

Innovations in Agricultural
& Biological Engineering

Technological Interventions in Management of Irrigated Agriculture



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CHAPTER 1

SIMPLE SPREADSHEET METHOD FOR SCHEDULING IRRIGATION

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ABSTRACT

A simple spreadsheet method for scheduling irrigation is presented. The water balance method used is based on the methodology of the United Nations Food and Agriculture Organization. Soil moisture is depleted from the soil profile by evapotranspiration. By maintaining the soil moisture content between the field capacity and the threshold moisture content, water stress can be avoided and 100% of the potential yield can be achieved, ignoring reductions in yield due to other factors such as fertility, disease, and salinity. The method provides an estimate of the crop stress factor, from which the relative seasonal yield can be estimated for many crops. Several graphs are provided in the spreadsheet, which help the user evaluate their real-time water management. In addition to estimates of the relative yield, the spreadsheet also provides an estimate of the lost irrigation (i.e., irrigation lost to surface runoff or deep percolation). Two examples are provided for the bell peppers located on the southern coast of Puerto Rico.

1.1 INTRODUCTION

Over-application of irrigation can result in loss of water, fuel, and chemicals and may contaminate surface or groundwater. Under-application of water can result in a reduction in crop yield.⁴ Figure 1.1 shows an example of the relationship between the relative crop yield and the relative seasonal crop water requirement. The curve is based on yield and water-use data for corn, wheat, cotton, barley, pepper, and rice.⁷⁻¹⁰ Assuming that the regression equation is applicable to crops grown in the Caribbean region and that the loss in net revenue for a crop is directly proportional to the relative yield reduction, Table 1.1 shows the loss, in dollars per acre, for 17 crops grown in the Caribbean region. The net potential revenue can be obtained when 100% of the crop water requirement is applied. The model budget information for the crops listed in Figure 1.2 was obtained from the *Conjunto Tecnológico* publications of the University of Puerto Rico Agricultural Experiment Station.¹² As an example, suppose that the seasonal water requirement for a 10-acre farm of peppers (pimientos) was 400 mm, but only 320 mm was applied and no additional rainfall was received during the season. The relative amount of water applied then was $320 \text{ mm}/400 \text{ mm} = 0.8$ or 80%. From Table 1.1, the dollar loss for a pepper crop is $\$129/\text{acre} \times 10 \text{ acres} = \1290 for 10 acres (4 ha). The purpose of this exercise is to illustrate the importance of applying the correct amount of water. The values (in dollar) in Table 1.1 are based on

model budgets that are several years old. Therefore, the values in the table should be used for illustration purposes only.

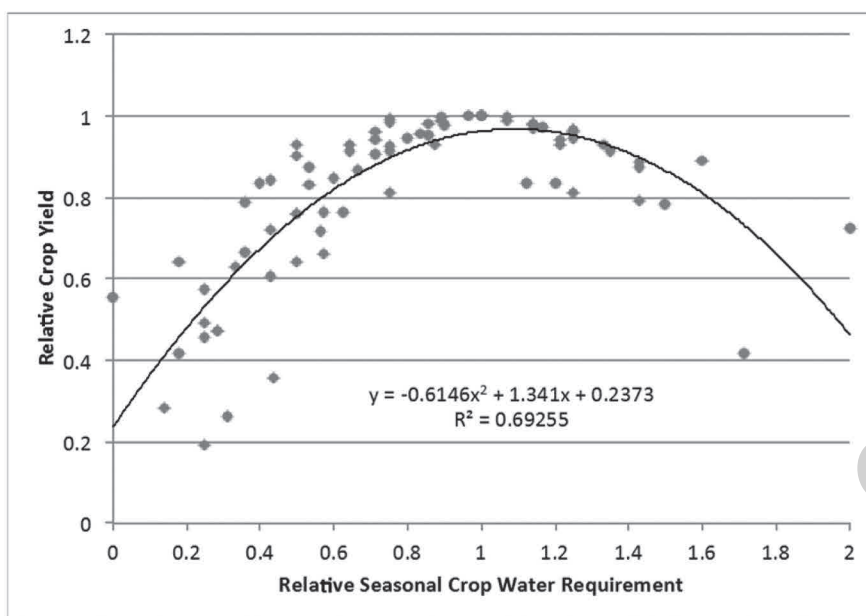


FIGURE 1.1 The relationship between the relative crop yield and the relative seasonal crop water requirement.

CROP*	Percentage of Crop Water Requirement Applied						
	40	50	80	100	130	150	180
	\$ Lost / Acre						
Gandules	47	32	10	0	12	35	69
Pepinillo	111	76	25	0	15	56	124
Repollo	256	174	57	0	21	103	247
Sandia	293	199	65	0	23	114	277
Platanos y Guineos, Plantilla	318	216	71	0	24	122	299
Calabaza	390	265	87	0	27	146	359
Cebolla	543	369	121	0	34	195	490
Pimiento	578	393	129	0	36	206	519
Barenjena	757	514	169	0	44	264	670
Platanos y Guineos, Reton~o	1,006	684	225	0	76	388	945
Melon, Cantaloupe y Honeydew	1,027	698	229	0	56	352	899
Raices y Tuberculos	1,041	707	232	0	57	356	911

FIGURE 1.2 Amount, in dollars, lost per acre as a percentage of crop water requirement applied (*based on model budget data from the *Conjunto Tecnológico, UPR Experiment Station*¹²).

Various methods for scheduling irrigation exist, including evapotranspiration, soil moisture, and water balance methods. The method discussed in this chapter is a combination of the evapotranspiration and water balance

methods. The advantage of this method is that soil samples do not need to be taken to obtain the soil moisture content. Harmsen⁴ presented an evapotranspiration approach based on daily maps of reference evapotranspiration for Puerto Rico. The operational algorithm provides estimates of daily reference evapotranspiration for these three methods.^{5,6}

This chapter presents simple spreadsheet method for scheduling irrigation.

1.2 METHODS

In this section, a simple spreadsheet method for scheduling irrigation is described. The methodology used in the spreadsheet is based on the United Nations Food and Agriculture Organization (FAO), Irrigation and Drainage Paper 56, *Crop evapotranspiration—Guidelines for computing crop water requirements*.¹ The spreadsheet can be downloaded from the Internet free of charge from: <https://pragwater.com/2011/12/17/a-simple-irrigation-scheduling-spreadsheet-program/>. Figures 1.3 and 1.4 show columns A–H

Enter	Enter	Enter		Enter	Enter		
Date	Field Capacity	Wilting Point	Total Available Water	Root Depth	Management Allowed Deficit	Readily Available Moisture Content	Threshold Moisture Content
	FC	WP	TAW	RD	MAD	RAW	θ_t
	%	%	%	m	fraction	%	%
3/14/16	37	20	17	0.25	0.3	5.1	31.9
3/15/16	37	20	17	0.26	0.3	5.1	31.9
3/16/16	37	20	17	0.27	0.3	5.1	31.9
3/17/16	37	20	17	0.28	0.3	5.1	31.9
3/18/16	37	20	17	0.29	0.3	5.1	31.9
3/19/16	37	20	17	0.30	0.3	5.1	31.9
3/20/16	37	20	17	0.31	0.3	5.1	31.9
3/21/16	37	20	17	0.32	0.3	5.1	31.9
3/22/16	37	20	17	0.33	0.3	5.1	31.9
3/23/16	37	20	17	0.34	0.3	5.1	31.9
3/24/16	37	20	17	0.35	0.3	5.1	31.9
3/25/16	37	20	17	0.36	0.3	5.1	31.9
3/26/16	37	20	17	0.37	0.3	5.1	31.9
3/27/16	37	20	17	0.38	0.3	5.1	31.9
3/28/16	37	20	17	0.39	0.3	5.1	31.9
3/29/16	37	20	17	0.40	0.3	5.1	31.9
3/30/16	37	20	17	0.41	0.3	5.1	31.9
3/31/16	37	20	17	0.42	0.3	5.1	31.9
4/1/16	37	20	17	0.43	0.3	5.1	31.9

FIGURE 1.3 Columns A–H of the irrigation scheduling spreadsheet (Soil Moisture Worksheet Tab).

and I–Q of the *Soil Moisture Worksheet*, respectively, and Table 1.1 lists the definition of these columns. Figure 1.5 shows columns A–H for *Application Rate Worksheet*. The user only needs to input data into the yellow highlighted cells. Values in all other cells are calculated automatically. The spreadsheet can be filled-in on a daily basis or could be updated once in a week. It can also be used to evaluate hypothetical scenarios to evaluate the potential

I	J	K	L	M	N	O	P	Q
Enter on First Date		Enter Daily				Enter		
Moisture Content	Crop Stress Factor	Average Crop Evapotranspiration	Average Evapotranspiration Adjusted for Stress	Soil Water Deficit	Irrigation needed	Applied Irrigation or Rainfall	Did Stress Occur?	Lost Irrigation
θ	K_s	ET_c	$ET_{c\text{adj}}$					
%		mm	mm	%	mm	mm		mm
34.00	1.00	3.80	3.80	3.0	8	0	NO	0
32.54	1.00	3.90	3.90	4.5	12	0	NO	0.00
31.09	0.93	3.80	3.54	5.9	16	0	YES	0.00
36.97	1.00	4.00	4.00	0.0	0	20	NO	0.00
35.59	1.00	4.20	4.20	1.4	4	0	NO	0.00
34.19	1.00	3.90	3.90	2.8	8	0	NO	0.00
32.93	1.00	3.90	3.90	4.1	13	0	NO	0.00
31.72	0.98	4.20	4.13	5.3	17	0	YES	0.00
37.00	1.00	4.20	4.20	0.0	0	22	NO	0.13
35.76	1.00	4.10	4.10	1.2	4	0	NO	0.00
34.59	1.00	4.30	4.30	2.4	8	0	NO	0.00
33.40	1.00	4.20	4.20	3.6	13	0	NO	0.00
32.26	1.00	4.30	4.30	4.7	18	0	NO	0.00
31.13	0.94	4.40	4.12	5.9	22	0	YES	0.00
35.72	1.00	4.50	4.50	1.3	5	22	NO	0.00
34.59	1.00	4.60	4.60	2.4	10	0	NO	0.00
33.47	1.00	4.70	4.70	3.5	14	0	NO	0.00
32.35	1.00	4.80	4.80	4.6	20	0	NO	0.00
31.24	0.94	4.80	4.53	5.8	25	0	YES	0.00

FIGURE 1.4 Columns I–Q of the irrigation scheduling spreadsheet (Soil Moisture Worksheet Tab).

TABLE 1.1 Definitions for the Spreadsheet Columns.

Worksheet	Column	Column label	Definition
Soil Moisture Worksheet	A	Date	Month/day/year
	B	FC	Field capacity (%)
	C	WP	Wilting point (%)
	D	TAW	Total available water (%)
	E	RD	Root depth (m)
	F	MAD	Management allowed deficit
	G	RAW	Readily available water (%)
	H	θ_t	Threshold moisture content (%)
	I	θ	Moisture content (%)
	J	K_s	Crop stress factor
	K	ET_c	Crop evapotranspiration (mm)

TABLE 1.1 (Continued)

Worksheet	Column	Column label	Definition
Application Rate	L	ET _{c adj}	Adjusted crop evapotranspiration (mm)
	M		Soil water deficit (%)
	N		Irrigation needed (mm)
	O		Applied irrigation or rainfall (mm)
	P		Did stress occur (yes or no)
	Q		Lost irrigation (mm)
	A		Date
	B	Irrigation needed (mm) copied from Soil Moisture Worksheet	
	C	Field area (acre)	
	D	Percent wetted area (%)	
	E	Irrigation efficiency (%)	
	F	Volume of water to apply (gallons)	
	G	Pump manifold flow rate (gallons per min)	
	H	Time to apply irrigation (h)	

	A	B	C	D	E	F	G	H
1			Enter				Enter	
2	Date	Applied Irrigation or Rainfall	Field Area	Percent Wetted Area	Irrigation Efficiency	Volume of Water to Apply	Pump Manifold Flow Rate	Time to Apply Irrigation
3								
4		mm	Acres	%	%	gallons	Gallons per Minute	Hours
5	3/14/16	0	5	100	90	0	500	0.0
6	3/15/16	0	5	100	90	0	500	0.0
7	3/16/16	0	5	100	90	0	500	0.0
8	3/17/16	20	5	100	90	118777	500	4.0
9	3/18/16	0	5	100	90	0	500	0.0
10	3/19/16	0	5	100	90	0	500	0.0
11	3/20/16	0	5	100	90	0	500	0.0
12	3/21/16	0	5	100	90	0	500	0.0
13	3/22/16	22	5	100	90	130655	500	4.4
14	3/23/16	0	5	100	90	0	500	0.0
15	3/24/16	0	5	100	90	0	500	0.0
16	3/25/16	0	5	100	90	0	500	0.0
17	3/26/16	0	5	100	90	0	500	0.0
18	3/27/16	0	5	100	90	0	500	0.0
19	3/28/16	22	5	100	90	130655	500	4.4
20	3/29/16	0	5	100	90	0	500	0.0
21	3/30/16	0	5	100	90	0	500	0.0
22	3/31/16	0	5	100	90	0	500	0.0
23	4/1/16	0	5	100	90	0	500	0.0

FIGURE 1.5 Columns A–H of the irrigation scheduling spreadsheet (Soil Moisture Worksheet Tab).

crop stress, estimate relative yield, water use, and so on. Owing to space limitations, Figures 1.3–1.5 show only the first 24 days of the crop season.

1.2.1 SPREADSHEET DATA ENTRY

1. In the Soil Moisture Worksheet, enter the date of the first day of the crop season.
2. Enter soil field capacity and wilting point (in %). If user knows the soil texture, one can obtain an estimate of the field capacity and wilting point online from various sources or from textbooks.²
3. The rooting depth needs to be entered for each day of the season. If this information is not available, the user can use the planting depth and the maximum root depth, obtained from the literature, and then creates a linear transition from the planting depth to the maximum depth at the end of the season. The maximum rooting depths for various crops are given in Table 22 of Allen et al.¹
4. Management allowed deficit (MAD) is given in *FAO 56 Table 22*¹; however, the FAO refers to it as the depletion fraction (P). The P and MAD refer to the same parameters.
5. Enter soil volumetric moisture content (in %) on the first day of the season. After the first day, the soil moisture will be estimated by the spreadsheet.
6. Enter the evapotranspiration (ET_c) for each day. Many meteorologic stations will provide estimates of daily reference evapotranspiration (ET_o). User will need to multiply the ET_o by the appropriate crop coefficient (K_c) for the crop under consideration to obtain ET_c . Growth stage lengths and K_c values for number of crops are available in Tables 11 and 12, respectively, in FAO Paper 56.¹
7. Enter the rainfall or irrigation each day.
8. In the next Worksheet Tab (Application Rate), enter the date of the first day of the crop season.
9. In the next Worksheet Tab (Application Rate), enter the area of the field in acres.
10. Enter the percent wetted area. If drip irrigation is used, only a portion of the field may become wet.
11. Enter the percent efficiency of the irrigation system.
12. Enter the pump flow rate in gallons per minute.

1.2.2 USING THE SPREADSHEET TO SCHEDULE THE IRRIGATION

The objective of the analysis is to minimize crop stress as indicated by the crop stress factor (K_s). If this parameter is <1 , then the crop is in a state of water stress. To simplify the analysis, the spreadsheet provides the column “Did Stress Occur?” (Column P, Soil Moisture Worksheet). When stress occurs, as indicated by “Yes,” then the user should irrigate the crop. To see how much the user should irrigate, see the column called “Irrigation Needed” (Column N, Soil Moisture Worksheet). Enter the amount the user wants to irrigate in the column called “Applied Irrigation or Rainfall” (Column O, Soil Moisture Worksheet). Finally, go to the Application Rate Worksheet Tab to see how many hours the user should run the irrigation system to put on the desired amount of water.

1.3 GRAPHICAL RESULTS

1.3.1 SOIL MOISTURE GRAPH WORKSHEET TAB

If the soil moisture content falls below the green line (threshold moisture content, θ_l), it indicates that the crop is in stress. Throughout the crop season, the graph should never fall below this line, if possible. It is also very important that the soil moisture does not exceed the field capacity because this water will be wasted, either through deep percolation or surface runoff.

1.3.2 $ET_{c\ adj}$ WORKSHEET TAB

The evapotranspiration is shown in this worksheet. $ET_{c\ adj}$ is the crop ET_c multiplied by the crop stress factor and represents the real ET_c . ET_c is also shown in the graph for comparison.

1.3.3 CROP STRESS FACTOR WORKSHEET TAB

This graph shows the crop stress factor as a function of time for the entire crop season. This line should be as close as possible to 1 throughout the season. Any value lower than 1 indicates that stress occurred. Note that in this worksheet, a value of the relative seasonal crop yield is also provided. The yield response factor (K_y) required to calculate the relative yield can be obtained from Table 24 of Allen et al.¹ for various crops.

1.3.4 CUMULATIVE ET VERSUS IRRIGATION WORKSHEET TAB

The purpose of this graph is to show how close the applied irrigation was to the ET_c . Throughout the season and at the end of the season, the value of the cumulative irrigation should be as close as possible to the cumulative ET_c . (Note in this graph that the ET used is the ET_c and not the $ET_{c\ adj}$).

1.3.5 APPLICATION EXAMPLES

1.3.5.1 EXAMPLE 1

In this example, we will schedule irrigations for a bell peppers. If the crop stress occurred for 1 day, then irrigation was applied the next day at more or less the value of the deficit (“Irrigation needed”). The following information applies to this example:

1. The soil is an silty clay loam having a field capacity and wilting point of 37 and 29%, respectively. The initial soil moisture content is 30%.
2. MAD for peppers is 0.3.
3. Initial soil moisture content is 34% for the irrigated area of 5 acre; the percent wetted area is 100%, irrigation efficiency is 90%; and the irrigation pump is capable of pumping 500 gallons per minute.
4. The location is Puerto Rico’s southern coast.
5. The length of the growing season is 85 days (March 14–June 6).
6. No rainfall occurred during the growing season.
7. The change in rooting depth with time was obtained from the field.
8. ET_c was obtained from the equation $ET_c = K_c \times ET_o$, where, ET_o is the reference evapotranspiration and the K_c values for peppers were obtained from the publication Allen et al.¹ ET_o was obtained from a weather station. Nowadays, weather stations routinely estimate ET_o .

Figure 1.6 shows the soil moisture content during the growth of the bell peppers. Note that irrigation was applied when the soil moisture became close to the threshold moisture content. And the amount of irrigation applied was just enough to increase the soil moisture content to the field capacity. Figure 1.7 shows the $ET_{c\ adj}$ and the ET_c . In this case, they are essentially identical because no stress was allowed to occur (i.e., $K_s = 1$ during the entire season; Fig. 1.8). Figure 1.9 shows the cumulative ET_c versus irrigation.

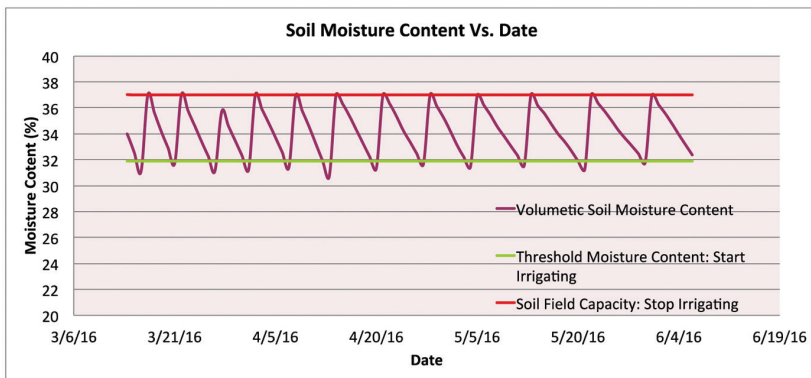


FIGURE 1.6 Soil moisture content during the growing season for Example 1.

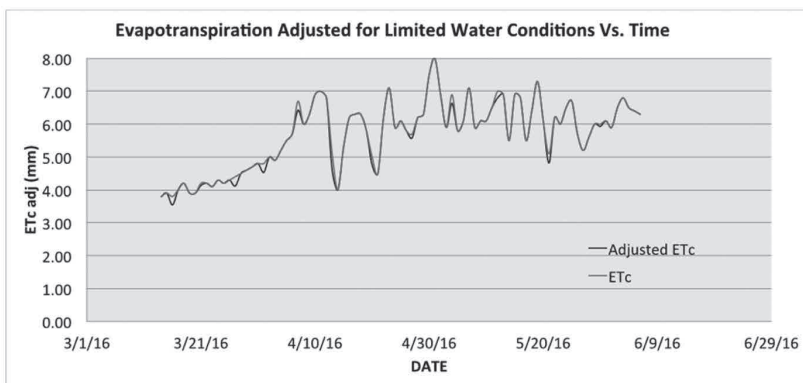


FIGURE 1.7 $ET_{c\ adj}$ and ET_c during the growing season for Example 1.

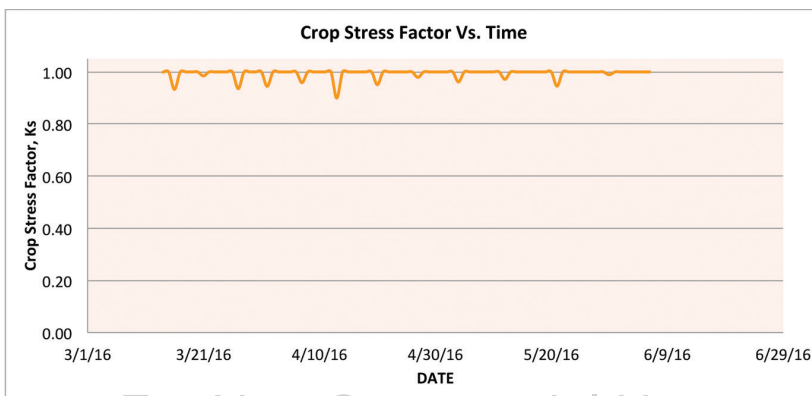


FIGURE 1.8 Crop stress factor (K_s) during the growing season for Example 1.

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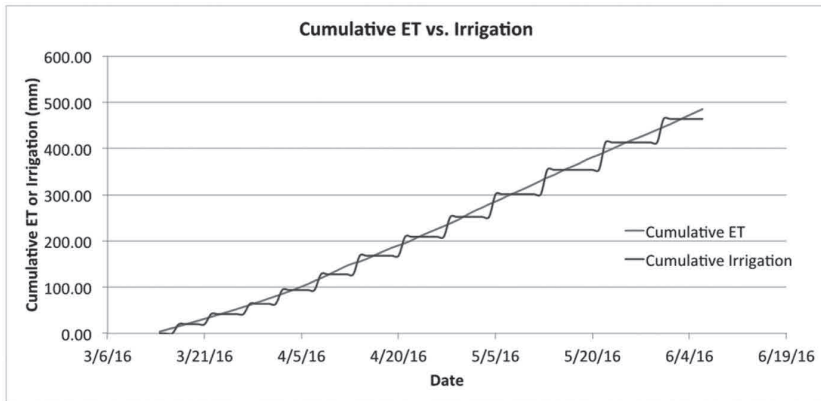


FIGURE 1.9 Cumulative ET_c and irrigation (plus rain) during the growing season for Example 1.

The estimated relative yield was 99.3% based on the value of the seasonal response function (K_y) of 1.1 for pepper.¹ The total water applied was 464 mm with no loss from surface runoff or deep percolation, and the pump was run for a total of 91.9 h during the season.

1.3.5.2 EXAMPLE 2

In this example, the user will apply 25.4 mm (1 in.) per week, which is a common practice. All other data from Example 1 are the same. Figures 1.10–1.13 show the soil moisture content, the $ET_{c\ adj}$ and ET_c , the crop stress factor, and the cumulative irrigation and ET_c during the season.

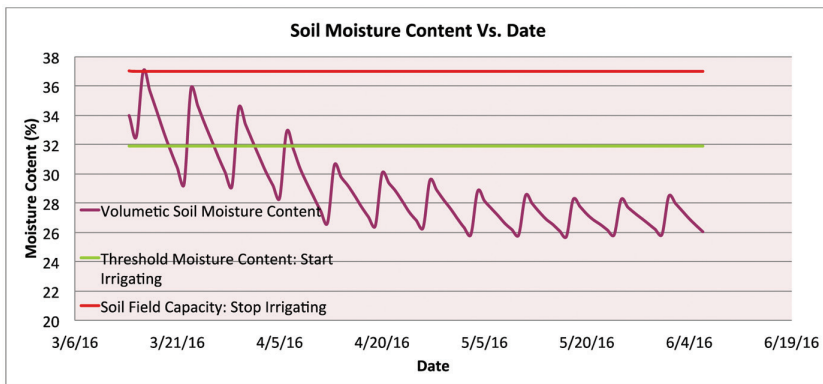


FIGURE 1.10 Soil moisture content during the growing season for Example 2.

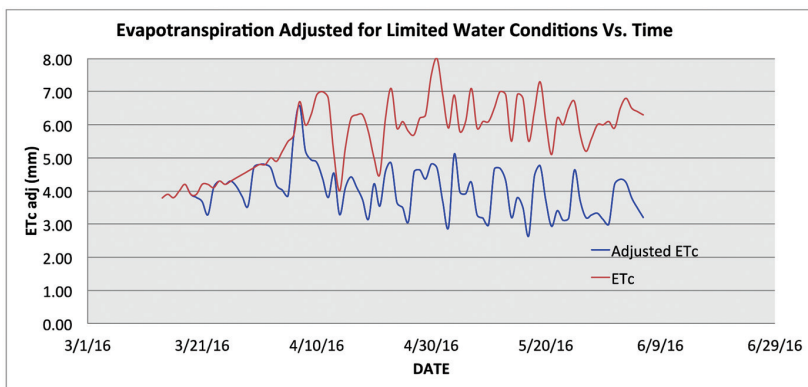


FIGURE 1.11 $ET_{c\ adj}$ and ET_c during the growing season for Example 2.

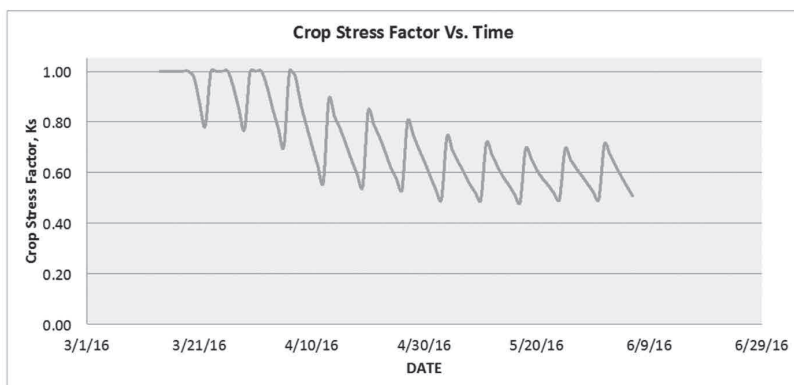


FIGURE 1.12 Crop stress factor (K_s) during the growing season for Example 2.

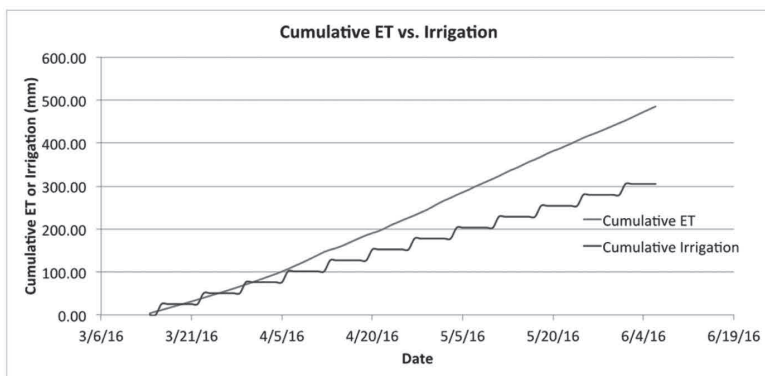


FIGURE 1.13 Cumulative ET_c and irrigation (plus rain) during the growing season for Example 2.

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The estimated relative yield is 69.5%. Interpolating the dollar loss per acre from Figure 1.2 gives \$300.60 per acre or \$1503 for 5 acre. The total water applied was 305 mm, with 3.5 mm irrigation lost to surface runoff and/or deep percolation and the pump was run for a total of 60.3 h during the season. This example clearly shows the potential for yield loss for the commonly used “1-inch per week” method.

1.4 DISCUSSION

The spreadsheet method can provide useful real-time information to an irrigator during the growing season. The method can also be used as an education tool to better understand the implications of different irrigation scheduling schemes. One of the challenges of using the spreadsheet is the requirement to enter the daily crop evapotranspiration. Operational models of ET_o are commonly available on the Internet, for example, the website <<https://prag-water.com/daily-reference-evapotranspiration-eto-for-puerto-rico-hispaniola-and-jamaica/>> provides high-resolution daily ET_o for Puerto Rico, the US Virgin Islands, Dominican Republic, Haiti, Jamaica, and Cuba. The methodologies, which include ET_o estimates using the Hargreaves–Samani,³ Penman–Monteith,¹ and Priestly–Taylor¹¹ methods, are described in Harmsen et al.⁵

1.4.1 METHOD LIMITATIONS

Using a spreadsheet method similar to the one described in this chapter is easier than done. If the spreadsheet is not updated frequently, it is quite possible that the crop will begin to experience stress without the grower knowing it. Updating the spreadsheet on a daily basis may not be possible if the source of the ET data is a weather station that needs to be physically downloaded. Weather stations that automatically upload their data to the Internet at least once a day are now commonly available.

Many of the input values used in the spreadsheet may be estimates, for example: field capacity, wilting point, initial soil moisture content (which varies spatially in the field), rooting depth, evapotranspiration, and so on. To the degree that these parameters are in error, then the results from the spreadsheet will also be in error (garbage-in garbage-out).

The spreadsheet graphs may need to be adjusted when the spreadsheet is used with new data. In general, the graphs have been designed with relative horizontal and vertical scales, which change with the data being used.

However, there may be some data that cause the graphical output to appear incorrectly, in which case the user should make the necessary adjustments to the graphs.

1.5 SUMMARY

Water, fuel, chemicals, and money can be lost if an irrigation system is not managed properly. In this chapter, a simple spreadsheet was presented that can help a farmer to schedule irrigation and achieve good water management. The method is based on the United Nations Food and Agriculture Organization Paper No. 56. An example problem was presented in which the soil moisture was maintained between the field capacity and the threshold moisture content, which resulted in no stress and no yield loss. A second example was presented in which 1 in. of water was applied each week to the pepper crop and the resulting yield and dollar losses were 69.5% and \$1503, respectively.

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KEYWORDS

- **evapotranspiration**
- **irrigation management**
- **Penman–Monteith**
- **soil water deficit**
- **water stress**

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