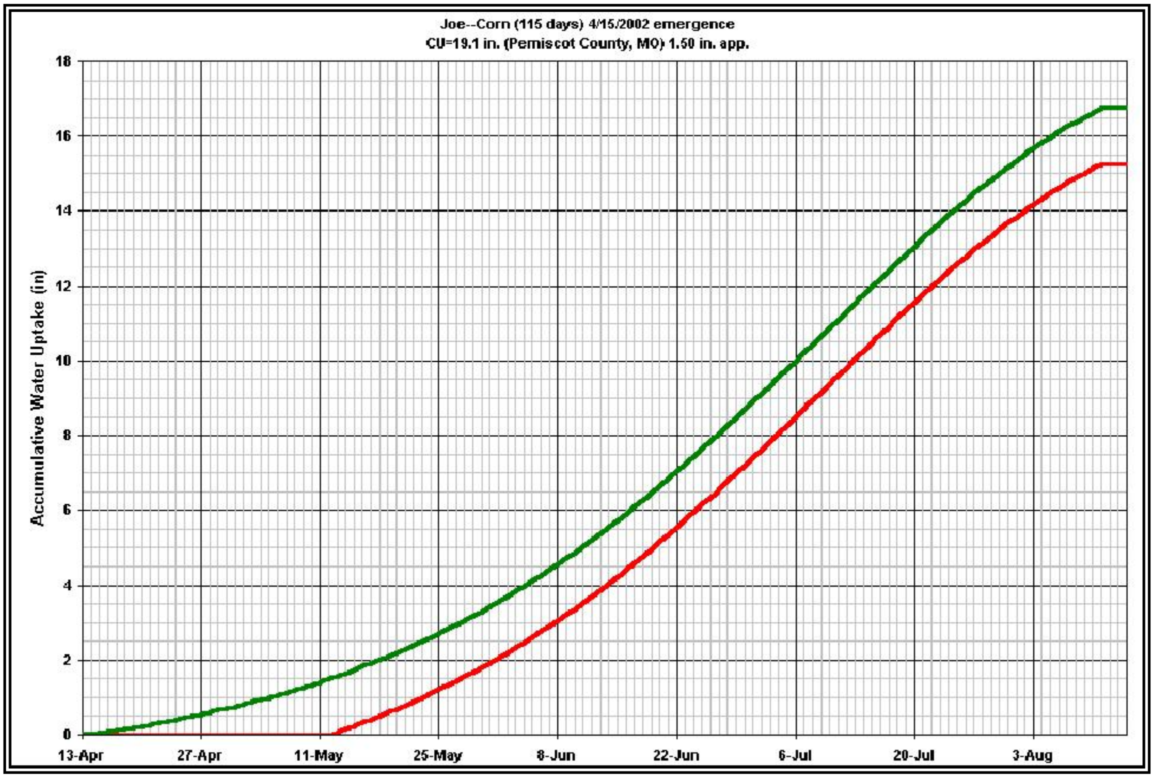


Fig. 13.16 – A customized Woodruff irrigation as it is delivered off the Internet. The green line is accumulative water use; the red line is drought region. A farmer pencils in the rains and irrigations, so as to stay between the two lines.

Computer irrigation scheduling programs (real time weather)

At the turn of the millennium, there were surprisingly few full-scale "checkbook" irrigation scheduling programs in popular circulation. This situation was probably due in part to the fact that the computer industry was changing over from DOS platforms to Windows operating systems around this time. Some existing DOS-based programs previously developed by agencies were "temporarily" shelved with the idea that when resources (mainly personnel) became available they would be re-released in Windows format

In recent years, the installation of many statewide weather station networks has rekindled an interest in agencies to develop or upgrade new generations of computer irrigation scheduling programs. Today when developing an irrigation scheduling program, many agencies choose to have the program web-based rather than having it available as a download to personal computers (PCs), since long-term management becomes a problem as different operating systems are introduced over time. A list is not provided here of the many current irrigation scheduling programs for horticultural/agricultural settings since web searches can easily locate them, except for one exception. The one exception is for the **CROPWAT,** (Smith, 1992) a decision support tool developed by the Land and Water Development Division of FAO since it is internationally supported and is built around FAO-56. This program, currently in Version 8.0, is built has access to weather databases worldwide and could serve as a computer irrigation scheduling and management program for those people who do not have regionally designed programs.

It can be found at: http://www.fao.org/nr/water/infores_databases_cropwat.html.

APPENDICES

The following four appendices include additional information they may be of interest to irrigation engineers and software designers who might be working on developing new scheduling tools. These appendices concern:

Appendix I: When soil moisture is limiting.

Appendix II: Separate the calculations of evaporation (E) and transpiration (T)

Appendix III: Adjusting default K_c values to better fit local conditions.

Appendix IV: Modifying the time scale used.

Appendix I:

When soil moisture is limiting.

K_s, Water Stress Coefficient. The crop water use equation that calculates ET_c assumes that soil moisture is adequate and the plant can readily extract water from the soil profile. While a soil has ample moisture, the plant readily removes it and normal transpiration occurs. However, when the root zone soil reservoir reaches a critically low stage the water use rate declines from what it would have normally been. Ideally, irrigation scheduling keeps crops from reaching this point because yields begin to suffer. In the cases where the soil moisture status does become limiting, the overall prediction of water uptake is improved by adding a function (K_s) to decrease the estimated normal uptake levels. At the onset of water stress, the plant is still able to draw some water, which decreases the remaining available root zone water profile for next day. Thus tomorrow's value of the stress coefficient, K_s, increases. When the plant can no longer extract soil moisture the $K_s = 0.0$. When soil moisture is not limiting then $K_s = 1.0$.

The concept of the water stress coefficient, K_s, has two benefits. The first is that it better models actual crop water uptake; without this function plotted data of soil moisture content would look different from plotted soil moisture data from sensors. Secondly, the process to predict crop yield loss is based on comparing actual water uptake that has been limited due to moisture stress to the water uptake had there been no stress. There is a large amount of research, including pioneer work by Hiler and Clark (1971) plus companion publication to FAO-56, entitled, *Yield Response to Water. Irrigation & Drainage Paper No 33* (Doorenbos and Kassam, 1979) that helps estimate yield loss due to moisture stress. FAO has developed a powerful computer version of FAO-33 called **AquaCrop** (FAO, 2009). Incorporating yield prediciton into irrigation scheduling programs as sub-routines increases the program's ability to help irrigators who may be short of water. Do I cut off water on my corn and start watering my soybeans? questions like that could be answered. The *Michiana Irrigation Scheduler* (Kelley, 2009) program has this capability.

Equation 13.12 models this decreased rate of water uptake when soil moisture is limiting ($ET_{c\ act}$) and is:

$$ET_{c\ act} = ET_o \times K_s K_c \qquad (13.12$$

Where,

$ET_{c\ act}$ = actual water use of crop during periods of stress [inches or mm/ time period]

K_s = water stress coefficient (range of 0.0 to 1.0)

When irrigation water is plentiful and crops are watered in a timely fashion, the value of K_s remains at 1.0. The purpose of "checkbook" scheduling is to avoid getting into situations where the value of K_s ever becomes much less than 1.0. Thus, for the irrigator with ample water, the primary use of the K_s term comes into play to model water extraction during pre-irrigation periods to ensure checkbook account is being correctly "balanced" or during hardening off periods at the end of the season.

Appendix II:

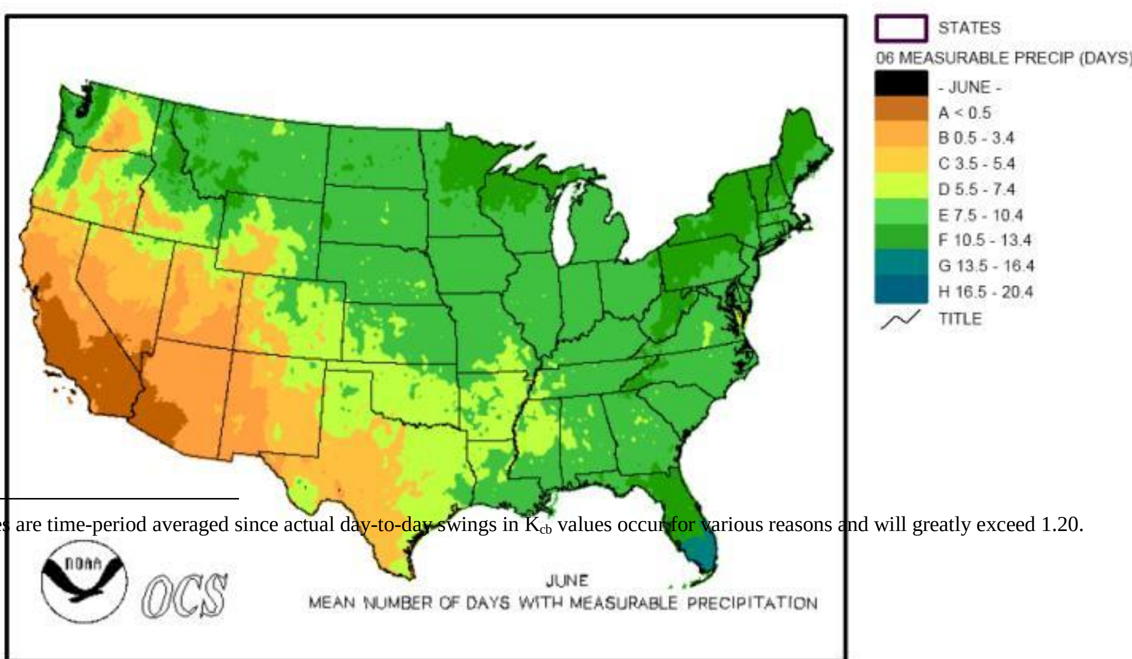
Separate the calculations of evaporation (E) and transpiration (T)

Single Coefficient values (K_c) vs Dual Coefficient Values (K_{cb}). Rain and irrigation events cause increased levels of soil evaporation to occur after each event. Anyone walking into a field soon after an irrigation or rainfall event can feel the increased evaporation being given off. This rapid water loss can occur for three or four days or more following the “wet surface” event, and must be accounted for by subtracting out this extra amount. ET equation estimates are improved when they account for wet surface evaporation. FAO-56 offers two separate approaches for this. The first one (single crop coefficient, Kc) involves calculating the total additional amount of soil evaporation that likely stems from all irrigation/rainfall events in a growing season and, thus, inflating the crop coefficient curve values enough to offset it. Predicting the total number of rainfall/irrigation occurrences and when they actually occur is, of course, impossible to do, so the single coefficient method formulates a "guess-timate" of what it will be. The other solution (*dual crop coefficient*, K_{cb}) uses the crop coefficient value set at actual ratio of ET_c / ET_o , but then separately accounts for increased wet surface evaporation, when and if it occurs. Using this strategy, the crop coefficient value specifically relates to the base amount of water transpired by the plant and thus is called the *basal crop coefficient* (K_{cb}). This method requires two coefficients (one for plant transpiration and one for evaporation) thus making it known as the *dual crop coefficient* approach. This approach uses Equation 5.43. A need for enhanced soil water bookkeeping in the top layer of soil to properly is required so a computer is necessary. Surprisingly, most computer scheduling programs today do not allow the dual crop coefficient approach to be used.

Ultimately, the type of crop coefficient used (i.e., single or dual coefficients) is dictated by what your computer program supports. The normal range of K_c values is from 0.30 to 1.20, whereas, the normal range of K_{cb} values is from 0.15 to 1.15[9].

Although the dual crop coefficient approach (K_{cb}) is slightly more involved then the single crop coefficient method, it has the benefit of quantifying actual amounts of applied water lost as evaporation. Evaporation, an important component of ET, is influenced by many factors, such as soil type, percent of area wetted, and canopy coverage. It is especially high early in the season before canopies are fully formed. People generally do not realize how frequently surface wetting occurs during the season and underestimate the impact of surface evaporation. Figure 13.18 shows the average number of rainfall events in the United States of 0.01 inches or more for the month of June; nearly 2/3rds of the country had ten precipitation events or more.

Single coefficient values (K_c) must always be used in situations where water use reports are generated for distribution by newspapers, radio and TV since no particular data is obtainable regarding when and where rainfall or irrigation events will occur in the region.



[9] These K_{cb} values are time-period averaged since actual day-to-day swings in K_{cb} values occur for various reasons and will greatly exceed 1.20.

Fig. 13.18. The number of days in June when a rainfall event of more thean 0.01 inches occurred.

Appendix III:

Adjusting default growth stage lengths and K_c values to develop a new crop coefficient curve that better fits local conditions.

FAO-56 and Chapter 5 are excellent resources that provide default values for many crop coefficients, as well as guidance in estimating the component length of time for the various stages of the growing season. Both of these items are used to develop a seasonal crop coefficient curve. The amplitude of the K_c values (i.e., how big or small they are) affect the vertical nature of the curve, while the time periods affect the horizontal nature of the curve. A crop coefficient curve can be made to better fit local conditions by adjusting one or both of these items. These adjustment are:

a. Changing the length of time for default growth stages (Table 5.5)
b. Increasing/decreasing the three default cardinal crop coefficient values (Table 5.2).

The crop coefficient curves are developed around just three crop coefficient values, located at three strategic points in the growing season. These coefficients are (a) Initial, (b) Mid-Season, and (c) End of Season. They are abbreviated as:

	Single coefficient	Dual coefficients
1.	K_{c_ini}	K_{cb_ini}
2.	K_{c_mid}	K_{cb_mid}
3.	K_{c_end}	K_{cb_end}

Adjusting these coefficient values changes the vertical nature of the curve.

Additionally, the growing season is broken into four periods and the unit length of time for these periods is days. Changing the length of any of these periods affects a horizontal shift in the crop coefficient curve. These four periods are:

1. Initial (prior to planting to 10% of canopy coverage).
2. Crop development (from 10% through about 70-80% coverage, corresponding to a Leaf Area Index of 3.0).
3. Mid-season (70-80% cover until start of maturity when leaves begin to show aging).
4. Late season (maturity to full senescence or crop harvest).

Figure 13.19 shows the four-period, three-coefficient approach of building a crop coefficient curve, and illustrates places where it can be adjusted. K_c values can be adjusted up or down from default values to better fit local climatic conditions. While K_c values are used in Figure 13.19, the same approach is applicable to K_{cb} values, except that the K_{cb_ini} is non adjustable.

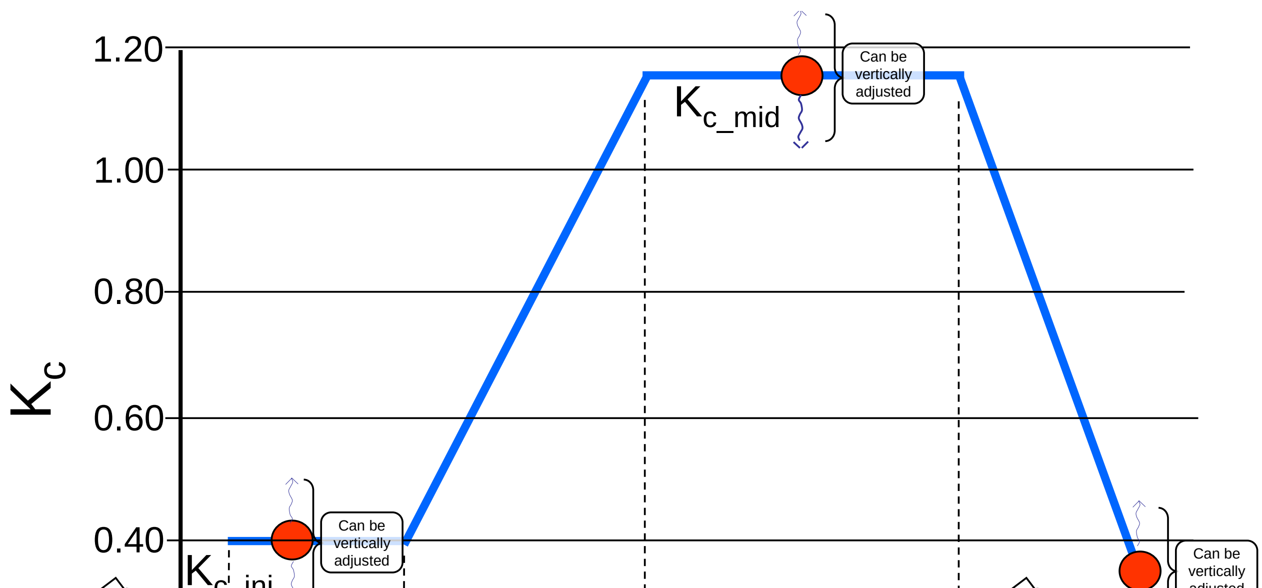


Fig. 13.19. A constructed crop coefficient (K_c) curve for a dry bean crop using growth stage lengths of 20, 26, 34 and 20 % of the season for the initial, crop development, mid-season, and late-season periods, respectively. Since the grower knows emergence date and probable plant senescence, these are considered "known points".

Making Horizontal Adjustments. The length of time for the four growth stage periods for crops can be found in Table 5.5. There are generally reports from two or three or more studies. However, the time periods for the given examples might not correspond to your local conditions. You may adjust the time scale of perennial crops to better fit your local crop and situation. The procedure is:

1) Determine the season length in days at your locale/planting date.
2) Average the length of times from the various studies in Table 5.5 and convert number of days into percentage of total season.
3) Multiply your total season length by the growth stage percentage to get new days per growth stage.
4) Apply some intuitive adjusting as necessary.

Season Length. It is important in irrigation scheduling programs to be able to have a projected season length that is close to reality. Since the planting date is known then the one unknown variable in calculating season length is the date when the crop terminates. Many times a farmer will have a good estimate of when that occurs and so season length can be determined. The total season length for soybeans can be estimated by Equation 13.13 which uses soybean Maturity Group and latitude in the calculation (Henggeler, 2004b). The total season length for corn of various relative maturities (RM) can be estimated by Equation 13.14 that is given in corn Heat Units (HU) until black layer (Henggeler, 2004b). The season length in days would then have to be extrapolated from HU weather files.

$$L = -(0.71 \times DOY) + (0.0015 \times DOY^2) + (0.92 \times Lat) + (9.1 \times MG) + 127.6 \qquad \text{Eq. 13.13}$$

where L = the season length of soybeans [days]
DOY = numerical day of year of planting
Lat = latitude of location {degrees]
MG = Maturity Group of soybean variety

$$HU_{bl} = -(0.0063 \times RM^3) + (2.20742 \times RM^2) - (204.17 \times RM) + 8407.5$$ Eq. 13.14

where HU_{bl} = cumulated HUs (86◦F limit on maximum temperature and 50◦F-base) to black layer
RM = seed company rating system for hybrid season length

Example 13.5
Calculating Adjusted Lengths for Plant Growth Stages

Given:

Crop = Soybeans; MG = Group V
Latitude = 28.5º
Planting date: May 20 (DOY = 140)
Row Spacing = 7 1/2 inches (drilled)

Find:
Adjusted lengths for growth periods

Procedures:

First: Find the length of the season with Eq.13.8

$$L = -(0.71 \times DOY) + (0.0015 \times DOY^2) + (0.92 \times Lat) + (9.1 \times MG) + 127.6$$

$$L = -(0.71 \times 140) + (0.0015 \times 140^2) + (0.92 \times 28.5) + (9.1 \times 5) + 127.6$$ = **129 days**

Second: Use Table 5.2 to gets periods lengths from research; average the time for each period in days and then calculate it as a percentage value.

Length of development stages for various planting dates/ climatic regions (from Table 5.2)

Crop	Init.	Dev.	Mid	Late	Total	Plant Date	Region
Soybean	------------------------ days ----------------------------						
	15	15	40	15	85	Dec	Tropics
	20	35	60	25	140	May	Central USA
	15	25	75	30	150	Jun	Japan

	Init.	Dev.	Mid	Late	Total
Average	17	25	58	33	125
%	**13%**	**20%**	**47%**	**19%**	

Third: Prorate the percentage values of the growth periods to the new season length.

Init.	Dev.	Mid	Late

Making Vertical Adjustments. The published default estimates for K_c and K_{cb} in FAO-56 and Table 5.2 were developed for conditions having a sub-humid climate with average daily minimum relative humidity values of 45% and average daily wind speeds of about 4 ½ mph. The K_{c_ini} values of Table 5.2 appears to have been developed for conditions of moderate ETo (≈ 4 mm/d) and wetting interval of about 10 days. If local weather conditions deviate from these parameters during the various growth stages then they can readily be fine-tuned to help develop a regionalized crop coefficient curve as illustrated in Figure 13.19. Chapter 5 explains this procedure. Table 13.13 shows the factors that influence adjustment of default FAO-56 single and dual crop coefficient values and their Chapter 5 resource.

The crop coefficient for the initial period, K_{c_ini}, is the coefficient that has the most room for error between FAO-56 default value and actual value. Climatic adjustment on the Mid- and End of Season coefficients create little change, maybe 5%, or 10% at the most. The K_{c_ini} values for various field crops in Table 5.2 ranges around 0.3 to 0.4. When there are a significant number of rain or irrigation events this value could be off by as much as 100%. Examining data from Missouri shows that K_{c_ini} values needed to be doubled in many cases. **For this reason the authors of FAO-56 emphasize that before accepting a default value for K_{c_ini} evaluate your initial period values by using Figure 5.3.**

Table 13.13. FAO-56 crop coefficients and factors influencing adjustment of default values

Form of Crop Coefficient	**Crop Coefficient**		
	Initial	**Mid-Season**	**End of Season**
Single, K_c	~ ETo ~ frequency of wetting events ~ soil type/application depth Resource: Fig. 5.3.	~ wind greater than 4 1/2 mph ~ RH_{min} < 45% ~ plant height Resource: Eq. 5.46.	~ wind greater than 4 1/2 mph ~ RH_{min} < 45% ~ plant height ~ end of season conditions Resource: Eq. 5.46.

Dual or Basal, K_{cb}	Does not need adjustment	~ wind greater than 4 1/2 mph ~ RH_{min} < 45% ~ plant height Resource: Eq. 5.46.	~ wind greater than 4 1/2 mph ~ RH_{min} < 45% ~ plant height ~ end of season conditions Resource: Eq. 5.46.

Although both Figure 5.3 and Equation 5.46 are straight forward to use, collecting the required input data for the appropriate period of time can be sometimes challenging. Especially challenging is obtaining the frequency of wetting events. To obtain this data one would to need to look at several years of rainfall patterns. In addition, wetting events on two or more consecutive days is considered just one single wetting event, so weather files need to be gone over by hand. To assist users Table 13.14 lists frequency of rainfall events by month (contiguous rainfall days accounted for) for nearly 300 cities in the US and her possessions. Table 13.15 lists monthly ET_o (developed from Hargreaves-Samani equation) for the same. Using data from these two tables plus Figure 5.3 will allow K_{c_ini} to be readily adjusted.

Table 13.16 lists the calculated amount of adjustment using Eq. 5.45 (adj_{clim}) that needs to be added or subtracted from the FAO-56 default K_{c_mid} and K_{c_end} values based on a plant height of 2 feet. An inset table in Table 13.16 gives a height adjustment factor (adj_h) that is multiplied by adj_{clim} to compensate for plant heights other than 2 feet.

Table 15.13 & 15.14 & Example 15.5.

Table 13. 16. Factor to be Added to Default Table Mid and End Crop Coefficients of FAO-56 to Account for Wind Speed other then 2.0 m/s and RH_{min} other then 45% -- Based on Plant Height of 2.0 feet. Adjust heights other than 2.0 feet by inset table below.

Plant Height (ft)	0.5	1	2	3	4	5	6	7	8
Height Adjustment Factor (adj_h):	0.66	0.81	1.00	1.13	1.23	1.32	1.39	1.46	1.52

LOCATION	Wind Data * YRS	RH Data * YRS	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
BIRMINGHAM AP,AL	**63**	**43**	**-0.01**	**0.00**	**0.02**	**0.01**	**-0.02**	**-0.02**	**-0.03**	**-0.03**	**-0.03**	**-0.02**	**-0.01**	**-0.01**
HUNTSVILLE, AL	39	39	-0.01	0.01	0.02	0.02	0.00	-0.02	-0.04	-0.04	-0.02	-0.01	-0.01	-0.01
MOBILE, AL	58	44	0.01	0.02	0.03	0.03	0.00	-0.01	-0.03	-0.03	-0.02	0.00	0.00	0.00
MONTGOMERY, AL	62	43	-0.02	0.00	0.01	-0.01	-0.02	-0.03	-0.04	-0.04	-0.03	-0.03	-0.02	-0.02
ANCHORAGE, AK	53	53	-0.05	-0.03	0.00	0.01	0.03	0.02	-0.01	-0.02	-0.02	-0.03	-0.05	-0.06
ANNETTE, AK	42	41	0.00	0.01	0.01	0.01	0.00	-0.01	-0.03	-0.03	-0.03	-0.01	-0.01	-0.01
BARROW, AK	73	55	0.02	0.02	0.02	0.01	-0.01	-0.02	-0.01	-0.01	0.00	0.00	0.00	0.01
BETHEL, AK	48	56	0.03	0.04	0.03	0.03	0.04	0.04	0.01	0.01	0.01	0.01	0.01	0.02
BETTLES,AK	31	56	-0.04	-0.03	-0.01	0.00	0.02	0.02	0.00	-0.02	-0.02	-0.05	-0.05	-0.05
BIG DELTA,AK	30	47	0.03	0.03	0.03	0.05	0.06	0.03	0.01	0.01	0.02	-0.01	0.00	0.01
COLD BAY,AK	51	37	0.05	0.06	0.06	0.07	0.06	0.05	0.03	0.04	0.05	0.06	0.06	0.05
FAIRBANKS, AK	55	54	-0.08	-0.06	-0.01	0.03	0.05	0.04	0.01	-0.01	-0.01	-0.05	-0.08	-0.09
GULKANA,AK	18	54	-0.07	-0.05	0.00	0.04	0.06	0.05	0.03	0.03	0.01	-0.03	-0.08	-0.08
HOMER, AK	32	57	-0.04	-0.03	-0.01	0.00	0.00	-0.01	-0.03	-0.04	-0.03	-0.02	-0.03	-0.04
JUNEAU, AK	61	40	-0.04	-0.02	-0.01	0.01	0.01	0.00	-0.02	-0.03	-0.03	-0.02	-0.04	-0.04
KING SALMON, AK	51	58	-0.01	0.01	0.02	0.03	0.04	0.03	0.01	0.01	0.01	0.01	-0.01	-0.02
KODIAK, AK	53	59	0.02	0.02	0.03	0.02	0.00	-0.02	-0.04	-0.03	-0.01	0.02	0.02	0.02
KOTZEBUE, AK	60	43	0.03	0.02	0.02	0.01	-0.01	0.01	0.01	0.01	0.03	0.02	0.03	0.02
MCGRATH, AK	56	52	-0.08	-0.05	-0.01	0.01	0.03	0.02	-0.01	-0.03	-0.02	-0.05	-0.09	-0.09
NOME, AK	59	43	0.00	0.01	0.00	-0.01	-0.01	-0.01	-0.02	-0.02	0.01	0.00	0.00	-0.01
ST. PAUL ISLAND, AK	32	28	0.08	0.07	0.06	0.05	0.03	0.00	-0.02	-0.01	0.03	0.06	0.09	0.08
TALKEETNA, AK	23	55	-0.04	-0.04	-0.02	-0.01	-0.01	-0.01	-0.04	-0.06	-0.06	-0.06	-0.06	-0.06
VALDEZ, AK	25	33	-0.03	-0.03	-0.02	-0.03	-0.02	-0.03	-0.06	-0.07	-0.07	-0.04	-0.03	-0.05
YAKUTAT, AK	58	42	-0.06	-0.05	-0.03	-0.03	-0.03	-0.04	-0.06	-0.06	-0.05	-0.05	-0.06	-0.06
FLAGSTAFF, AZ	39	49	0.01	0.02	0.04	0.07	0.08	0.09	0.03	0.01	0.03	0.04	0.03	0.01
PHOENIX, AZ	61	46	0.04	0.06	0.08	0.10	0.11	0.11	0.09	0.08	0.08	0.07	0.06	0.04
TUCSON, AZ	61	66	0.07	0.08	0.10	0.12	0.13	0.13	0.09	0.07	0.09	0.09	0.08	0.07
WINSLOW, AZ	46	29	0.03	0.08	0.11	0.14	0.14	0.14	0.10	0.08	0.08	0.08	0.06	0.02
YUMA, AZ	28	14	0.07	0.08	0.10	0.11	0.12	0.12	0.11	0.10	0.08	0.08	0.07	0.06
FORT SMITH, AR	61	42	-0.01	0.00	0.02	0.02	-0.01	-0.02	-0.02	-0.02	-0.02	-0.01	-0.01	-0.01
LITTLE ROCK, AR	64	42	-0.01	0.00	0.02	0.01	-0.01	-0.01	-0.02	-0.02	-0.02	-0.01	0.00	-0.01
BAKERSFIELD, CA	54	30	-0.04	0.00	0.02	0.06	0.08	0.09	0.09	0.08	0.06	0.04	-0.01	-0.03
FRESNO, CA	57	43	-0.05	-0.01	0.02	0.06	0.09	0.10	0.09	0.08	0.06	0.04	-0.02	-0.05
LONG BEACH, CA	37	36	-0.01	-0.01	0.00	0.02	0.00	0.00	0.00	0.00	0.00	-0.01	-0.01	-0.01
LOS ANGELES AP, CA	58	47	-0.02	-0.01	-0.01	0.00	-0.01	-0.02	-0.02	-0.02	-0.02	-0.03	-0.02	-0.01
LOS ANGELES C.O., CA	32	47	0.00	0.00	0.00	-0.01	-0.01	-0.02	-0.02	-0.02	-0.01	-0.02	0.01	0.01
MOUNT SHASTA, CA	3	13	-0.05	-0.03	0.00	0.02	0.03	0.03	0.04	0.04	0.03	-0.01	-0.03	-0.04
REDDING, CA	20	20	-0.03	0.01	0.03	0.04	0.06	0.08	0.08	0.08	0.08	0.05	0.00	-0.01
SACRAMENTO, CA	56	20	-0.04	-0.01	0.03	0.05	0.07	0.09	0.09	0.08	0.07	0.04	-0.01	-0.03
SAN DIEGO, CA	66	46	-0.02	-0.01	0.00	0.00	-0.01	-0.02	-0.02	-0.02	-0.02	-0.03	-0.02	-0.02
SAN FRANCISCO AP, CA	79	47	-0.03	-0.01	0.02	0.05	0.06	0.07	0.06	0.05	0.04	0.02	-0.01	-0.03

SAN FRANCISCO C.O., CA	28	8	-0.02	-0.01	0.00	0.02	0.01	0.03	0.02	0.02	0.02	0.01	0.00	0.00
SANTA BARBARA, CA	35	7	-0.02	-0.02	-0.01	0.00	-0.02	-0.02	-0.02	-0.03	-0.03	-0.03	-0.02	-0.03
SANTA MARIA, CA	26	30	-0.02	-0.01	-0.01	0.00	0.00	0.00	-0.02	-0.02	-0.03	-0.03	-0.02	-0.02
STOCKTON, CA	46	30	-0.04	-0.01	0.02	0.05	0.08	0.09	0.09	0.08	0.06	0.04	-0.01	-0.04
ALAMOSA, CO	15	49	-0.01	0.02	0.07	0.10	0.10	0.10	0.05	0.04	0.06	0.05	0.01	-0.02
COLORADO SPRINGS, CO	58	46	0.05	0.07	0.09	0.10	0.09	0.09	0.07	0.06	0.07	0.08	0.06	0.05
DENVER, CO	50	38	0.04	0.05	0.07	0.09	0.07	0.08	0.07	0.07	0.07	0.06	0.03	0.03
GRAND JUNCTION, CO	60	43	-0.03	0.02	0.07	0.10	0.11	0.12	0.11	0.10	0.10	0.07	0.02	-0.02
PUEBLO, CO	51	27	0.03	0.06	0.09	0.10	0.09	0.10	0.08	0.06	0.07	0.06	0.03	0.02
BRIDGEPORT, CT	34	40	0.05	0.06	0.07	0.06	0.04	0.02	0.01	0.01	0.02	0.04	0.04	0.04
HARTFORD, CT	52	47	0.02	0.03	0.05	0.06	0.04	0.02	0.02	0.01	0.01	0.02	0.02	0.01
WILMINGTON, DE	58	59	0.02	0.04	0.05	0.05	0.03	0.02	0.01	0.01	0.01	0.02	0.03	0.02
WASHINGTON DULLES AP, D.C.	44	37	0.01	0.02	0.03	0.04	0.01	0.00	-0.01	-0.01	-0.01	0.00	0.01	0.01
WASHINGTON NAT'L AP, D.C.	58	46	0.04	0.05	0.06	0.06	0.04	0.03	0.02	0.02	0.02	0.02	0.03	0.03
APALACHICOLA, FL	54	42	-0.01	0.00	0.00	0.00	-0.01	-0.03	-0.04	-0.05	-0.02	0.00	-0.01	-0.02
DAYTONA BEACH, FL	61	62	0.02	0.03	0.03	0.03	0.02	-0.01	-0.02	-0.02	-0.01	0.01	0.01	0.01
FORT MYERS, FL	61	62	0.02	0.03	0.04	0.04	0.03	0.00	-0.01	-0.01	-0.01	0.02	0.01	0.01
GAINESVILLE, FL	23	23	-0.01	0.00	0.02	0.02	0.01	-0.01	-0.02	-0.03	-0.03	-0.02	-0.01	-0.02
JACKSONVILLE, FL	57	70	0.01	0.03	0.04	0.04	0.03	0.01	0.00	-0.01	-0.01	0.00	0.01	0.00
KEY WEST, FL	53	58	0.02	0.03	0.03	0.04	0.02	0.00	0.00	0.00	0.00	0.01	0.02	0.02
MIAMI, FL	57	42	0.02	0.03	0.04	0.04	0.02	-0.01	-0.01	-0.01	-0.01	0.01	0.02	0.01
ORLANDO, FL	58	43	0.02	0.04	0.05	0.05	0.04	0.01	0.00	-0.01	0.00	0.02	0.02	0.01
PENSACOLA, FL	42	43	0.00	0.01	0.01	0.01	0.00	-0.01	-0.03	-0.03	-0.01	0.00	0.00	0.00
TALLAHASSEE, FL	45	45	-0.01	0.01	0.02	0.02	0.01	-0.01	-0.03	-0.03	-0.02	0.00	-0.01	-0.01
TAMPA, FL	60	43	0.01	0.02	0.03	0.04	0.03	0.00	-0.02	-0.02	-0.01	0.01	0.01	0.01
VERO BEACH, FL	23	43	0.01	0.02	0.03	0.03	0.02	0.00	-0.01	-0.01	0.00	0.01	0.02	0.01
WEST PALM BEACH, FL	64	42	0.03	0.04	0.05	0.05	0.03	-0.01	-0.01	-0.01	0.00	0.02	0.03	0.02
ATHENS, GA	51	51	0.01	0.02	0.03	0.03	0.01	0.00	-0.01	-0.02	-0.01	0.00	0.01	0.01
ATLANTA, GA	68	46	0.03	0.04	0.06	0.05	0.03	0.01	0.00	0.00	0.01	0.02	0.03	0.03
AUGUSTA,GA	55	42	0.01	0.02	0.03	0.03	0.01	0.00	-0.01	-0.02	-0.01	0.00	0.00	0.01
COLUMBUS, GA	48	61	0.00	0.01	0.03	0.03	0.01	0.00	-0.02	-0.02	0.00	0.00	0.00	0.00
MACON, GA	58	42	0.01	0.02	0.03	0.03	0.02	0.01	0.00	-0.01	0.00	0.01	0.01	0.01
SAVANNAH, GA	56	42	0.02	0.03	0.04	0.04	0.02	0.00	0.00	-0.01	-0.01	0.01	0.01	0.01
HILO, HI	57	57	-0.02	-0.01	-0.02	-0.02	-0.02	-0.02	-0.03	-0.03	-0.03	-0.03	-0.04	-0.03
HONOLULU,HI	57	37	0.01	0.03	0.04	0.05	0.06	0.07	0.08	0.07	0.05	0.04	0.03	0.03
KAHULUI, HI	34	42	0.03	0.04	0.05	0.07	0.07	0.09	0.10	0.09	0.07	0.05	0.04	0.03
LIHUE, HI	56	57	0.02	0.03	0.04	0.05	0.04	0.05	0.05	0.04	0.03	0.03	0.03	0.03
BOISE, ID	67	67	-0.02	0.01	0.07	0.08	0.08	0.09	0.10	0.10	0.08	0.06	0.01	-0.02
POCATELLO, ID	54	43	0.00	0.02	0.06	0.10	0.09	0.10	0.10	0.11	0.09	0.08	0.02	-0.01
CHICAGO,IL	48	48	0.02	0.02	0.03	0.05	0.03	0.02	0.00	0.00	0.01	0.02	0.02	0.01
MOLINE, IL	63	46	0.01	0.01	0.03	0.05	0.03	0.01	-0.01	-0.02	-0.01	0.02	0.02	0.00
PEORIA, IL	63	47	0.00	0.01	0.03	0.04	0.02	0.01	-0.01	-0.02	0.00	0.01	0.01	0.00
ROCKFORD, IL	56	43	0.00	0.01	0.03	0.04	0.03	0.01	-0.01	-0.02	-0.01	0.01	0.01	-0.01
SPRINGFIELD, IL	59	47	0.02	0.02	0.04	0.05	0.04	0.02	0.00	-0.01	0.00	0.02	0.03	0.01
EVANSVILLE, IN	66	45	-0.01	0.00	0.02	0.02	0.00	-0.01	-0.03	-0.03	-0.02	-0.01	-0.01	-0.01
FORT WAYNE, IN	60	45	0.01	0.02	0.04	0.05	0.04	0.02	0.01	0.00	0.01	0.02	0.02	0.00
INDIANAPOLIS, IN	58	47	0.01	0.02	0.04	0.05	0.03	0.01	0.00	-0.01	0.01	0.02	0.02	0.00
SOUTH BEND, IN	58	43	0.01	0.02	0.04	0.05	0.04	0.03	0.01	0.00	0.01	0.02	0.02	0.00
DES MOINES, IA	57	45	0.01	0.02	0.04	0.06	0.04	0.02	0.00	0.00	0.01	0.02	0.02	0.01
SIOUX CITY, IA	65	47	0.01	0.01	0.03	0.06	0.04	0.02	0.00	0.00	0.01	0.03	0.02	0.00
WATERLOO, IA	50	47	0.01	0.01	0.03	0.05	0.04	0.02	-0.01	-0.01	0.00	0.02	0.01	0.00
CONCORDIA, KS	44	44	0.02	0.03	0.06	0.07	0.04	0.04	0.04	0.03	0.04	0.05	0.03	0.02
DODGE CITY, KS	64	43	0.06	0.07	0.09	0.10	0.08	0.08	0.08	0.07	0.08	0.08	0.07	0.06
GOODLAND, KS	58	40	0.05	0.07	0.10	0.12	0.10	0.10	0.10	0.09	0.09	0.08	0.05	0.05
TOPEKA, KS	57	42	0.00	0.01	0.04	0.04	0.02	0.00	0.00	-0.01	0.00	0.01	0.01	0.00

WICHITA, KS	53	53	0.03	0.04	0.07	0.08	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.03
GREATER CINCINNATI AP	59	44	0.01	0.02	0.04	0.05	0.02	0.01	0.00	0.00	0.01	0.01	0.02	0.00
JACKSON, KY	25	25	-0.02	-0.01	0.01	0.02	-0.02	-0.04	-0.04	-0.05	-0.03	-0.01	-0.01	-0.02
LEXINGTON, KY	59	43	0.01	0.02	0.04	0.04	0.02	0.01	0.00	-0.01	0.00	0.01	0.02	0.01
LOUISVILLE, KY	59	46	0.01	0.02	0.04	0.04	0.01	0.00	0.00	-0.01	0.00	0.01	0.01	0.00
PADUCAH KY	22	22	-0.02	-0.02	0.00	0.00	-0.03	-0.05	-0.05	-0.06	-0.05	-0.04	-0.02	-0.03
BATON ROUGE, LA	55	47	-0.01	0.00	0.01	0.00	-0.01	-0.03	-0.04	-0.04	-0.03	-0.02	-0.01	-0.01
LAKE CHARLES, LA	45	42	-0.01	0.00	0.00	0.00	-0.01	-0.03	-0.05	-0.04	-0.03	-0.01	-0.01	-0.01
NEW ORLEANS, LA	58	58	-0.01	0.01	0.01	0.01	-0.01	-0.03	-0.04	-0.04	-0.03	-0.01	0.00	-0.01
SHREVEPORT, LA	54	54	0.00	0.01	0.02	0.01	0.00	-0.01	-0.01	-0.02	-0.01	0.00	0.00	0.00
CARIBOU, ME	26	62	0.01	0.02	0.04	0.04	0.04	0.02	0.01	0.00	0.01	0.01	-0.01	0.00
PORTLAND, ME	66	66	0.01	0.02	0.03	0.04	0.02	0.00	0.00	0.00	0.00	0.01	0.01	0.01
BALTIMORE, MD	56	53	0.02	0.04	0.06	0.06	0.03	0.03	0.01	0.01	0.01	0.02	0.02	0.02
BLUE HILL, MA	65	53	0.10	0.11	0.11	0.11	0.09	0.07	0.07	0.06	0.07	0.09	0.09	0.10
BOSTON, MA	49	42	0.07	0.07	0.07	0.07	0.05	0.04	0.04	0.04	0.04	0.05	0.06	0.07
WORCESTER, MA	40	51	0.05	0.05	0.06	0.06	0.05	0.02	0.01	0.01	0.01	0.03	0.03	0.03
ALPENA, MI	46	47	-0.01	-0.01	0.01	0.03	0.03	0.02	0.01	-0.01	-0.01	0.00	-0.01	-0.02
DETROIT, MI	48	48	0.02	0.03	0.04	0.06	0.04	0.03	0.02	0.01	0.02	0.03	0.03	0.01
FLINT, MI	65	43	0.01	0.02	0.04	0.06	0.04	0.02	0.02	0.00	0.02	0.02	0.02	0.01
GRAND RAPIDS, MI	43	43	0.01	0.01	0.03	0.05	0.04	0.02	0.02	0.01	0.01	0.01	0.01	0.00
HOUGHTON LAKE, MI	25	42	-0.01	-0.01	0.01	0.04	0.03	0.01	0.01	-0.01	0.00	0.00	-0.01	-0.02
LANSING, MI	47	43	0.01	0.02	0.03	0.05	0.04	0.02	0.01	0.00	0.00	0.01	0.01	0.00
MUSKEGON, MI	45	46	0.01	0.02	0.03	0.05	0.04	0.02	0.01	0.01	0.01	0.02	0.02	0.01
SAULT STE. MARIE, MI	65	65	-0.01	-0.01	0.01	0.03	0.03	0.00	0.00	-0.01	-0.01	0.00	-0.02	-0.02
DULUTH, MN	57	45	0.01	0.02	0.03	0.05	0.05	0.02	0.01	0.00	0.01	0.02	0.01	0.00
INTERNATIONAL FALLS, MN	54	64	-0.01	0.00	0.01	0.03	0.03	0.01	-0.01	-0.02	-0.01	0.00	-0.02	-0.03
MINNEAPOLIS-ST.PAUL, MN	68	47	0.01	0.01	0.03	0.06	0.05	0.03	0.02	0.01	0.01	0.03	0.02	0.00
ROCHESTER, MN	46	46	0.03	0.03	0.04	0.06	0.05	0.04	0.02	0.01	0.02	0.04	0.03	0.02
SAINT CLOUD, MN	20	54	-0.02	-0.01	0.00	0.03	0.03	0.00	-0.01	-0.02	-0.01	0.00	-0.02	-0.03
JACKSON, MS	43	43	-0.02	0.00	0.00	0.00	-0.02	-0.03	-0.04	-0.04	-0.03	-0.02	-0.02	-0.02
MERIDIAN, MS	47	42	-0.02	-0.01	0.00	-0.01	-0.03	-0.04	-0.05	-0.05	-0.04	-0.03	-0.02	-0.03
TUPELO, MS	23	23	-0.03	-0.02	-0.01	-0.01	-0.03	-0.05	-0.05	-0.05	-0.04	-0.04	-0.03	-0.03
COLUMBIA, MO	36	37	0.01	0.01	0.03	0.04	0.00	-0.01	-0.01	-0.01	0.00	0.01	0.01	0.00
KANSAS CITY, MO	34	34	0.02	0.02	0.04	0.05	0.02	0.01	0.00	0.00	0.00	0.02	0.02	0.01
ST. LOUIS, MO	57	46	0.01	0.02	0.04	0.04	0.01	0.01	0.00	-0.01	0.00	0.01	0.01	0.00
SPRINGFIELD, MO	61	46	0.02	0.03	0.05	0.05	0.01	0.00	0.00	0.00	0.00	0.03	0.03	0.02
BILLINGS, MT	67	47	0.06	0.07	0.07	0.09	0.08	0.08	0.09	0.10	0.09	0.08	0.07	0.07
GLASGOW, MT	37	42	-0.01	0.00	0.05	0.10	0.10	0.09	0.10	0.11	0.09	0.06	0.01	-0.01
GREAT FALLS, MT	65	45	0.07	0.08	0.08	0.10	0.09	0.08	0.10	0.10	0.09	0.10	0.08	0.08
HELENA, MT	66	41	-0.02	0.01	0.04	0.07	0.07	0.06	0.08	0.07	0.06	0.03	0.00	-0.02
KALISPELL, MT	44	42	-0.07	-0.04	0.00	0.04	0.04	0.03	0.05	0.05	0.02	-0.01	-0.06	-0.08
MISSOULA, MT	62	46	-0.07	-0.04	0.01	0.04	0.04	0.04	0.06	0.06	0.03	0.00	-0.06	-0.08
GRAND ISLAND, NE	57	45	0.03	0.03	0.05	0.08	0.06	0.05	0.03	0.02	0.04	0.05	0.04	0.03
LINCOLN, NE	34	34	0.00	0.00	0.03	0.05	0.02	0.02	0.01	0.00	0.01	0.02	0.01	0.00
NORFOLK, NE	30	61	0.03	0.02	0.04	0.07	0.05	0.04	0.02	0.02	0.03	0.05	0.03	0.02
NORTH PLATTE, NE	54	42	0.00	0.01	0.04	0.06	0.04	0.03	0.02	0.02	0.03	0.03	0.01	0.00
OMAHA EPPLEY AP, NE	70	42	0.01	0.02	0.04	0.06	0.03	0.02	0.00	0.00	0.01	0.02	0.02	0.00
OMAHA (NORTH), NE	9	9	0.02	0.01	0.03	0.04	0.02	0.02	-0.01	-0.01	0.01	0.03	0.01	0.00
SCOTTSBLUFF, NE	55	41	0.04	0.06	0.09	0.10	0.09	0.08	0.08	0.07	0.07	0.07	0.04	0.03
VALENTINE, NE	38	39	0.00	0.00	0.02	0.05	0.04	0.03	0.02	0.03	0.04	0.03	0.02	0.01
ELKO, NV	51	39	-0.03	0.00	0.03	0.06	0.07	0.08	0.09	0.08	0.07	0.05	0.00	-0.03
ELY, NV	65	54	0.04	0.05	0.08	0.10	0.11	0.12	0.13	0.12	0.12	0.10	0.06	0.04
LAS VEGAS, NV	58	46	0.06	0.09	0.12	0.14	0.15	0.15	0.14	0.13	0.12	0.10	0.08	0.07
RENO, NV	64	43	0.00	0.03	0.07	0.08	0.09	0.09	0.10	0.09	0.07	0.06	0.02	0.00
WINNEMUCCA, NV	50	57	0.00	0.03	0.07	0.08	0.09	0.10	0.12	0.11	0.10	0.07	0.03	0.00

CONCORD, NH	64	41	0.00	0.02	0.02	0.04	0.02	0.01	0.00	-0.01	-0.01	0.00	-0.01	-0.01
ATLANTIC CITY AP, NJ	48	42	0.04	0.05	0.06	0.06	0.04	0.02	0.01	0.01	0.01	0.02	0.03	0.03
NEWARK, NJ	62	41	0.04	0.06	0.07	0.07	0.05	0.04	0.03	0.03	0.03	0.03	0.04	0.04
ALBUQUERQUE, NM	67	46	0.06	0.08	0.11	0.13	0.13	0.13	0.09	0.08	0.08	0.08	0.06	0.04
CLAYTON, NM	14	49	0.08	0.09	0.12	0.14	0.12	0.12	0.09	0.07	0.09	0.09	0.08	0.07
ROSWELL, NM	33	33	0.05	0.08	0.11	0.12	0.11	0.11	0.08	0.06	0.06	0.06	0.05	0.04
ALBANY, NY	68	41	0.01	0.03	0.05	0.06	0.03	0.02	0.01	0.00	0.00	0.01	0.01	0.00
BINGHAMTON, NY	55	55	0.01	0.02	0.03	0.05	0.04	0.02	0.01	0.01	0.00	0.02	0.01	0.01
BUFFALO, NY	67	46	0.04	0.04	0.05	0.06	0.05	0.04	0.04	0.03	0.03	0.04	0.03	0.03
ISLIP, NY	23	46	0.02	0.03	0.04	0.04	0.02	0.02	0.01	0.01	0.01	0.02	0.03	0.03
NEW YORK C.PARK, NY	69	72	0.03	0.04	0.05	0.05	0.03	0.02	0.01	0.01	0.01	0.02	0.03	0.03
NEW YORK (JFK AP), NY	48	45	0.06	0.07	0.08	0.07	0.05	0.03	0.03	0.03	0.03	0.05	0.05	0.06
NEW YORK (LAGUARDIA AP), NY	58	44	0.07	0.08	0.08	0.08	0.06	0.05	0.05	0.04	0.05	0.05	0.06	0.07
ROCHESTER, NY	66	43	0.02	0.02	0.03	0.04	0.03	0.02	0.01	0.01	0.00	0.01	0.01	0.00
SYRACUSE, NY	57	43	0.01	0.02	0.03	0.05	0.03	0.02	0.01	0.00	0.00	0.01	0.01	0.00
ASHEVILLE, NC	42	42	0.02	0.03	0.03	0.03	0.00	-0.02	-0.03	-0.04	-0.03	0.00	0.01	0.01
CAPE HATTERAS, NC	48	49	0.03	0.03	0.04	0.04	0.02	0.01	0.00	0.00	0.01	0.02	0.02	0.02
CHARLOTTE, NC	57	46	0.01	0.03	0.04	0.04	0.02	0.00	0.00	-0.01	0.00	0.01	0.01	0.01
GREENSBORO-WNSTN-SALM-HGHPT,NC	78	43	0.02	0.03	0.04	0.04	0.01	0.00	-0.01	-0.02	-0.01	0.01	0.02	0.01
RALEIGH, NC	57	42	0.02	0.03	0.04	0.05	0.02	0.00	-0.01	-0.01	-0.01	0.00	0.01	0.01
WILMINGTON, NC	55	43	0.03	0.04	0.05	0.05	0.03	0.01	0.00	-0.01	-0.01	0.01	0.02	0.02
BISMARCK, ND	67	47	0.00	0.00	0.02	0.05	0.05	0.03	0.03	0.03	0.03	0.03	0.00	-0.01
FARGO, ND	64	47	0.02	0.02	0.03	0.06	0.07	0.04	0.03	0.04	0.04	0.04	0.03	0.01
WILLISTON, ND	42	45	-0.02	-0.01	0.01	0.05	0.05	0.03	0.03	0.03	0.03	0.03	-0.01	-0.02
AKRON, OH	58	43	0.02	0.02	0.04	0.05	0.03	0.01	0.01	0.00	0.00	0.02	0.02	0.01
CLEVELAND, OH	65	46	0.02	0.03	0.04	0.05	0.03	0.02	0.02	0.00	0.01	0.03	0.03	0.02
COLUMBUS, OH	57	47	0.00	0.01	0.04	0.04	0.02	0.01	0.00	-0.01	-0.01	0.01	0.01	0.00
DAYTON, OH	63	43	0.01	0.02	0.04	0.05	0.03	0.02	0.01	0.00	0.01	0.02	0.02	0.01
MANSFIELD, OH	22	40	0.02	0.02	0.03	0.05	0.03	0.01	0.00	0.00	0.00	0.02	0.02	0.01
TOLEDO, OH	51	51	0.01	0.01	0.03	0.05	0.04	0.02	0.01	0.00	0.01	0.02	0.01	0.00
YOUNGSTOWN, OH	57	59	0.01	0.02	0.03	0.05	0.03	0.02	0.01	0.00	0.01	0.02	0.02	0.01
OKLAHOMA CITY, OK	58	41	0.04	0.05	0.08	0.08	0.04	0.04	0.04	0.04	0.03	0.05	0.05	0.04
TULSA, OK	58	46	0.02	0.03	0.05	0.05	0.02	0.01	0.02	0.02	0.01	0.02	0.02	0.02
ASTORIA, OR	53	53	-0.03	-0.02	-0.02	-0.01	-0.01	-0.02	-0.01	-0.02	-0.03	-0.04	-0.04	-0.04
EUGENE, OR	54	49	-0.05	-0.03	-0.01	0.00	0.01	0.02	0.06	0.05	0.04	-0.02	-0.05	-0.06
MEDFORD, OR	57	45	-0.07	-0.03	0.00	0.01	0.03	0.05	0.06	0.06	0.04	0.00	-0.06	-0.08
PENDLETON, OR	53	65	-0.04	-0.01	0.04	0.07	0.07	0.09	0.10	0.10	0.08	0.03	-0.02	-0.04
PORTLAND, OR	58	66	-0.01	0.00	0.01	0.01	0.01	0.02	0.04	0.03	0.02	-0.02	-0.03	-0.03
SALEM, OR	58	44	-0.04	-0.02	0.00	0.00	0.00	0.01	0.04	0.04	0.02	-0.02	-0.05	-0.05
SEXTON SUMMIT, OR	58	8	0.02	0.03	0.02	0.02	0.04	0.06	0.09	0.08	0.07	0.05	0.03	0.03
GUAM, PC	16	13	0.00	0.02	0.02	0.01	-0.01	-0.02	-0.05	-0.05	-0.06	-0.05	-0.02	0.00
JOHNSTON ISLAND, PC	23	23	0.05	0.07	0.08	0.07	0.06	0.07	0.07	0.06	0.04	0.05	0.06	0.07
KOROR, PC	41	55	-0.04	-0.04	-0.04	-0.04	-0.06	-0.06	-0.06	-0.05	-0.05	-0.05	-0.06	-0.05
KWAJALEIN, MARSHALL IS., PC	40	46	0.07	0.07	0.07	0.05	0.03	0.02	-0.01	-0.02	-0.03	-0.02	0.01	0.06
MAJURO, MARSHALL IS, PC	42	51	0.02	0.02	0.02	0.01	-0.01	-0.02	-0.04	-0.04	-0.05	-0.04	-0.03	0.00
PAGO PAGO, AMER SAMOA, PC	39	38	-0.02	-0.02	-0.03	-0.03	-0.01	0.01	0.02	0.02	0.02	0.01	-0.01	-0.02
POHNPEI, CAROLINE IS., PC	32	36	-0.04	-0.03	-0.04	-0.06	-0.06	-0.07	-0.08	-0.08	-0.08	-0.08	-0.08	-0.06
CHUUK, E. CAROLINE IS., PC	41	36	0.00	0.00	0.00	-0.02	-0.03	-0.05	-0.05	-0.04	-0.04	-0.04	-0.04	-0.02
WAKE ISLAND, PC	43	45	0.05	0.05	0.06	0.07	0.05	0.03	0.03	0.02	0.02	0.04	0.07	0.06
YAP, W CAROLINE IS., PC	37	58	-0.02	-0.01	-0.01	-0.02	-0.04	-0.05	-0.05	-0.05	-0.05	-0.06	-0.05	-0.03
ALLENTOWN, PA	57	56	0.02	0.03	0.05	0.05	0.03	0.02	0.01	0.00	0.00	0.01	0.02	0.02
ERIE, PA.	52	41	0.03	0.02	0.03	0.03	0.02	0.01	0.01	0.00	0.01	0.03	0.04	0.03
HARRISBURG, PA	48	49	0.01	0.03	0.04	0.04	0.02	0.01	0.00	-0.01	-0.01	0.00	0.01	0.01
MIDDLETOWN/HARRISBURG INTL APT	64	41	0.01	0.03	0.04	0.04	0.02	0.01	0.00	-0.01	-0.01	0.00	0.01	0.01

PHILADELPHIA, PA	66	47	0.03	0.05	0.06	0.06	0.04	0.03	0.02	0.02	0.02	0.03	0.03	0.03
PITTSBURGH, PA	54	46	0.01	0.02	0.04	0.05	0.03	0.02	0.01	0.00	0.00	0.02	0.02	0.01
AVOCA, PA	51	51	0.00	0.01	0.03	0.04	0.03	0.01	0.01	0.00	0.00	0.00	0.00	-0.01
WILLIAMSPORT, PA	44	61	0.00	0.02	0.03	0.04	0.02	0.00	0.00	-0.02	-0.02	0.00	0.00	0.00
PROVIDENCE, RI	53	43	0.04	0.06	0.06	0.07	0.05	0.03	0.03	0.03	0.03	0.03	0.04	0.04
CHARLESTON AP,SC	57	64	0.03	0.04	0.05	0.05	0.03	0.01	0.00	-0.01	-0.01	0.01	0.02	0.02
COLUMBIA, SC	58	40	0.01	0.03	0.04	0.05	0.02	0.01	0.00	-0.01	-0.01	0.00	0.01	0.01
GREENVILLE-SPARTANBURG AP, SC	44	44	0.01	0.02	0.03	0.03	0.01	0.00	-0.01	-0.02	-0.01	0.01	0.01	0.01
ABERDEEN, SD	30	38	0.00	0.00	0.02	0.05	0.05	0.02	0.01	0.02	0.03	0.03	0.00	-0.01
HURON, SD	67	47	0.01	0.01	0.03	0.06	0.05	0.03	0.03	0.03	0.04	0.04	0.03	0.01
RAPID CITY, SD	56	56	0.02	0.04	0.07	0.09	0.08	0.06	0.07	0.09	0.09	0.07	0.04	0.02
SIOUX FALLS, SD	58	43	0.01	0.01	0.03	0.06	0.04	0.03	0.02	0.01	0.02	0.03	0.01	0.00
BRISTOL-JHNSN CTY-KNGSPRT,TN	52	45	-0.02	-0.01	0.01	0.01	-0.02	-0.03	-0.04	-0.04	-0.03	-0.02	-0.01	-0.02
CHATTANOOGA, TN	66	76	-0.01	0.00	0.02	0.02	0.00	-0.02	-0.02	-0.03	-0.02	-0.02	-0.01	-0.02
KNOXVILLE, TN	64	46	-0.01	0.00	0.02	0.03	0.00	-0.01	-0.02	-0.03	-0.02	-0.01	-0.01	-0.01
MEMPHIS, TN	58	67	0.01	0.02	0.04	0.04	0.01	0.00	-0.01	-0.01	0.00	0.01	0.02	0.01
NASHVILLE, TN	65	41	0.00	0.01	0.03	0.02	-0.01	-0.01	-0.02	-0.03	-0.02	-0.01	0.00	0.00
ABILENE, TX	62	43	0.05	0.06	0.08	0.09	0.06	0.06	0.05	0.05	0.03	0.05	0.05	0.05
AMARILLO, TX	65	45	0.07	0.08	0.11	0.12	0.10	0.09	0.08	0.07	0.07	0.08	0.08	0.07
AUSTIN, TX	65	45	0.00	0.01	0.02	0.02	0.01	0.00	0.01	0.01	-0.01	0.00	0.00	0.00
BROWNSVILLE, TX	64	40	0.01	0.03	0.04	0.05	0.04	0.03	0.03	0.02	0.00	0.00	0.01	0.01
CORPUS CHRISTI, TX	64	42	0.02	0.03	0.05	0.05	0.03	0.02	0.02	0.02	0.01	0.02	0.03	0.02
DALLAS-FORT WORTH, TX	53	43	0.03	0.04	0.05	0.05	0.02	0.03	0.03	0.02	0.02	0.02	0.03	0.03
DEL RIO, TX	27	27	0.00	0.01	0.04	0.03	0.02	0.03	0.03	0.02	0.00	-0.01	-0.01	0.00
EL PASO, TX	64	46	0.07	0.10	0.13	0.14	0.14	0.12	0.08	0.07	0.07	0.07	0.07	0.06
GALVESTON, TX	60	96	0.00	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.01	0.01	0.01	0.00
HOUSTON, TX	37	37	-0.02	-0.01	0.00	0.00	-0.02	-0.02	-0.03	-0.03	-0.03	-0.02	-0.02	-0.02
LUBBOCK, TX	57	59	0.06	0.08	0.11	0.12	0.10	0.09	0.06	0.04	0.04	0.06	0.07	0.06
MIDLAND-ODESSA, TX	53	43	0.05	0.06	0.09	0.10	0.09	0.08	0.07	0.05	0.04	0.05	0.05	0.05
PORT ARTHUR, TX	53	46	0.00	0.02	0.02	0.02	0.00	-0.02	-0.03	-0.03	-0.02	0.00	0.00	0.00
SAN ANGELO, TX	57	46	0.03	0.05	0.07	0.07	0.05	0.04	0.04	0.03	0.01	0.02	0.03	0.03
SAN ANTONIO, TX	64	64	0.01	0.02	0.03	0.03	0.01	0.02	0.02	0.02	0.01	0.01	0.01	0.01
VICTORIA, TX	45	45	0.00	0.02	0.03	0.03	0.01	0.00	0.00	0.00	-0.01	0.00	0.00	0.00
WACO, TX	57	43	0.02	0.03	0.04	0.04	0.02	0.03	0.04	0.04	0.02	0.02	0.02	0.02
WICHITA FALLS, TX	58	46	0.04	0.05	0.07	0.07	0.05	0.05	0.06	0.05	0.03	0.04	0.04	0.04
SALT LAKE CITY, UT	77	46	-0.03	0.00	0.05	0.07	0.08	0.10	0.12	0.11	0.09	0.05	0.00	-0.03
BURLINGTON, VT	63	41	0.01	0.02	0.02	0.04	0.03	0.02	0.02	0.01	0.01	0.01	0.01	0.01
LYNCHBURG, VA	39	43	0.02	0.02	0.03	0.04	0.01	-0.01	-0.02	-0.02	-0.01	0.00	0.01	0.01
NORFOLK, VA	58	58	0.04	0.05	0.06	0.07	0.04	0.03	0.01	0.01	0.02	0.03	0.04	0.04
RICHMOND, VA	58	72	0.01	0.03	0.04	0.05	0.02	0.01	0.00	-0.01	0.00	0.01	0.02	0.01
ROANOKE, VA	58	42	0.04	0.04	0.06	0.05	0.02	0.00	0.00	-0.01	-0.01	0.01	0.02	0.03
OLYMPIA, WA	53	46	-0.06	-0.04	-0.01	0.00	0.00	0.00	0.01	0.01	-0.01	-0.04	-0.06	-0.07
QUILLAYUTE, WA	40	40	-0.07	-0.05	-0.05	-0.04	-0.04	-0.04	-0.04	-0.05	-0.05	-0.07	-0.08	-0.08
SEATTLE SEA-TAC AP, WA	58	47	-0.02	0.00	0.01	0.02	0.03	0.03	0.03	0.02	0.01	-0.01	-0.02	-0.03
SPOKANE, WA	59	47	-0.04	-0.01	0.04	0.06	0.06	0.08	0.09	0.09	0.07	0.03	-0.03	-0.05
YAKIMA, WA	52	57	-0.06	-0.01	0.05	0.08	0.08	0.08	0.09	0.08	0.07	0.03	-0.03	-0.07
SAN JUAN, PR	51	51	0.00	0.00	0.01	0.01	-0.01	0.00	0.00	-0.01	-0.02	-0.03	-0.02	-0.01
BECKLEY, WV	42	43	0.00	0.01	0.03	0.04	0.02	-0.01	-0.02	-0.02	-0.02	0.00	0.01	0.01
CHARLESTON, WV	59	59	-0.02	-0.01	0.01	0.02	0.00	-0.02	-0.03	-0.03	-0.03	-0.02	-0.01	-0.02
ELKINS, WV	35	43	-0.02	0.00	0.01	0.02	-0.01	-0.03	-0.04	-0.04	-0.04	-0.02	-0.02	-0.03
HUNTINGTON, WV	44	45	-0.02	0.00	0.02	0.03	0.00	-0.02	-0.03	-0.03	-0.03	-0.01	-0.01	-0.02
GREEN BAY, WI	57	45	0.00	0.00	0.01	0.03	0.02	0.01	0.00	-0.02	-0.01	0.01	0.00	-0.01
LA CROSSE, WI	54	45	-0.01	-0.01	0.01	0.04	0.03	0.01	0.00	-0.01	0.00	0.01	0.00	-0.02
MADISON, WI	60	47	0.00	0.01	0.02	0.04	0.03	0.01	-0.01	-0.01	-0.01	0.01	0.00	-0.01
MILWAUKEE, WI	66	46	0.03	0.03	0.04	0.05	0.03	0.02	0.01	0.00	0.01	0.03	0.03	0.02

CASPER, WY	56	42	0.09	0.09	0.10	0.10	0.09	0.10	0.11	0.11	0.11	0.09	0.08	0.08
CHEYENNE, WY	49	47	0.11	0.10	0.11	0.11	0.09	0.09	0.09	0.08	0.09	0.09	0.09	0.10
LANDER, WY	60	60	-0.02	0.00	0.03	0.05	0.06	0.07	0.08	0.08	0.06	0.03	-0.01	-0.02
SHERIDAN, WY	63	42	-0.01	0.00	0.04	0.06	0.05	0.04	0.06	0.07	0.05	0.03	-0.01	-0.01

* Data ending 2006.

Example 13.6

Adjusting K_{c_mid} and K_{c_end} to Reflect Local Deviation from RH_{min} of 45% and Wind of 4 1/2 mph.

Given:

Crop = sweet corn

Location = Fresno, CA

Planting date = Jan 15

Find:

Modified values for: K_{c_mid} and K_{c_end}

Procedure:

- Get default K_c values from Table 5.2 (K_{c_table}).
- Based on location/month find the climate adjustment factor (adj_{clim}) to be added/subtracted to K_{c_table}.
- Using inset table in Table 13.16 find height adjustment factor (adj_h) and multiply adj_{clim} by adj_h.
- Add this product to the original default value from Table 5.2 (K_{c_table}).

Results:

K_{c_mid} = 1.15 (Table 5.2)
K_{c_end} = = 1.05 (Table 5.2)
K_{c_mid} appears to occur April (Table 5.5)
K_{c_end} appears to occur May (Table 5.5)
estimated height in mid period ≈ 5 ft
estimated height in end period ≈ 6 ft

$$\text{Modified } K_{c\_mid} = K_{c\_table} + (adj_{clim})\ (adj_h) = 1.15 + (0.06)\ (1.32) = 1.23$$

$$\text{Modified } K_{c\_end} = K_{c\_table} + (adj_{clim})\ (adj_h) = 1.05 + (0.09)\ (1.39) = 1.18$$

Appendix IV:

Modifying the time scale of the crop coefficient curve.

The timescale associated with the seasonally changing coefficient values are found in a large variety of forms: days after planting or emergence, Growing Degree Days after planting or emergence, Growing Degree Days after 1 Jan, percentage of growing season, crop growth stage, percentage crop cover, crop image, etc. A computer program can not readily use some timescales such as growth stage, percentage of canopy cover, or crop image, since a program requires a calculable value, but these timescales work fine in charts.

Growing Degree Days (GDDs) are a concept of thermal time and are often calculated in a method similar to equation 13.15.

$$GDD = ([T_{max} - T_{min}]/2 - T_{base}) \qquad (13.15)$$

where

GDD = growing degree day [° F/day]
T_{max} = maximum daily temperature, [° F]
T_{min} = minimum daily temperature, [° F]
T_{base} = base daily temperature, [° F]

Daily GDD values are summed to give accumulative GDDs for the season. T_{base} can be any value, and is frequently 50°, 55° or 60° F, but oftentimes is a value that makes the data fit better. Sometimes the T_{max} can have an upper and/or the T_{min} have a lower limit value. Results < 0.0 are usually recorded as 0.

Using GDD-driven coefficient values offers certain benefits. First, in non-typical years they may be more accurate (especially in the early part of the season) then days-after-planting crop coefficients. Corn growth is better modeled with GDDs than with days. For example, corn hybrids are classified as to Relative Maturity (RM) values, approximating the number of days to reach physical maturity. A hybrid with a RM value of 119 should approximately have a 119-day growing season, but depending on what time in the spring or summer planting occurred they might be anywhere from 110 to 140 days in the length. On the other hand, a GDD scale predicts events much closer, and many seed companies provide information on GDDs to reach maturity.

Accumulated GDDs. Smeal et al. (1998) used the concept of accumulative GDDs to estimate the initiation of "green up" in turf grasses. The tally of GDDs begins January 1, but because of the value of the base temperature purposely chosen, GDDs values will not accumulate to appreciable levels until the temperature is warm enough for the grass species to start growth. Until this point, the crop is dormant and has an appropriate K_{c_ini} value. Cool and warm season grass GDD-based crop coefficients were developed at Las Cruces, New Mexico using a 60 ° F- and a 40 °F-base, respectively. When applied to grass estimates in St. Louis they closely predicted green up and daily water use. Washington State was a pioneer in the concept of using certain temperature values in irrigation scheduling to model important events like crop coefficients and the initiation of spring growth (James et al., 1988). Figure 13.19 shows a crop coefficient curve for apples with ground cover that uses accumulated GDDs since 1 Jan (97ºF/41ºF with 41ºbase); after first fall frost the K_c value defaults to 0.15.

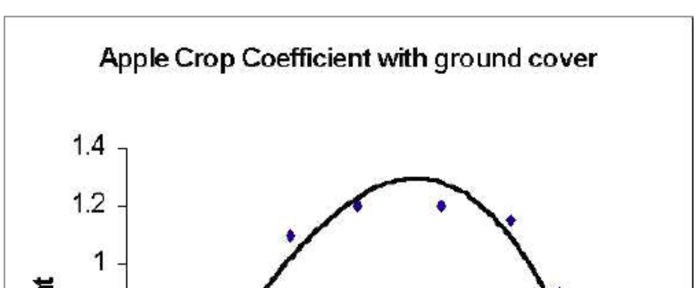


Fig. 13.19. Crop coefficient curve for apples with ground cover using accumulated GDDS from 1 Jan (after James et al., 1998).

Crop Image. One very interesting timescale, which is actually a form of growth stage timescale, is the Geisenheim method used in Germany (Paschold, 2009). They use an actual drawing or photograph of the crop at the various growth stages (Figure 13.20). One of the nice things about this method is that the commencement of the *end of season stage* is shown as an image. The commencement of this stage is difficult to quantify with measureable traits like plant height or canopy coverage, but can be identified by visual clues, such as change in leaf color. A photograph illustrating this stage would be beneficial in all computer programs.

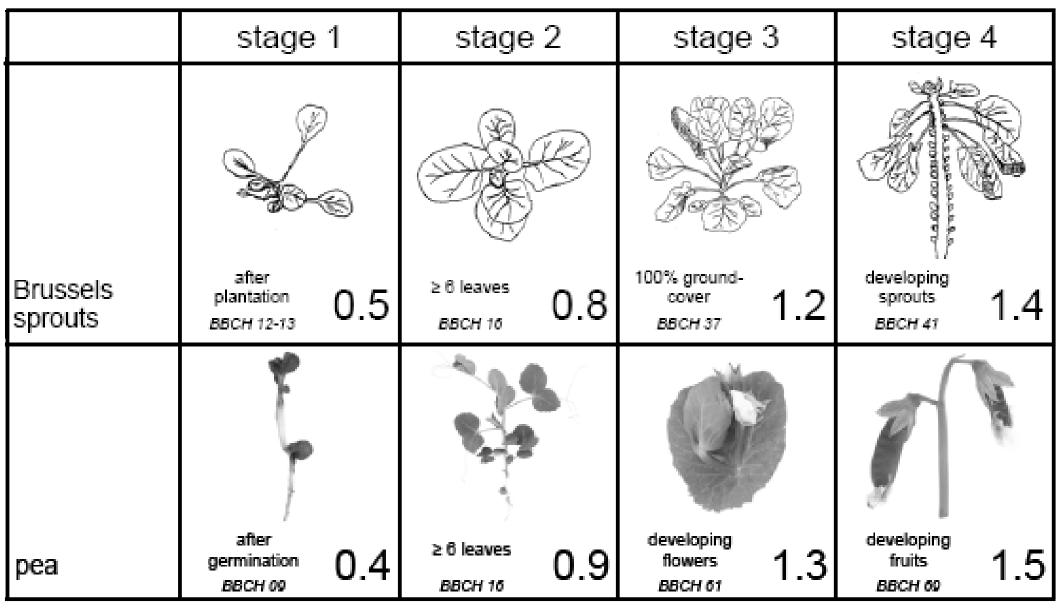


Fig. 13.20 Crop coefficients based on growth stage appearance (after Paschold, 2009).

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