# 8 Evaluating and Managing Crops Water Requirement

*Zohrab Samani*

**CONTENTS**



## 8.1 INTRODUCTION

Crops use water for cooling, nutrient transport to the leaves, and photosynthesis. Most of the water used by the crop evaporates from the surface of the leaves. Plants function like an evaporative cooler where large amount of water is used for cooling, which is an integral part of the photosynthesis process. The growth of plant is tied to the ability of leaves to produce carbohydrate via photosynthesis. The carbohydrate is the basis for the accumulation of biomass and growth of the plant. The leaves capture light over the surface area of the leaves exposed to the sun. Upon exposure to the solar energy, the leaves open thousands of tiny pores (stomata) to let in carbon dioxide ($CO_2$) and solar energy to produce carbohydrate. The open stomata and solar energy also result in water evaporation at the same time. The water evaporated through the stomata is referred to as transpiration. The sum of water loss through transpiration and evaporation outside of stomata such as soil surface is referred to as evapotranspiration (ET). The ET is a function of climate condition, plant leaf area, and the stomata behavioral characteristic of the plant. The water that evaporates through ET is supplied from the stored moisture within the root zone of the plant. Thus the success of the crop growth and yield production depends on the climate, the plant, and the ability of the producer to provide the soil reservoir with timely and sufficient quantity of water. Water is the single most important production parameter in irrigated agriculture. This chapter describes how the crops' water requirement (ET) can be estimated and how the soil moisture reservoir can be managed to achieve successful production.

## 8.2 EVAPOTRANSPIRATION

To estimate the crops' water requirement, the ET is divided into two distinct parameters: the crop coefficient ($K_c$) representing the crop, and reference evapotranspiration ($ET_r$), which is calculated from the climate parameters. The ET thus can be described as

$$ET = K_c \times ET_r \tag{8.1}$$

$ET_r$ is calculated using various equations of Hargreaves and Samani (1982, 1985) and Penman–Monteith (Allen 1986), Allen et al. (1998), and ASCE-EWRI standardized reference AQ1



K15267_C008.indd 179 9/30/2013 5:36:38 PM

evapotranspiration (2005). The ASCE-EWRI (2005) has recommended two equations for calculating reference evapotranspiration ($ET_r$). Those are standardized Penman–Monteith and Hargreaves and Samani (1985). The Hargreaves–Samani equation is as follows:

$$ET_r = 0.0023 \times RA(Tc + 17.8)(TD)^{0.5} \tag{8.2}$$

where
- RA is the extraterrestrial radiation representing the amount of solar energy received at any latitude above the atmosphere
- Tc is the average of daily maximum and minimum temperatures in degree Celsius
- TD is the difference between daily maximum and minimum temperatures in degree Celsius
- $ET_r$ is the daily ET value in mm

The extraterrestrial values as a function of the latitude of location is shown in Table 8.1. Equation 8.2 uses the temperature difference to account for the loss of solar energy in the atmosphere due to cloudiness or humidity.

### 8.2.1 Crop Coefficient ($K_c$)

The most difficult parameter to be determined in assessing ET and managing water is the $K_c$. The $K_c$ value changes not only with crop, but also with time or stage of growth of the crop, crop density, and general growth conditions. The $K_c$ is also temporally and spatially variable. This means that a $K_c$ value determined for one climatic condition cannot be used for another climatic condition. One of the easiest ways to determine the $K_c$ value for a given crop under a given climatic condition and growth stage is through the use of growing degree days (GDDs) as described in the following text. The crop growth starts with the start of growing season, where plants develop leaves and start to actively grow. In annual crops, regardless of when the seed is planted, the crop growth stage starts with a minimum average temperature called the base temperature and the growth stops once a minimum temperature is occurred. The same is true for the perennial crops where the plants start to grow when a minimum base temperature is reached and will stop growth when a final minimum temperature occurs. Table 8.2 shows the base temperature and final (end) temperature for some common crops.

### 8.2.2 Calculating Growing Degree Days

The GDD calculation starts when the minimum temperature has reached the base temperature shown in Table 8.2. The equation to calculate GDD is as follows:

$$GDD = \frac{Tmax + Tmin}{2} - Tbase \tag{8.3}$$

where
- GDD is the growing degree day calculated for each day
- Tmax is the maximum daily temperature
- Tmin is the minimum daily temperature
- Tbase is the minimum start-up temperature

In calculating GDD, the Tmax is normally limited to a maximum cutoff daily temperature, which is normally 86°F. For example, if the Tmax of the day for corn crop is 90°F, Tmax is set equal to 86°F. Some crops like alfalfa and pecan do not have cutoff temperature.

**TABLE 8.1**
**Extraterrestrial Radiation (RA) (mm/day)**

| Jan | Feb | Mar | Apr | May | June | Jul | Aug | Sep | Oct | Nov | Dec | Lat° | Jan | Feb | Mar | Apr | May | June | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3.8 | 6.1 | 9.4 | 12.7 | 15.8 | 17.1 | 16.4 | 14.1 | 10.9 | 7.4 | 4.5 | 3.2 | 50 | 17.5 | 14.7 | 10.9 | 7.0 | 4.2 | 3.1 | 3.5 | 5.5 | 8.9 | 12.9 | 16.5 | 18.2 |
| 4.3 | 6.6 | 9.8 | 13.0 | 15.9 | 17.2 | 16.5 | 14.3 | 11.2 | 7.8 | 5.0 | 3.7 | 48 | 17.6 | 14.9 | 11.2 | 7.5 | 4.7 | 3.5 | 4.0 | 6.0 | 9.3 | 13.2 | 16.6 | 18.2 |
| 4.9 | 7.1 | 10.2 | 13.3 | 16.0 | 17.2 | 16.6 | 14.5 | 11.5 | 8.3 | 5.5 | 4.3 | 46 | 17.7 | 15.1 | 11.5 | 7.9 | 5.2 | 4.0 | 4.4 | 6.5 | 9.7 | 13.4 | 16.7 | 18.3 |
| 5.3 | 7.6 | 10.6 | 13.7 | 16.1 | 17.2 | 16.6 | 14.7 | 11.9 | 8.7 | 6.0 | 4.7 | 44 | 17.8 | 15.3 | 11.9 | 8.4 | 5.7 | 4.4 | 4.9 | 6.9 | 10.2 | 13.7 | 16.7 | 18.3 |
| 5.9 | 8.1 | 11.0 | 14.0 | 16.2 | 17.3 | 16.7 | 15.0 | 12.2 | 9.1 | 6.5 | 5.2 | 42 | 17.8 | 15.5 | 12.2 | 8.8 | 6.1 | 4.9 | 5.4 | 7.4 | 10.6 | 14.0 | 16.8 | 18.3 |
| 6.4 | 8.6 | 11.4 | 14.3 | 16.4 | 17.3 | 16.7 | 15.2 | 12.5 | 9.6 | 7.0 | 5.7 | 40 | 17.9 | 15.7 | 12.5 | 9.2 | 6.6 | 5.3 | 5.9 | 7.9 | 11.0 | 14.2 | 16.9 | 18.3 |
| 6.9 | 9.0 | 11.8 | 14.5 | 16.4 | 17.2 | 16.7 | 15.3 | 12.8 | 10.0 | 7.5 | 6.1 | 38 | 17.9 | 15.8 | 12.8 | 9.6 | 7.1 | 5.8 | 6.3 | 8.3 | 11.4 | 11.4 | 17.0 | 18.3 |
| 7.4 | 9.4 | 12.1 | 14.7 | 16.4 | 17.2 | 16.7 | 15.4 | 13.1 | 10.6 | 8.0 | 6.6 | 36 | 17.9 | 16.0 | 13.2 | 10.1 | 7.5 | 6.3 | 6.8 | 8.8 | 11.7 | 14.6 | 17.0 | 18.2 |
| 7.9 | 9.8 | 12.4 | 14.8 | 16.5 | 17.1 | 16.8 | 15.5 | 13.4 | 10.8 | 8.5 | 7.2 | 34 | 17.8 | 16.1 | 13.5 | 10.5 | 8.0 | 6.8 | 7.2 | 9.2 | 12.0 | 14.9 | 17.1 | 18.2 |
| 8.3 | 10.2 | 12.8 | 15.0 | 16.5 | 17.0 | 16.8 | 15.6 | 13.6 | 11.2 | 9.0 | 7.8 | 32 | 17.8 | 16.2 | 13.8 | 10.9 | 8.5 | 7.3 | 7.7 | 9.6 | 12.4 | 15.1 | 17.2 | 18.1 |
| 8.8 | 10.7 | 13.1 | 15.2 | 16.5 | 17.0 | 16.8 | 15.7 | 13.9 | 11.6 | 9.5 | 8.3 | 30 | 17.8 | 16.4 | 14.0 | 11.3 | 8.9 | 7.8 | 8.1 | 10.1 | 12.7 | 15.3 | 17.3 | 18.1 |
| 9.3 | 11.1 | 13.4 | 15.3 | 16.5 | 16.8 | 16.7 | 15.7 | 14.1 | 12.0 | 9.9 | 8.8 | 28 | 17.7 | 16.4 | 14.3 | 11.6 | 9.3 | 8.2 | 8.6 | 10.4 | 13.0 | 15.4 | 17.2 | 17.9 |
| 9.8 | 11.5 | 13.7 | 15.3 | 16.4 | 16.7 | 16.6 | 15.7 | 14.3 | 12.3 | 10.3 | 9.3 | 26 | 17.6 | 16.4 | 14.4 | 12.0 | 9.7 | 8.7 | 9.1 | 10.9 | 13.2 | 15.5 | 17.2 | 17.8 |
| 10.2 | 11.9 | 13.9 | 15.4 | 16.4 | 16.6 | 16.5 | 15.8 | 14.5 | 12.6 | 10.7 | 9.7 | 24 | 17.5 | 16.5 | 14.6 | 12.3 | 10.2 | 9.1 | 9.5 | 11.2 | 13.4 | 15.6 | 17.1 | 17.7 |
| 10.7 | 12.3 | 14.2 | 15.5 | 16.3 | 16.4 | 16.4 | 15.8 | 14.6 | 13.0 | 11.1 | 10.2 | 22 | 17.4 | 16.5 | 14.8 | 12.6 | 10.6 | 9.6 | 10.0 | 11.6 | 13.7 | 15.7 | 17.0 | 17.5 |
| 11.2 | 12.7 | 14.4 | 15.6 | 16.3 | 16.4 | 16.3 | 15.9 | 14.8 | 13.3 | 11.6 | 10.7 | 20 | 17.3 | 16.5 | 15.0 | 13.0 | 11.0 | 10.0 | 10.4 | 12.0 | 13.9 | 15.8 | 17.0 | 17.4 |
| 11.6 | 13.0 | 14.6 | 15.6 | 16.1 | 16.3 | 16.1 | 15.8 | 14.9 | 13.6 | 12.0 | 11.1 | 18 | 17.1 | 16.5 | 15.1 | 13.2 | 11.4 | 10.4 | 10.8 | 12.3 | 14.1 | 15.8 | 16.8 | 17.1 |
| 12.0 | 13.3 | 14.7 | 15.6 | 16.0 | 15.9 | 15.9 | 15.7 | 15.0 | 13.9 | 12.4 | 11.6 | 16 | 16.9 | 16.4 | 15.2 | 13.5 | 11.7 | 10.8 | 11.2 | 12.6 | 14.3 | 15.8 | 16.7 | 16.8 |
| 12.4 | 13.6 | 14.9 | 15.7 | 15.8 | 15.7 | 15.7 | 15.7 | 15.1 | 14.1 | 12.8 | 12.0 | 14 | 16.7 | 16.4 | 15.3 | 13.7 | 12.1 | 11.2 | 11.6 | 12.9 | 14.5 | 15.8 | 16.5 | 16.6 |
| 12.8 | 13.9 | 15.1 | 15.7 | 15.7 | 15.5 | 15.5 | 15.6 | 15.2 | 14.4 | 13.3 | 12.5 | 12 | 16.6 | 16.3 | 15.4 | 14.0 | 12.5 | 11.6 | 12.0 | 13.2 | 14.7 | 15.8 | 16.4 | 16.5 |
| 13.2 | 14.2 | 15.3 | 15.7 | 15.5 | 15.3 | 15.3 | 15.5 | 15.3 | 14.7 | 13.6 | 12.9 | 10 | 16.4 | 16.3 | 15.5 | 14.2 | 12.8 | 12.0 | 12.4 | 13.5 | 14.8 | 15.9 | 16.2 | 16.2 |
| 13.6 | 14.5 | 15.3 | 15.6 | 15.3 | 15.0 | 15.1 | 15.4 | 15.3 | 14.8 | 13.9 | 13.3 | 8 | 16.1 | 16.1 | 15.5 | 14.4 | 13.1 | 12.4 | 12.7 | 13.7 | 14.9 | 15.8 | 16.0 | 16.0 |
| 13.9 | 14.8 | 15.4 | 15.4 | 15.1 | 14.7 | 14.9 | 15.2 | 15.3 | 15.0 | 14.2 | 13.7 | 6 | 15.8 | 16.0 | 15.6 | 14.7 | 13.4 | 12.8 | 13.1 | 14.0 | 15.0 | 15.7 | 15.8 | 15.7 |
| 14.3 | 15.0 | 15.5 | 15.5 | 14.9 | 14.4 | 14.6 | 15.1 | 15.3 | 15.1 | 14.5 | 14.1 | 4 | 15.5 | 15.8 | 15.6 | 14.9 | 13.8 | 13.2 | 13.4 | 14.3 | 15.1 | 15.6 | 15.5 | 15.4 |
| 14.7 | 15.3 | 15.6 | 15.3 | 14.6 | 14.2 | 14.3 | 14.9 | 15.3 | 15.3 | 14.8 | 14.4 | 2 | 15.3 | 15.7 | 15.7 | 15.1 | 14.1 | 13.5 | 13.7 | 14.5 | 15.2 | 15.5 | 15.3 | 15.1 |
| 15.0 | 15.5 | 15.7 | 15.3 | 14.4 | 13.9 | 14.1 | 14.8 | 15.3 | 15.4 | 15.1 | 14.8 | 0 | 15.0 | 15.5 | 15.7 | 15.3 | 14.4 | 13.9 | 14.1 | 14.8 | 15.3 | 15.4 | 15.1 | 14.8 |

**TABLE 8.2**
**Plant Growing Season Start-Up and End Temperature in °F**

| Crop | Earliest Mean Temperature (°F) | End Temperature |
|---|---|---|
| *Perennial crops* | | |
| Alfalfa | 50 | 28°frost |
| Cool season grasses | 45 | 45°F |
| AQ2 Decides orchards | 50 | 45°F |
| Grapes | 55 | 50°F |
| Pecan | 60 | 25°frost |
| Pomegranate and almond | 50 | 28°frost |
| *Annual crops* | | |
| Dry beans | 60 | 32°frost |
| Corn | 55 | 32°frost |
| Cotton | 62 | 32°frost |
| Spring grain | 45 | 32°frost |
| Potatoes | 60 | 32°frost |
| Sorghum, grain | 60 | 32°frost |
| Sugar beets | 28 | 28°frost |
| AQ3 Wheat | 45 | 45° |
| Tomato | 50 | 32°frost |

AQ4 **TABLE 8.3**
**Relationship between $K_c$ and GDD for Various Stages of Growth**

| **Corn—Grain** | **Tbase** | **55°F** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Time % to full cover | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 |
| GDD | 5.3 | 23.4 | 53.5 | 102 | 164 | 222 | 318 | 425 | 541 | 644 |
| $K_c$, before full cover | 0.345 | 0.345 | 0.345 | 0.345 | 0.368 | 0.483 | 0.633 | 0.805 | 0.98 | 1.093 |
| Days-after-full cover | 10 | 20 | 30 | 40 | 50 | 60 | 68 | | | |
| GDD | 833 | 1002 | 1168 | 1341 | 1472 | 1567 | 1603 | | | |
| $K_c$ | 1.104 | 1.093 | 1.081 | 1.035 | 0.978 | 0.909 | 0.85 | | | |

Once the daily GDD is calculated, the cumulative (sum-GDD) is calculated starting from day 1 and related to crop coefficient $K_c$. There is a direct relationship between sum-GDD and $K_c$ of crop throughout the growing season. Tables 8.3 through 8.7 show the relationship between sum-GDD and $K_c$ for several crops. Tables 8.3 through 8.7 were created using 8 years of experimental data presented by Wright (1981).

### Example 8.1

AQ5
AQ6 Table 8.8 shows the procedure to calculate daily ET and growing season ET of grain corn crop for Laguna, New Mexico, using GDD. In this example, Table 8.8 for grain corn was used to calculate GDD from temperature data. The calculation starts from day 120 of the year when the average daily temperature reaches 55°F, and a positive GDD can be calculated. The daily GDD is then summed up starting from day 120 until the maximum GDD value of 1603°F when the crop matures. The daily $K_c$ is then calculated based on the cumulative GDD (sum-GDD) value.

**TABLE 8.4**
**Relationship between $K_c$ and GDD for Various Stages of Growth**

| **Corn—Sweet** | **Tbase** | **55°F** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Time % to full cover | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 |
| GDD | 5.3 | 23.4 | 53.5 | 101 | 164 | 222 | 318 | 423 | 541 | 644 |
| $K_c$, before full cover | 0.345 | 0.345 | 0.345 | 0.345 | 0.368 | 0.483 | 0.632 | 0.805 | 0.98 | 1.093 |
| Days after full cover | 10 | 20 | 30 | | | | | | | |
| GDD | 833 | 1002 | 1168 | | | | | | | |
| kc, after full cover | 1.07 | 1.07 | 1.035 | | | | | | | |

**TABLE 8.5**
**Relationship between $K_c$ and GDD for Various Stages of Growth**

| **Bean** | **Tbase** | **60°F** | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Time % to full cover | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 |
| Sum-GDD | 20 | 35 | 70.3 | 106 | 164 | 220 | 292 | 341 |
| $K_c$ | 0.345 | 0.403 | 0.518 | 0.633 | 0.78 | 0.92 | 1.035 | 1.093 |
| Days after | 10 | 20 | 30 | 40 | 45 | | | |
| Sum-GDD | 463 | 582 | 698 | 808 | 865 | | | |
| kc | 1.093 | 1.035 | 0.77 | 0.38 | 0.173 | | | |

AQ7

**TABLE 8.6**
**Relationship between $K_c$ and GDD for Various Stages of Growth**

| **Barley** | **Tbase** | **45°F** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Time % to full cover | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 |
| GDD | | 8.23 | 25.6 | 67.1 | 140 | 204 | 293 | 421 | 531 | 613 |
| kc, before | | 0.345 | 0.368 | 0.46 | 0.748 | 0.978 | 1.093 | 1.14 | 1.15 | 1.15 |
| Days after | 20 | 30 | 40 | 50 | 55 | | | | | |
| GDD | 1030 | 1276 | 1529 | 1781 | 1827 | | | | | |
| $K_c$ | 1.15 | 1.035 | 0.575 | 0.288 | 0.173 | | | | | |

AQ8

**TABLE 8.7**
**Relationship between $K_c$ and GDD for Various Stages of Growth**

| **Alfalfa 1146 GDD/Cut** | **Tbase** | **41°F** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Time % of total cycle | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 |
| $K_c$, first cut | 0.805 | 0.94 | 1.05 | 1.104 | 1.15 | 1.15 | 1.127 | 1.104 | 1.093 | 1.093 |
| $K_c$, second + third cuts | 0.46 | 0.575 | 0.92 | 1.104 | 1.13 | 1.15 | 1.15 | 1.13 | 1.093 | 1.093 |
| Fourth cut | 0.46 | 0.51 | 0.69 | 0.75 | 0.63 | 0.58 | 0.52 | 0.4 | 0.35 | 0.29 |

AQ9

**TABLE 8.8**
**ET Calculation for Grain Corn in Laguna, New Mexico**

| DOY | Sum-GDD | $ET_r$ | $K_c$ | ET (mm) | DOY | Sum-GDD | $ET_r$ | $K_c$ | ET (mm) |
|---|---|---|---|---|---|---|---|---|---|
| 120 | 0.69 | 4.8 | 0.345 | 1.65 | 166 | 354 | 6.8 | 0.805 | 5.49 |
| 121 | 1.11 | 4.7 | 0.345 | 1.62 | 167 | 368 | 6.8 | 0.805 | 5.44 |
| 122 | 1.59 | 4.7 | 0.345 | 1.61 | 168 | 382 | 6.8 | 0.805 | 5.44 |
| 123 | 2.07 | 4.8 | 0.345 | 1.65 | 169 | 397 | 6.8 | 0.805 | 5.51 |
| 124 | 4.27 | 4.9 | 0.345 | 1.7 | 170 | 411 | 7 | 0.805 | 5.6 |
| 125 | 7.63 | 5 | 0.345 | 1.74 | 171 | 427 | 6.9 | 0.805 | 5.52 |
| 126 | 10.6 | 5 | 0.345 | 1.73 | 172 | 442 | 6.8 | 0.98 | 6.64 |
| 127 | 13.4 | 5 | 0.345 | 1.74 | 173 | 458 | 6.8 | 0.98 | 6.7 |
| 128 | 16.4 | 5.1 | 0.345 | 1.75 | 174 | 473 | 6.9 | 0.98 | 6.8 |
| 129 | 20.3 | 5.2 | 0.345 | 1.78 | 175 | 489 | 7 | 0.98 | 6.82 |
| 130 | 23.9 | 5.2 | 0.345 | 1.79 | 176 | 504 | 7 | 0.98 | 6.83 |
| 131 | 27.6 | 5.2 | 0.345 | 1.8 | 177 | 520 | 7 | 0.98 | 6.86 |
| 132 | 31.4 | 5.3 | 0.345 | 1.82 | 178 | 536 | 6.9 | 0.98 | 6.76 |
| 133 | 35.9 | 5.3 | 0.345 | 1.84 | 179 | 552 | 7 | 1.093 | 7.62 |
| 134 | 40.7 | 5.3 | 0.345 | 1.84 | 180 | 568 | 7 | 1.093 | 7.6 |
| 135 | 46.3 | 5.4 | 0.345 | 1.85 | 181 | 585 | 6.8 | 1.093 | 7.46 |
| 136 | 51.8 | 5.4 | 0.345 | 1.87 | 182 | 602 | 6.7 | 1.093 | 7.37 |
| 137 | 58 | 5.5 | 0.368 | 2.03 | 183 | 618 | 6.8 | 1.093 | 7.45 |
| 138 | 64.4 | 5.5 | 0.368 | 2.03 | 184 | 635 | 6.6 | 1.093 | 7.24 |
| 139 | 71.5 | 5.6 | 0.368 | 2.08 | 185 | 652 | 6.6 | 1.093 | 7.27 |
| 140 | 79.4 | 5.7 | 0.368 | 2.08 | 186 | 669 | 6.7 | 1.104 | 7.35 |
| 141 | 86.1 | 5.6 | 0.368 | 2.05 | 187 | 686 | 6.7 | 1.104 | 7.44 |
| 142 | 92.8 | 5.7 | 0.368 | 2.09 | 188 | 703 | 6.7 | 1.104 | 7.45 |
| 143 | 99.9 | 5.7 | 0.368 | 2.1 | 189 | 720 | 6.7 | 1.104 | 7.45 |
| 144 | 108 | 5.8 | 0.368 | 2.12 | 190 | 737 | 6.7 | 1.104 | 7.37 |
| 145 | 116 | 5.8 | 0.368 | 2.12 | 191 | 754 | 6.6 | 1.104 | 7.32 |
| 146 | 125 | 5.7 | 0.368 | 2.11 | 192 | 772 | 6.6 | 1.104 | 7.32 |
| 147 | 134 | 5.7 | 0.368 | 2.11 | 193 | 789 | 6.6 | 1.104 | 7.26 |
| 148 | 142 | 5.9 | 0.368 | 2.15 | 194 | 807 | 6.6 | 1.104 | 7.27 |
| 149 | 151 | 6 | 0.368 | 2.21 | 195 | 824 | 6.6 | 1.104 | 7.33 |
| 150 | 161 | 6 | 0.368 | 2.22 | 196 | 841 | 6.5 | 1.104 | 7.12 |
| 151 | 170 | 6 | 0.483 | 2.91 | 197 | 859 | 6.5 | 1.093 | 7.11 |
| 152 | 180 | 6.1 | 0.483 | 2.94 | 198 | 876 | 6.4 | 1.093 | 7.01 |
| 153 | 190 | 6.1 | 0.483 | 2.94 | 199 | 894 | 6.4 | 1.093 | 7.02 |
| 154 | 201 | 6.1 | 0.483 | 2.96 | 200 | 912 | 6.4 | 1.093 | 7.01 |
| 155 | 211 | 6.1 | 0.483 | 2.96 | 201 | 929 | 6.4 | 1.093 | 6.97 |
| 156 | 222 | 6.2 | 0.483 | 2.99 | 202 | 946 | 6.3 | 1.093 | 6.87 |
| 157 | 234 | 6.3 | 0.633 | 4.01 | 203 | 964 | 6.3 | 1.093 | 6.91 |
| 158 | 247 | 6.4 | 0.633 | 4.05 | 204 | 981 | 6.4 | 1.093 | 6.97 |
| 159 | 260 | 6.4 | 0.633 | 4.06 | 205 | 998 | 6.3 | 1.093 | 6.9 |
| 160 | 273 | 6.4 | 0.633 | 4.07 | 206 | 1016 | 6.3 | 1.081 | 6.76 |
| 161 | 285 | 6.4 | 0.633 | 4.08 | 207 | 1034 | 6.2 | 1.081 | 6.67 |
| 162 | 299 | 6.4 | 0.633 | 4.06 | 208 | 1051 | 6.2 | 1.081 | 6.67 |
| 163 | 312 | 6.4 | 0.633 | 4.03 | 209 | 1068 | 6.2 | 1.081 | 6.65 |
| 164 | 326 | 6.6 | 0.633 | 4.17 | 210 | 1086 | 6.1 | 1.081 | 6.58 |
| 165 | 340 | 6.6 | 0.805 | 5.34 | 211 | 1103 | 6.2 | 1.081 | 6.71 |

**TABLE 8.8 (continued)**
**ET Calculation for Grain Corn in Laguna, New Mexico**

| DOY | Sum-GDD | $ET_r$ | $K_c$ | ET (mm) | DOY | Sum-GDD | $ET_r$ | $K_c$ | ET (mm) |
|---|---|---|---|---|---|---|---|---|---|
| 212 | 1121 | 6.1 | 1.081 | 6.58 | 227 | 1380 | 5.6 | 0.978 | 5.47 |
| 213 | 1139 | 6.1 | 1.081 | 6.64 | 228 | 1396 | 5.6 | 0.978 | 5.48 |
| 214 | 1156 | 6.1 | 1.081 | 6.59 | 229 | 1413 | 5.6 | 0.978 | 5.48 |
| 215 | 1174 | 6 | 1.081 | 6.47 | 230 | 1429 | 5.6 | 0.978 | 5.5 |
| 216 | 1191 | 5.9 | 1.035 | 6.07 | 231 | 1446 | 5.6 | 0.978 | 5.48 |
| 217 | 1208 | 5.8 | 1.035 | 6.05 | 232 | 1462 | 5.5 | 0.978 | 5.38 |
| 218 | 1226 | 5.9 | 1.035 | 6.1 | 233 | 1479 | 5.4 | 0.978 | 5.26 |
| 219 | 1243 | 5.9 | 1.035 | 6.06 | 234 | 1495 | 5.4 | 0.909 | 4.88 |
| 220 | 1261 | 6 | 1.035 | 6.17 | 235 | 1511 | 5.4 | 0.909 | 4.92 |
| 221 | 1278 | 5.9 | 1.035 | 6.09 | 236 | 1527 | 5.3 | 0.909 | 4.83 |
| 222 | 1295 | 5.8 | 1.035 | 5.99 | 237 | 1542 | 5.4 | 0.909 | 4.95 |
| 223 | 1312 | 5.8 | 1.035 | 5.99 | 238 | 1558 | 5.4 | 0.909 | 4.88 |
| 224 | 1329 | 5.7 | 1.035 | 5.92 | 239 | 1574 | 5.3 | 0.909 | 4.86 |
| 225 | 1346 | 5.7 | 1.035 | 5.88 | 240 | 1590 | 5.3 | 0.85 | 4.48 |
| 226 | 1363 | 5.7 | 0.978 | 5.53 | 241 | 1606 | 5.2 | 0.85 | 4.43 |

Thedaily ET values are then calculated by multiplying daily $ET_r$ by daily $K_c$ values as shown in Equation 8.1. Note that even though in Table 8.2 the end temperature is shown as 32°frost, the actual maturity and end of growing season occur on day 241 of the year when the cumulative GDD reaches the 1603°F value, which is the required GDD for maturity. In this example, the length of growing season for grain corn is 122 days (from day 120–241). The same crop will reach maturity in only 106 days in Las Cruces, New Mexico, due to higher daily temperature. The growing season will also vary depending on when the crop is planted. If a crop is planted later than day 120, then it will mature at a later day, but most likely at a shorter growing season.

### 8.2.3 Irrigation Interval

One of the main questions to be answered in an irrigation management is when to irrigate. In drip, and sprinkler irrigation, it is possible to irrigate every day. However, from practical, agronomic, and economic points of view, the best time of irrigation is when the readily available water (RAW) is consumed. One can calculate the RAW by having the knowledge of soil type, root depth, and crop management allowed depletion known as MAD. To calculate RAW, one needs to know the soil field capacity (FC) and the crop root depth. The MAD is also a function of crop.

The RAW is calculated as

$$RAW = MAD \cdot (F)(FC)(RD) \tag{8.4}$$

where

RAW is the readily available water
MAD is the management allowed depletion from Table 8.9
RD is the root depth
F is the soil factor, which is taken as 0.5 for medium soil, 0.4 for clay soil, and 0.6 for sandy soil

Table 8.10 shows MAD and root depth for various crops. The root depth can vary depending on the soil type and age of the crop. If not sure, one can always use the lower value of root depth to calculate RAW and irrigation interval. AQ10

AQ11

**TABLE 8.9**
**Typical Root Depth and MAD Values for Various Crops**

| Crop | MAD | Root Depth (ft) | Root Depth (m) |
|---|---|---|---|
| Almond | 0.6 | 3–4 | 1–1.3 |
| Alfalfa | 0.55 | 3–10 | 1–3 |
| Banana | 0.35 | 2–3 | 0.6–0.9 |
| Barley | 0.55 | 3–5 | 1–1.5 |
| Beans | 0.45 | 1–2 | 0.3–0.7 |
| Beets | 0.5 | 2–3 | 0.6–1.0 |
| Cabbage | 0.45 | 1–2 | 0.3–0.6 |
| Carrots | 0.35 | 1–3 | 0.3–1.0 |
| Celery | 0.20 | 1–2 | 0.3–0.5 |
| Citrus | 0.5 | 4–5 | 1.2–1.5 |
| Clover | 0.35 | 2–3 | 0.6–0.9 |
| Corn | 0.6 | 3–5 | 1–1.7 |
| Cotton | 0.6 | 3–5 | 1–1.7 |
| Cucumber | 0.5 | 2–4 | 0.7–1.2 |
| Dates | 0.5 | 5–8 | 1.5–2.5 |
| Flax | 0.5 | 3–5 | 1.0–1.5 |
| Grains, small | 0.55 | 3–5 | 1–1.5 |
| Grapes | 0.35 | 3–6 | 1–1.8 |
| Grass | 0.5 | 2–5 | 0.6–1.5 |
| Lettuce | 0.30 | 1–2 | 0.3–0.6 |
| Melons | 0.35 | 3–5 | 1–1.5 |
| Olives | 0.65 | 4–5 | 1.2–1.5 |
| Onions | 0.25 | 1–2 | 0.3–0.6 |
| Peas | 0.35 | 2–3 | 0.6–1.0 |
| Pepper (Chile) | 0.25 | 2–3 | 0.6–1.0 |
| Pecan | 0.55 | 3–6 | 1.0–2.0 |
| Pineapple | 0.5 | 1–2 | 0.3–0.6 |
| Potatoes | 0.25 | 1–2 | 0.3–0.6 |
| Pomegranate | 0.55 | 3–6 | 1–2 |

### Example 8.2

AQ12 Table 8.11 shows the $K_c$ values for mature almond. If the $ET_r$ for the month of June is 8 mm/day and the crop coefficient from Table 8.11 is 0.9, then the ET can be calculated as

$$ET = kc \times ET_r = 0.9(8) = 7.2 \text{ mm/day}$$

Taking the MAD value of 0.6 and root depth of 1 m from Table 8.9, for a medium soil with an FC of 0.3 (30%), the RAW can then be calculated as

$$RAW = 0.6(0.5)(0.3)(1.0) = 0.09 \text{ m} = 90 \text{ mm}$$

That means that the soil can hold 90 mm of water within the root zone of the crop without causing stress. If the ET is 7.2 mm/day in the month of June, then there is enough water to last 13 days (90/7.2) before the next irrigation. One factor that can change is the effective rainfall. There are

**TABLE 8.10**
**Typical Root Depth and MAD Values for Various Crops**

| Crop | MAD | Root Depth (ft) | Root Depth (m) |
|---|---|---|---|
| Safflower | 0.6 | 3–6 | 1–2 |
| Sorghum | 0.55 | 3–6 | 1–2 |
| Soybeans | 0.5 | 2–4 | 0.6–1.2 |
| Spinach | 0.2 | 1–2 | 0.3–0.6 |
| Strawberries | 0.15 | 0.5–1.0 | 0.2–0.6 |
| Sugar beets | 0.5 | 2–4 | 0.6–1.2 |
| Sugarcane | 0.65 | 4–6 | 1.2–2 |
| Sunflower | 0.45 | 3–5 | 1–1.5 |
| Sweet potatoes | 0.65 | 3–5 | 1–1.5 |
| Tomatoes | 0.4 | 2–5 | 0.6–1.5 |
| Vegetables | 0.2 | 1–2 | 0.3–0.6 |
| Wheat | 0.55 | 3–5 | 1–1.5 |

**TABLE 8.11**
**Almond Crop Coefficient ($K_c$) Recommended by UN-FAO**

| Month | Dec/Jan | Feb | Mar | April | May | June/July/Aug | Sep | Oct | Nov |
|---|---|---|---|---|---|---|---|---|---|
| $K_c$ with cover crop | 0.85 | 0.85 | 0.85 | 0.95 | 1.05 | 1.15 | 1.10 | 0.90 | 0.85 |
| $K_c$ without cover crop | 0.00 | 0.00 | 0.50 | 0.70 | 0.85 | 0.90 | 0.80 | 0.75 | 0.65 |

various ways to calculate the effective rainfall. One of the simplest equations is the NRCS/USDA (1970), which is described as AQ13

$$\text{Re} = (0.70917 \cdot [\text{Rt}]^{0.82416} - 0.11556) \cdot (10^{0.02426[\text{U}]}) \quad (8.5)$$

where
 Re is the effective rainfall
 Rt is the monthly rainfall in inches
 U is the monthly consumptive use in inches

In this example, if we had 1 in. (25.4) of rainfall during the 13 days, that would be equivalent to 2.3 in./month. Using Equation 8.5, and monthly equivalent of 8.5 in. (216 mm) of ET, the effective rainfall for the equivalent month is calculated as

$$\text{Re} = 2.08 \text{ in.} = 52.8 \text{ mm}$$

Adjusting the monthly Re for 13 days, the effective rainfall during the 13 days would be 22.9 mm. This can then prolong the irrigation for another 3 days (22.9/7.2). This results in the total irrigation interval of 13 + 3 = 16 days. AQ14

### 8.2.4 Alternative Method "Calculating ET without GDD"

In the absence of $K_c$–GDD relationship shown in Tables 8.3 through 8.7, a simplified approach can be used to calculate $K_c$ and ET. Allen et al. (1998), in FAO-56, has provided some information on the stages of growth and the relevant $K_c$ for various climate conditions. Allen et al. (1998) has divided the stages of growth into four phases of initial, growing stage, midseason, and late season similar to Figure 8.1. The definition of each stage is as follows:

Stage 1. From planting to 10% ground cover
Stage 2. From 10% ground cover to maximum growth
Stage 3. From maximum growth to the start of maturity
Stage 4. From the start of maturity to maturity or harvest

AQ15 Allen et al. (1998) have then provided corresponding number of days for each stage and $k_c$ values
for initial, midseason, and end date. Table 8.8 shows an example of such data. For growing crops
in a new region or a different planting date, one can construct $K_c$ versus days or GDD similar to
AQ16 Figure 8.1, by knowing the duration of each growth stage and the corresponding $K_c$ values for Kc1,
AQ17 Kc3, and Kc-end shown in Table 8.12. However, the information on stages and corresponding kc
AQ18 need to be reconfigured for a new location or new planting date. Example 8.3 shows how informa-
tion on stage and kc can be transferred for a new location or a new planting date.

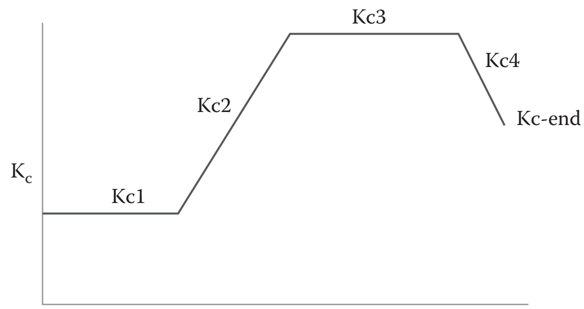


**FIGURE 8.1** $K_c$ versus the stages of growth in a typical crop.

**TABLE 8.12**
**Stages of Growth and $K_c$ Values for Typical Crops**

AQ19

| Crop | Stages (Days) | | | | Total (Days) | $K_c$ | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | Kc1 | kc3 | kc-end |
| Tomato | 35 | 40 | 50 | 30 | 155 | 0.6 | 1.15 | 0.8 |
| Cantaloupe | 30 | 45 | 35 | 10 | 120 | 0.5 | 0.85 | 0.60 |
| Potato | 25 | 30 | 45 | 30 | 130 | 0.5 | 1.15 | 0.75 |

*Source:* Allen, R.G. et al., Crop evapotranspiration: Guidelines for computing crop water requirements, Food and Agriculture Organization, FAO Irrigation and Drainage Paper No. 56, Rome, Italy, 1998.

**Example 8.3**

Research has shown that tomato requires between 1600 and 1850 GDD with a base temperature of 50°F from planting to maturity depending on the variety. If we intend to plant an early variety tomato in Las Cruces, New Mexico, the crop can be planted as early as day 83. Calculating cumulative GDD, for the area, it shows that the crop will reach maturity on day 176, a total of 94 days. Looking at Table 8.8, the total growing season is given as 155 days. A simple way to determine the $K_c$–days relationship would be to scale the growing season by multiplying the length of each stage by the ratio of (94/155 = 0.605). The new stages of growth for the tomato will then be calculated as follows:

| Stages 1 | 2 | 3 | 4 |
|---|---|---|---|
| Days 21 | 24 | 31 | 18 |

And the corresponding kc for each stage can then be calculated using the $K_c$ values in Table 8.8.

A more accurate relationship can be established by modifying the length of each stage by observing the duration of the first two stages in the field and calculating the duration of the third and fourth stages using the remaining days.

### 8.2.5 Perennial Crops

The crop coefficients for perennial crops such as almond, pecan, or grapes are normally shown on monthly basis as is shown in Tables 8.11 and 8.13. The growing season in such crops starts as the minimum beginning temperature is reached and ends when minimum temperature is reached at the end of season. In perennial crops, the ET values are normally calculated for growing season, and irrigation is practiced during growing season. However, the perennial crops never stop using water even during what is called the dormant season. When perennial crops lose their leaves, their physiological activities slow down but do not cease. During this period, the $K_c$ reduces to basic $K_c$, which is typically 0.3–0.40. During this dormant period, the plants continue to lose water and may

**TABLE 8.13**
**Monthly $K_c$ Values for Grapes Based on Four Climatic Conditions**

| Cond. | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov |
|---|---|---|---|---|---|---|---|---|---|
| Mature grapes grown in areas with killing frost, ground cover 40%–50% | | | | | | | | | |
| 1 | — | — | 0.50 | 0.65 | 0.75 | 0.80 | 0.75 | 0.65 | — |
| 2 | — | — | 0.50 | 0.70 | 0.80 | 0.85 | 0.80 | 0.70 | — |
| 3 | — | — | 0.45 | 0.70 | 0.85 | 0.90 | 0.80 | 0.70 | — |
| 4 | — | — | 0.50 | 0.75 | 0.90 | 0.95 | 0.90 | 0.75 | — |
| Mature grapes grown in areas of light frost, ground cover 30%–35% | | | | | | | | | |
| 1 | — | 0.50 | 0.55 | 0.60 | 0.60 | 0.60 | 0.60 | 0.50 | 0.40 |
| 2 | — | 0.50 | 0.55 | 0.65 | 0.65 | 0.65 | 0.55 | 0.55 | 0.40 |
| 3 | — | 0.45 | 0.60 | 0.70 | 0.70 | 0.60 | 0.60 | 0.60 | 0.35 |
| 4 | — | 0.45 | 0.65 | 0.75 | 0.75 | 0.75 | 0.75 | 0.65 | 0.35 |
| Mature grapes grown in hot dry areas, ground cover 30%–35% | | | | | | | | | |
| 3 | 0.25 | 0.45 | 0.60 | 0.70 | 0.70 | 0.65 | 0.55 | 0.45 | 0.35 |
| 4 | 0.25 | 0.45 | 0.65 | 0.75 | 0.75 | 0.70 | 0.55 | 0.45 | 0.35 |

*Notes:* 1—Humid, light to moderate wind; 2—humid, strong wind; 3—dry, light to moderate wind; 4—dry, strong wind.

AQ20 need irrigation. In dry climates, such as that of Southwestern United States, crops like pecans are often irrigated during the dormant season to maintain sufficient moisture in the root zone.

## REFERENCES


Allen, R.G., L.S. Pereira, D. Raes, and M. Smith (1998). Crop evapotranspiration: Guidelines for computing crop water requirements. Food and Agriculture Organization, FAO Irrigation and Drainage Paper No. 56. Rome, Italy.

ASCE-EWRI (2005). The ASCE standardized reference evapotranspiration equation. In: Allen, R.G., Walter, I.A., Elliot, R.L., Howell, T.A., Itenfisu, D., Jensen, M.E., and Snyder, R.L. (eds.), *American Society of Civil Engineers (ASCE) Task Committee on Standardization of Reference Evapotranspiration*. Reston, VA: ASCE, 0-7844-0805-X, 204p.

Hargreaves, G.H. and Z.A. Samani (1982). Estimating potential evapotranspiration. *Journal of Irrigation and Drainage Engineering Division ASCE* 108(3): 225–230.

Hargreaves, G.H. and Z.A. Samani (1985). Reference crop evapotranspiration from temperature. *Applied Engineering in Agriculture* 1(2): 96–99.

AQ21 NRCS/USDA (1970). The crop water requirements, Technical release #21.

Wright, J. (1981). Crop coefficients for estimates of daily crop evapotranspiration. *ASAE Irrigation Scheduling Conference*, Chicago, IL.


## AUTHOR QUERIES

[AQ1] Please include Allen (1986) in the reference list with complete details.

[AQ2] Please check the correctness of the term “Decides orchards.”

[AQ3] Please check the value “45°” for correctness.

[AQ4] Table 8.3 through 8.7 captions are one and the same. Please check.

[AQ5] Tables 8 and 11 (in original) have has been changed to Tables 11 and 8 as per the explanation. Please check for correctness.

[AQ6] Here the explanation is about Table 8.8. Please check the change made.

[AQ7] Please check the phrase “Days after” for completeness.

[AQ8] Please check if the phrases “kc, before” and “Days after” are used appropriately in Table 8.6.

[AQ9] Table 8.11 has been changed as Table 8.8 for sequential order of text citation. Please check for correctness.

[AQ10] Root depth and MAD values are described in Table 8.10 not in Table 8.9. Please check the change made.

[AQ11] Table 8.9 and 8.10 captions are similar. Please check.

[AQ12] “Kc” has been changed as “$K_c$” throughout. Please check.

[AQ13] “SCS-21” has been changed as “NRCS/USDA” as per the reference list. Please check for correctness.

[AQ14] Please check if edit to the sentence starting with “Adjusting the monthly Re…” is correct.

[AQ15] Please check if the variable “$k_c$” “kc” could be changed to “$K_c$” throughout.

[AQ16] Please check if “Kc1, Kc3, and Kc-end” should be changed as “$K_{c1}$, $K_{c3}$, and $K_{c\text{-}end}$”, respectively.

[AQ17] Table 8.11 has been changed to Table 8.12. Please check.

[AQ18] Please check if edit to the sentence starting with “Example 8.3 shows…” is okay.

[AQ19] Please check if stages such as “Stage 1, Stage 2..” should be mentioned in Table 8.12.

[AQ20] Please check if edit to the sentence “…and may need irrigation” is correct.

[AQ21] Please provide more details if any for “NRCS/USDA, 1970.”