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4 Evaporation and Evapotranspiration

Two phases of the hydrologic cycle of particular interest in agriculture are evaporation and transpiration. About three-fourths of the total precipitation received on land areas of the world returns directly to the atmosphere by evaporation or transpiration. Most of the balance returns to the ocean as surface or subsurface flow.

Evaporation is the transfer of liquid surface water into vapor in the atmosphere. The water molecules, both in the air and in the water, are in rapid motion. Evaporation occurs when the number of moving molecules that break from the water surface and escape into the air as vapor is larger than the number that re-enter the water surface from the air and become entrapped in the liquid. Evaporation, which may occur from water surfaces, wet leaf surfaces, or from water on soil particles, is important in water management and conservation.

The vapor pressure of water is the partial pressure exerted by the water molecules in their gaseous form. For example, if liquid water is introduced into a closed container, water will evaporate from the surface until there is a balance or equilibrium between the molecules leaving the water and those re-entering the water. A pressure guage attached to the container will indicate an increase in pressure. This increase is the vapor pressure of the water. The saturation vapor pressure is related to temperature and can be determined by the following equation (ASCE, 2005 and Allen et al., 2007):

$$e_s(T) = 0.6108 \exp\left[\frac{17.27\ T}{T + 237.3}\right] \tag{4.1}$$

where e_s is the saturation vapor pressure in kPa and T is the air temperature in °C.

Wind increases the rate of evaporation, particularly as it disperses the vapor layer found directly over the evaporating water surface under stagnant conditions. Because of this mixing, the characteristics of the atmosphere above the surface are of interest. As might be expected from the decreased concentration of water molecules, evaporation increases with decreased vapor pressure. Also, the rate of evaporation decreases slightly with increases in the salt content of the water.

Transpiration is the process through which water vapor passes into the atmosphere through the tissues of living plants. The amount of water that passes through plants by the transpiration process is often a substantial portion of the total water available during the growing season and, besides energy availability, is governed by total leaf area and plant stomatal control. It can vary from near zero to as much as 2000 mm per year, depending largely on the water available, type of plant, density of plant growth, amount of sunshine, climatic dryness, and soil fertility and structure. Less than 1% of water uptake is actually retained by the plant. The rate of evaporation or transpiration increases with a rise in temperature of the surface because saturation vapr pressure at the surface increases with increases in surface temperature.

In areas with growing plants, water passes into the atmosphere by evaporation from soil surfaces and by transpiration from plants. Evaporation and transpiration are difficult to separate and are frequently considered together and called evapotranspiration. Estimated evapotranspiration is needed for determining irrigation requirements for crops as well as water storage in ponds and reservoirs. High evapotranspiration from such crops as grass may be beneficial for the removal of soil water. Methods for predicting evaporation from water surfaces or evapotranspiration can be grouped into three categories. The newest methods use combinations of these.

Mass Transfer. This approach recognizes that water moves away from evaporating and transpiring surfaces in response to the combined phenomena of turbulent mixing of the air and the vapor pressure gradient. Thornthwaite and Holzman (1942) proposed such a method. Application of methods based on mass transfer principles are often combined with other methods.

Energy Balance. Energy is required for evaporation of water, so if there is no change in water temperature, the net radiation or heat supplied can be related to evaporation. Most methods include an energy component.

Empirical Methods. Several such methods, developed from experience and field research, are based primarily on the assumption that energy available for evaporation or evapotranspiration is proportional to the temperature. Blaney and Criddle (1950), Thornthwaite (1948), and many others have proposed equations of this type.

Evaporation

4.1 Evaporation from Water Surfaces

Dalton's Law. Dalton's law for evaporation from free-water surfaces is

$$E = C(e_s - e_a) \tag{4.2}$$

where E = rate of evaporation (mm/day),
C = a constant (mm day^{-1} kPa^{-1}),
e_s = saturation vapor pressure at the temperature of the water surface (kPa),
e_a = actual vapor pressure of the air (e_s of the air times relative humidity) (kPa).

Rohwer (1931) evaluated the constant C in Equation 4.2 as (in SI units, mm/day)

$$C = (3.30 + 1.973\ U_{0.15})(1.465 - 0.00548P) \tag{4.3}$$

where $U_{0.15}$ = average water surface wind velocity (estimated to be at a height of 0.15 m) (m/s),
P = atmospheric pressure (kPa).

Based on measured evaporation from large and small water surface areas, Rohwer (1931) determined that the evaporation from the small water surface areas can be multiplied by 0.77 to estimate the evaporation from large water surface areas. Equations 4.20 or 4.21 can be used to calculate winds speeds for the desired height from wind speed measured at other heights.

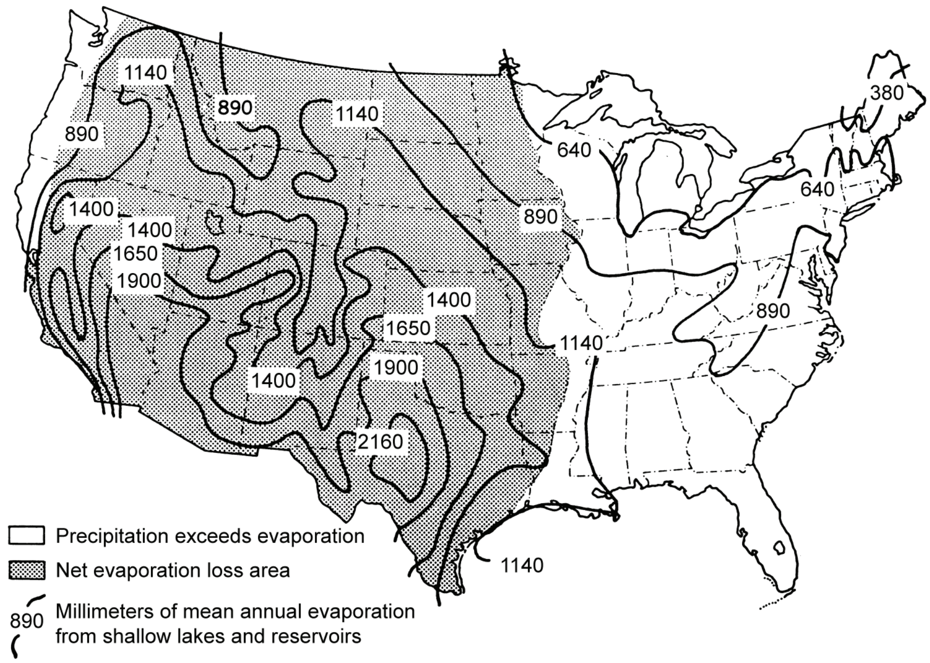


Figure 4.1–Average annual evaporation from shallow lakes and net evaporative loss area. (Revised from USDA, 1981.)

Meyer (1942) evaluated the constant C for pans and shallow ponds (in SI units, mm/month), as

$$C = 112.5 + 25.1\, U_{7.6} \tag{4.4}$$

and for small lakes and reservoirs,

$$C = 82.6 + 18.5\, U_{7.6} \tag{4.5}$$

where $U_{7.6}$ = average wind velocity for the period in m/s at a height of 7.6 m. The vapor pressure e_a should be measured at 7.6 m height in application of Equations 4.4 and 4.5, and the air temperature is the average of the daily minimum and maximum. The geographical distribution of average annual evaporation from shallow lakes is shown in Figure 4.1. Note that evaporation is higher from small water surface areas than large water surface areas because of an “oasis effect.” The “oasis effect” describes the condition where a small water surface area is surrounded by dry air and consequentially has more evaporation. For a detailed analysis of evaporation from free water surfaces see Jones (1992).

Example 4.1

Compute the evaporation for the month of June from a shallow pond if the surface water temperature is 15°C, the average wind speed at 7.6 m height is 1.4 m/s, and the average temperature and relative humidity at 7.6 m height are 22°C and 40%, respectively.

Solution. Substituting into Equation 4.1 the saturation vapor pressures for 15°C and 22°C are

$$e_s(15) = 0.6108 \exp\left[\frac{17.27 \times 15}{15 + 237.3}\right] = 1.70 \text{ kPa}$$

$$e_s(22) = 0.6108 \exp\left[\frac{17.27 \times 22}{22 + 237.3}\right] = 2.64 \text{ kPa}$$

Now substituting into Equations 4.2 and 4.4 (Meyer equation) where e_a for the air is calculated as $e_s(T_{air}) \times RH/100$,

$$E = (112.5 + 25.1 \times 1.4)(1.70 - 2.64 \times 40/100) = 95 \text{ mm/month}$$

Pan Evaporation. Evaporation measurements from free-water surfaces are commonly made using evaporation pans. The Class A pan, accepted as standard by the U.S. Weather Bureau, is 1.21 m in diameter and 250 mm deep. The water level should be kept between 50 and 75 mm below the rim. The pan is supported about 150 mm above the ground so that air may circulate under it, and the materials and color of the pan are specified. The pan is widely used around the world. Description of other styles of pans and correction coefficients for converting evaporation data from a pan of one type to that of another are given by Allen et al. (1998). These pans have higher rates of evaporation than do larger free-surfaces, a factor of about 0.7 being recommended for converting observed evaporation rates to those for larger surface areas (Meyer, 1942; USGS, 1952). The pan area should be fenced to prevent animals from drinking from the pan. If birds are a problem, a convenient nearby water source can be installed. A screen cover may be placed over the pan, but it will reduce pan evaporation about 10% (Allen et al., 1998).

4.2 Evaporation from Land Surfaces

Because of differences in soil texture and in expected soil water movement, it is difficult to generalize on the amounts of evaporation from soil surfaces. For saturated soils, the evaporation may be expected to be similar to that from an open free-water surface. As the water table drops below the soil surface, the evaporation rate will decrease greatly. Prolonged evaporation from the soil surface is generally small at water contents below field capacity, as soil water movement is very slow when the soil surface is relatively dry. Mulches reduce evaporation by restricting air movement, maintaining a high air vapor pressure near the soil surface, and shielding the soil from solar energy. Freezing of a bare soil surface can cause ice to accumulate at the soil surface through condensation of vapor transport from deeper soils, which can greatly increase the evaporation after thawing.

Evapotranspiration

For convenience, evaporation and transpiration are combined into evapotranspiration, ET, also referred to as consumptive use. The various methods for determining evapotranspiration include: (1) tank and lysimeter experiments; (2) field experimental plots where the quantity of water applied is controlled to avoid deep percolation losses and surface runoff is measured; (3) soil water studies, with large numbers of samples taken at various depths in the root zone; (4) analysis of climatological data; (5) integration methods where the water used by plants and evaporation from the water and soil surfaces are combined for the entire area involved; and (6) inflow-outflow methods for large areas where yearly inflow into the area, annual precipitation, yearly outflow from the area, and the change in groundwater level are evaluated.

There are many practical applications for evapotranspiration estimates, but a principal use is to predict soil water deficits for irrigation. Analyzing weather records and estimating evapotranspiration rates, drought frequencies, and excess water periods can show potential needs for irrigation and drainage. Similar studies to determine available tillage and harvesting days can aid in selecting optimum sizes of agricultural equipment. The average daily evapotranspiration during the year obtained from lysimeters at Coshocton, Ohio, is shown in Figure 4.2. Excess soil water at the beginning of the season may delay planting or cause plant diseases. A water deficit at midseason may reduce growth and yield. Reduced ET and excess soil water at the end of the summer may delay maturation of corn and harvesting and tillage operations. Several approaches have been used to develop methods for estimating evapotranspiration.

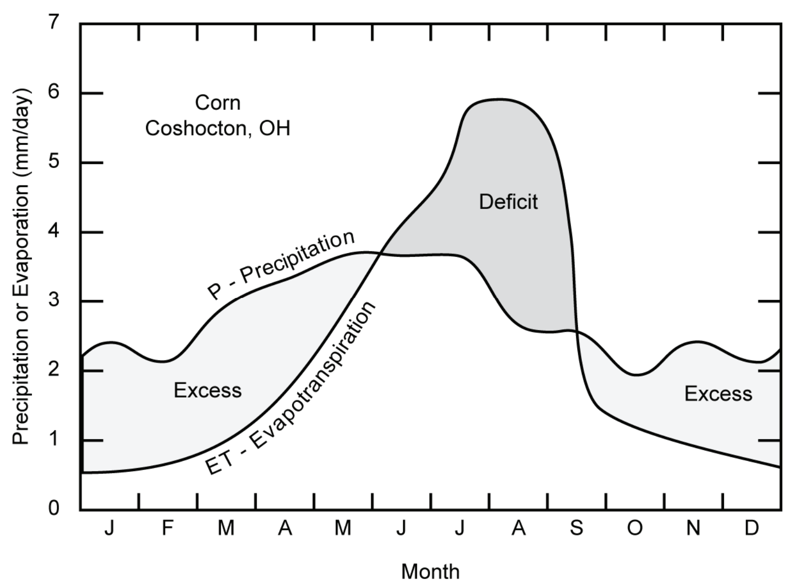


Figure 4.2–Average precipitation and evapotranspiration from corn at Coshocton, Ohio, showing excess and deficit water periods.

4.3 Transpiration Ratio

The effectiveness of the plant's use of water in producing dry matter is often given in terms of its transpiration ratio. This is the ratio of the mass of water transpired to the mass of dry matter in the plant and it varies with the same factors as transpiration. Transpiration ratios for several common crops are 304 for sorghum, 350 for corn, 557 for wheat, 568 for cotton, 575 for potatoes, 682 for rice, and 844 for alfalfa (Howell et al., 1990). This ratio is important, especially where irrigation water is limited.

4.4 Evapotranspiration Definitions

Potential Evapotranspiration. ET_p as defined by Jensen et al. (1990) is "…the rate at which water, if available, would be removed from wet soil and plant surfaces expressed as the rate of latent heat transfer per unit area λET_p or as a depth of water per unit time." Potential evapotranspiration is difficult to sustain and measure because of the need to maintain a saturated surface, so reference crop ET is used as a standard climatic index of evapotranspiration.

Reference Crop Evapotranspiration. ET_{ref} as defined by Jensen et al. (1990) is "…the rate at which water , if readily available, would be removed from the soil and plant surfaces expressed as the rate of latent heat transfer per unit area λET_{ref} or expressed as a depth of water evaporated and transpired from a reference crop. The leaf surfaces of the reference crop are typically not wet." Full cover alfalfa and clipped, cool-season grass are used as reference crops. Both must fully cover the soil surface and be fully transpiring (i.e., not short of water). Alfalfa is a good reference crop because it is aerodynamically more similar to other agricultural crops than grass, it has a deep root system, which makes it less likely to be short of water, and its high ET rates are similar to agricultural crops. Alfalfa also has a low leaf resistance to water vapor diffusion. Grass is becoming the standard reference crop under automated weather stations because it is easier to maintain at a nearly constant height. These automated weather stations are capable of measuring the climatic data for the most sophisticated methods for predicting reference crop ET. With the establishment of the "standardized" ET_r for alfalfa, it is not necessary to grow alfalfa. Weather measurements taken over grass can be used to calculate the alfalfa reference ET_r (Jensen et al., 1990; Allen et al., 1998). Many states have installed networks of automatic weather stations that measure the data needed to calculate reference ET and/or crop ET. These ET values are disseminated through various media for use by water managers.

Evapotranspiration Estimation Methods

4.5 Evaporation Pan Method

Evaporation pan data, E_{pan}, can be used to calculate reference ET or crop ET_c with the appropriate coefficient. Converting to reference ET, as in the following equation, allows using crop coefficients for many crops with one calibration.

$$ET_o = K_{pan} E_{pan} \quad (4.6)$$

where ET_o = grass based reference ET (L/T),
K_{pan} = factor for converting pan evaporation to ET_o,
E_{pan} = measured pan evaporation (L/T).

The best source for K_{pan} is a local or regional calibration. Table 4.1 may be used for a Class A pan if local values for K_{pan} are not available. Values of K_{pan} vary with relative humidity, wind speed, and windward side distance (fetch) of a green crop Case A or dry fallow Case B (Figure 4.3). For desert or semi-desert conditions with no agricultural development and bare soils, K_{pan} may need to be reduced up to 20%. If the pan is located in tall crops, K_{pan} may need to be increased up to 30% (Allen et al., 1998).

Example 4.2

Estimate the grass reference crop ET_o if pan evaporation for July 10 and 11 was 16 mm. The wind was 3 m/s, relative humidity was 50%, and the pan has a 10 m grass fetch.

Solution. From Table 4.1 for Case A read K_{pan} is 0.7 then substitute into Equation 4.6:

$$ET_o = K_{pan} \times E_{pan} = 16 \times 0.7 = 11.2 \text{ mm or } 5.6 \text{ mm/day}$$

Table 4.1 Pan Coefficients K_{pan} for Class A Pan for Different Pan Siting and Environment Conditions and Different Levels of Mean Relative Humidity and Wind Speed

Wind Speed (m/s)	Case A: Pan Placed in Short Green Cropped Area				Case B: Pan Placed in Dry Fallow Area			
	Distance[a] (m)	RH (mean percent) Low, < 40	Medium, 40 to 70	High, > 70	Distance[b] (m)	RH (mean percent) Low, < 40	Medium, 40 to 70	High, > 70
Light <2	1	0.55	0.65	0.75	1	0.70	0.80	0.85
	10	0.65	0.75	0.85	10	0.60	0.70	0.80
	100	0.70	0.80	0.85	100	0.55	0.65	0.75
	1000	0.75	0.85	0.85	1000	0.50	0.60	0.70
Moderate 2 to 5	1	0.50	0.60	0.65	1	0.65	0.75	0.80
	10	0.60	0.70	0.75	10	0.55	0.65	0.70
	100	0.65	0.75	0.80	100	0.50	0.60	0.65
	1000	0.70	0.80	0.80	1000	0.45	0.55	0.60
Strong 5 to 8	1	0.45	0.50	0.60	1	0.60	0.65	0.70
	10	0.55	0.60	0.65	10	0.50	0.55	0.65
	100	0.60	0.65	0.70	100	0.45	0.50	0.60
	1000	0.65	0.70	0.75	1000	0.40	0.45	0.55
Very strong >8	1	0.40	0.45	0.50	1	0.50	0.60	0.65
	10	0.45	0.55	0.60	10	0.45	0.50	0.55
	100	0.50	0.60	0.65	100	0.40	0.45	0.50
	1000	0.55	0.60	0.65	1000	0.35	0.40	0.45

[a] Length of the green crop area upwind from the pan.
[b] Length of dry fallow area upwind from the pan.
Source: Doorenbos and Pruitt (1977).

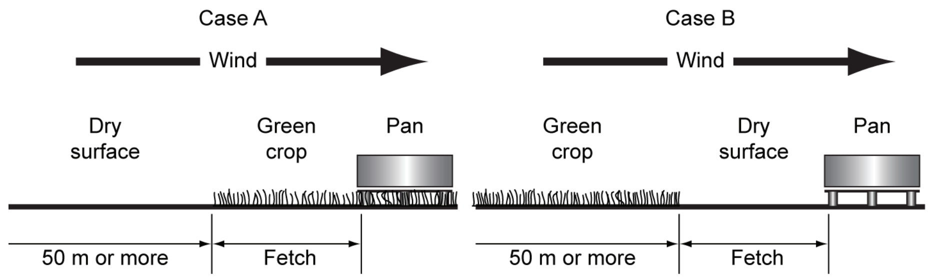


Figure 4.3–Illustration showing two cases of evaporation pan site and environment conditions. (Source: Allen et al., 1998.)

4.6 Penman-Monteith Combination Method

Penman (1948, 1956) first derived a combination equation by combining components for the energy required to sustain evaporation and a mechanism for removal of the vapor. The Penman combination equation combined with aerodynamic and surface resistance terms is called the Penman-Monteith equation (Jensen et al., 1990). The ASCE Standardized Penman-Monteith equation for daily time steps is (ASCE, 2005):

$$ET_{ref} = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{C_n}{T+273}(e_s - e_a)\,u_2}{\Delta + \gamma(1 + C_d\,u_2)} \quad (4.7)$$

where ET_{ref} = reference ET for a well-watered crop (mm/day),
Δ = slope of the saturation vapor pressure curve (kPa/°C),
R_n = net radiation at the crop surface (MJ m^{-2} day^{-1}),
G = heat flux density to the soil (MJ m^{-2} day^{-1}) (G is usually small for daily time steps compared to R_n and is neglected),
γ = psychrometric constant (kPa/°C),
T = mean daily temperature at 1.5 to 2.5-m height (°C),
u_2 = mean daily wind speed at 2 m above the soil surface (m/s),
e_s = mean saturation vapor pressure at 1.5- to 2.5-m height (kPa),
e_a = mean actual vapor pressure at 1.5- to 2.5-m height (kPa),
C_n = numerator constant that changes with the reference crop,
C_d = denominator constant that changes with the reference crop.

Values for C_n and C_d are given in Table 4.2.

Table 4.2 Values for C_n and C_d in Equation 4.7 with Daily Time Steps.

	C_n	C_d
Short reference crop (grass)	900	0.34
Tall reference crop (alfalfa)	1600	0.38
Source: Itenfisu et al. (2003)		

The following equations and explanations (from Allen et al., 1998; ASCE, 2005; and Allen et al., 2007) assume the Penman-Monteith equation will be applied on a daily basis. The procedures and constants are different for other time intervals. The latent heat of vaporization λ varies only slightly and is taken as the value for T = 20°C or 2.45 MJ/kg, which is the reciprocal of 0.408.

The slope of the saturation vapor pressure and temperature curve at a given temperature is computed from the following equation:

$$\Delta = \frac{2504 \exp\left(\frac{17.27T}{T+237.3}\right)}{\left(T+237.3\right)^2} \tag{4.8}$$

where Δ is in kPa/°C and T is the daily mean air temperature in °C obtained by averaging the daily maximum and minimum temperatures.

Net radiation can be obtained from local correlations with solar radiation (Jensen et al., 1990) or calculated from

$$R_n = R_{ns} - R_{nl} = (1-\alpha)R_s - R_{nl} \tag{4.9}$$

where R_{ns} = net solar or short-wave radiation (MJ m^{-2} day^{-1}),
R_{nl} = net long-wave radiation leaving the earth's surface (MJ m^{-2} day^{-1}),
α = radiation reflection coefficient or albedo = 0.23,
R_s = measured or calculated solar or short-wave radiation received at the earth's surface (MJ m^{-2} day^{-1}).

Solar radiation is generally measured by a weather station. Net long-wave radiation is determined from

$$R_{nl} = \sigma\left[\frac{(T_{\max}+273)^4 + (T_{\min}+273)^4}{2}\right]\left[0.34 - 0.14(e_a)^{0.5}\right]\left(1.35\frac{R_s}{R_{so}} - 0.35\right) \tag{4.10}$$

where σ = Stefan-Boltzmann constant = 4.903 × 10^{-9} (MJ K^{-4} day^{-1}),
T_{max} = maximum temperature during the 24-hour period (°C),
T_{min} = minimum temperature during the 24-hour period (°C),
R_{so} = calculated clear-sky radiation (MJ m^{-2} day^{-1}).

The ratio R_s/R_{so} in Equation 4.10 cannot exceed 1.0. Clear-sky radiation can be calculated by

$$R_{so} = (0.75 + 2\times10^{-5}z)R_a \tag{4.11}$$

where z is the elevation above sea level in meters and R_a is the extraterrestrial radiation in MJ m^{-2} day^{-1} and given by

$$R_a = \frac{24}{\pi}G_{sc}d_r\left[\omega_s \sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\sin(\omega_s)\right] \tag{4.12}$$

where G_{sc} = solar constant = 4.92 (MJ m^{-2} h^{-1}),
d_r = inverse square of relative distance Earth to Sun,
ω_s = sunset hour angle (radians),

φ = latitude (radians),
δ = solar declination (radians).

The inverse square of the relative distance Earth to Sun, d_r, is given by

$$d_r = 1 + 0.033\cos\left(2\pi\frac{J}{365}\right) \quad (4.13)$$

where J is the day of the year given by

$$J = D_M - 32 + Int\left(\frac{275M}{9}\right) + 2Int\left(\frac{3}{M+1}\right) + Int\left(\frac{M}{100} - \frac{Mod(Y,4)}{4} + 0.975\right) \quad (4.14)$$

where D_M = day of the month,
M = month of the year,
Y = year (4 digits).

Degrees latitude are changed to radians by

$$\text{Radians} = \frac{\pi}{180} \times \text{degrees latitude} \quad (4.15)$$

The solar declination is

$$\delta = 0.409\sin\left(\frac{2\pi}{365}J - 1.39\right) \quad (4.16)$$

The sunset angle is given by

$$\omega_s = \arccos[-\tan(\varphi)\tan(\delta)] \quad (4.17)$$

The psychrometric constant using λ = 2.45 MJ/kg is

$$\gamma = 0.000665\ P \quad (4.18)$$

where P is the mean atmospheric pressure in kPa at the weather station with elevation z in m above mean sea level. The pressure P in kPa is given by

$$P = 101.3\left(\frac{293 - 0.0065z}{293}\right)^{5.26} \quad (4.19)$$

If the wind speed is measured at a height other than 2 m above the soil surface, the wind speed u_2 at 2 m over a grassed surface can be obtained from

$$u_2 = u_z\frac{4.87}{\ln(67.8z_w - 5.42)} \quad (4.20)$$

where z_w is the height (m) of the wind measurement above the soil surface and u_z is the measured wind speed (m/s) at height z. If the wind speed is measured at a height other than 2 m over a surface having vegetation taller than grass, such as alfalfa, or other vegetation about 0.5 m height, and to be consistent with the standardized ET equation (Equation 4.7), the following equation is used to translate the wind speed to 2 m above the soil surface:

$$u_2 = u_z \frac{3.44}{\ln(16.26 z_w - 5.42)} \tag{4.21}$$

The saturation vapor pressure is related to the air temperature by Equation 4.1. The mean saturation vapor pressure is the average of the saturation vapor pressures for maximum and minimum air temperatures or

$$e_s = \frac{e_s(T_{\max}) + e_s(T_{\min})}{2} \tag{4.22}$$

The actual vapor pressure can be calculated from Equation 4.1 using the daily mean dewpoint temperature T_{dew} as

$$e_a = e_s(T_{dew}) \tag{4.23}$$

If the dew point temperature is not available, e_a can be calculated from the relative humidity using

$$e_a = \frac{e_s(T_{\min})\frac{RH_{\max}}{100} + e_s(T_{\max})\frac{RH_{\min}}{100}}{2} \tag{4.24}$$

where RH_{max} and RH_{min} are maximum and minimum readings of relative humidity during the 24-hour period in percent.

Values for the constants C_n and C_d are given in Table 4.2 for daily calculations. Values for C_n vary with the aerodynamic roughness of the reference crop. Values for C_d vary with the "bulk" surface resistance and aerodynamic roughness of the surface. Both values were derived by simplifying terms and rounding the result (Allen et al., 1998; ASCE, 2005).

Example 4.3

Compute the grass reference crop ET_o for June 20, 2002, near Bakersfield, California, 35°N, using the Standardized Penman-Monteith equation and these values:

maximum temperature = 38°C	wind speed at 2 m = 1.5 m/s
minimum temperature = 22°C	measured solar radiation = 26 MJ m^{-2} day^{-1}
maximum relative humidity = 60%	elevation = 50 m
minimum relative humidity = 25%	assume G = 0.0

Solution.

(1) Begin the calculations by determining the climatic constants. Calculate the mean temperature T = (38+22)/2 = 30, then calculate Δ from Equation 4.8:

$$\Delta = \frac{2504 \exp\left(\frac{17.27 \times 30}{30 + 237.3}\right)}{(30 + 237.3)^2} = 0.243 \text{ kPa/}^{\circ}\text{C}$$

(2) Calculate the saturation vapor pressure at maximum temperature using Equation 4.1:

$$e_s(38) = 0.6108\exp\left[\frac{17.27\times 38}{38+237.3}\right] = 6.625 \text{ kPa}$$

(3) Calculate the saturation vapor pressure at minimum temperature using Equation 4.1:

$$e_s(22) = 0.6108\exp\left[\frac{17.27\times 22}{22+237.3}\right] = 2.644 \text{ kPa}$$

(4) Calculate the mean saturation vapor pressure from Equation 4.22:

$$e_s = \frac{6.625+2.644}{2} = 4.634 \text{ kPa}$$

(5) Calculate the actual vapor pressure from Equation 4.24:

$$e_a = \frac{2.644\frac{60}{100}+6.625\frac{25}{100}}{2} = 1.62 \text{ kPa}$$

(6) Calculate the mean atmospheric pressure at the station from Equation 4.19:

$$P = 101.3\left(\frac{293-0.0065\times 50}{293}\right)^{5.26} = 100.7 \text{ kPa}$$

(7) Calculate the psychrometric constant from Equation 4.18:

$$\gamma = 0.000665\times 100.7 = 0.067 \text{ kPa}/^{\circ}\text{C}$$

(8) Determine the day of the year with Equation 4.14:

$$J = 20-32+Int\left(\frac{275\times 6}{9}\right)+2Int\left(\frac{3}{6+1}\right)+Int\left(\frac{6}{100}-\frac{Mod(2002,4)}{4}+0.975\right)=171$$

(9) Determine the latitude in radians from Equation 4.15:

$$\varphi = \frac{\pi}{180}\times 35 = 0.611 \text{ radians}$$

(10) Calculate the solar declination from Equation 4.16:

$$\delta = 0.409\sin\left(\frac{2\pi}{365}171-1.39\right) = 0.409$$

(11) Calculate the sunset angle from Equation 4.17:

$$\omega_s = \arccos[-\tan(0.611)\tan(0.409)] = 1.879$$

(12) Calculate the inverse square of the relative distance Earth to Sun from Equa-

tion 4.13:

$$d_r = 1 + 0.033\cos\left(\frac{2\pi}{365}171\right) = 0.968$$

(13) Calculate the extraterrestrial radiation from Equation 4.12:

$$R_a = \frac{24}{\pi}4.92 \times 0.968\left[1.879\sin(0.611)\sin(0.409) + \cos(0.611)\cos(0.409)\sin(1.879)\right]$$

$$= 41.63 \text{ MJ m}^{-2}\text{day}^{-1}$$

(14) Calculate the clear-sky radiation from Equation 4.11:

$$R_{so} = (0.75 + 2\times10^{-5} \times 50)41.63 = 31.27 \text{ MJ m}^{-2}\text{day}^{-1}$$

(15) Calculate the net long-wave radiation from Equation 4.10:

$$R_{nl} = 4.903\times10^{-9}\left[\frac{(38+273)^4 + (22+273)^4}{2}\right]\left[0.34 - 0.14(1.62)^{0.5}\right]\times\left(1.35\frac{26}{31.27} - 0.35\right)$$

$$= 5.186 \text{ MJ m}^{-2}\text{day}^{-1}$$

(16) Calculate the net radiation from Equation 4.9:

$$R_n = (1-0.23)26 - 5.185 = 14.83 \text{ MJ m}^{-2}\text{day}^{-1}$$

(17) Find the values for C_n and C_d from Table 4.2 for a grass reference:

$$C_n = 900 \qquad C_d = 0.34$$

(18) Substitute the above values into Equation 4.7 to obtain ET_o:

$$ET_o = \frac{0.408\times0.243\ (14.83-0) + 0.067\dfrac{900}{30+273}(4.634-1.62)\,1.5}{0.243 + 0.067\ (1+0.34\times1.5)} = 6.89 \text{ mm/day}$$

Thus the calculated ET for a grass reference ET_o is 6.89 mm/day or round to 6.9 mm/day.

4.7 Temperature-Based Methods

Early researchers (Thornthwaite, 1948; Blaney and Criddle, 1950) in water management developed temperature-based methods for estimating consumptive use or ET. These were simple to use and worked reasonably well where they were developed and calibrated. The Blaney-Criddle method was the most popular in the semiarid western parts of the United States and was based on a consumptive use coefficient, mean air temperature, and percent of annual daylight hours occurring during the period of calculation. This method estimated monthly or seasonal water use. More accurate estimates for evapotranspiration were needed and the Blaney-Criddle method was revised by the SCS (1970) and by FAO-24 (Doorenbos and Pruit, 1977). The SCS Blaney-Criddle method added a temperature coefficient to the consumptive use coefficient, but has been superceded by newer methods. FAO-24 made a more fundamental revision to the Blaney-Criddle method by including relative humidity, ratio of actual to possible sunshine hours, and wind speed. This increased the data requirement significantly and the FAO-24 revision has been dropped in favor of combination methods. It should be noted that when these methods have been locally calibrated, they are reliable for periods of one month or longer.

4.8 Radiation Methods

Empirical radiation methods for estimating potential ET were developed that included an energy term by adding a solar radiation variable. The Jensen-Haise alfalfa-reference radiation method (Jensen and Haise, 1963; Jensen, 1966) was the most widely accepted of these methods. The main variables were mean air temperature, solar radiation, and two constants. The constants were based on elevation and the saturation vapor pressures for the mean maximum and mean minimum temperatures for the warmest month of the year.

The Hargreaves grass-related radiation method (Hargreaves and Samani, 1982, 1985) is based on solar radiation and mean air temperature. Hargreaves and Samani (1982, 1985) recommended estimating solar radiation from extraterrestrial radiation and the difference between mean maximum and mean minimum monthly temperatures (Equation 4.28). In this case, the Hargreaves method becomes essentially a temperature-based method (Jensen et al., 1990). When calibrated to local conditions, these radiation methods have proven reliable in predicting ET.

4.9 Estimating Missing Climatic Data

The ASCE Standardized Penman-Monteith equation requires air temperature, vapor pressure or relative humidity, radiation, and wind speed data. It is normally assumed that these data will be from the area where the ET estimate is required. The quality of the weather data will affect the quality of the reference ET values. “If some of the required data are missing or do not accurately represent an irrigated site/region or are erroneous, then it may be possible that data may be estimated in order to apply the equation” (ASCE, 2005). If reasonably reliable estimates of missing or erroneous data are determined, ET estimates from the ASCE standardized equation are expected to be more reliable than estimates from more empirical methods (ASCE, 2005; Allen et al., 1998).

When estimated rather than measured data are used to estimate ET, the data should be flagged and the estimated parameters should be noted. The following describes procedures for estimating missing or questionable data.

Vapor Pressure. If humidity and dew-point data are missing or questionable, the actual vapor pressure can be estimated for the site by assuming the dew-point temperature is near the daily minimum temperature or

$$T_{dew} = T_{\min} - K_o \tag{4.25}$$

where K_o is approximately 2° to 4°C in arid and semiarid climates and approximately 0°C in humid and subhumid climates (ASCE, 2005). Additional discussion of this assumption is given by Allen et al. (1998). The value of K_o can be estimated or obtained by analyzing the data from a nearby weather station.

Solar Radiation. If solar radiation is not measured, it can be estimated from the hours of sunshine and extraterrestrial radiation by the Angstrom formula (ASCE, 2005):

$$R_s = \left(a_s + b_s \frac{n}{N} \right) R_a \tag{4.26}$$

where a_s = fraction of extraterrestrial radiation reaching the earth's surface on overcast days (n = 0),
b_s = the additional fraction of extraterrestrial radiation reaching the earth's surface on a clear day,
$a_s + b_s$ = fraction of extraterrestrial radiation reaching the earth's surface on a clear day ($n = N$),
n = actual duration of sunshine (h),
N = maximum possible duration of sunshine (h).

Radiation in Equation 4.26 is expressed in MJ m^{-2} day^{-1}. Values of a_s and b_s vary with atmospheric conditions (dust, humidity) and solar declination (latitude and month). If no actual radiation or no calibration data are available, the values $a_s = 0.25$ and $b_s = 0.50$ are recommended (Allen et al., 1998). The potential daylight hours N are given by

$$N = \frac{24}{\pi} \omega_s \tag{4.27}$$

Data from nearby weather stations can be utilized if the climate and physiography are nearly identical. Estimates of ET using estimated radiation data are better when calculated over periods of multiple days.

Solar radiation can be estimated from the difference between maximum and minimum temperatures because temperatures are influenced by cloud cover. Hargreaves and Samani (1982) developed an empirical equation for the relationship

$$R_s = k_{Rs}(T_{\max} - T_{\min})^{0.5} R_a \tag{4.28}$$

Table 4.3 Suggested Mean Monthly Wind Speeds for Various General Classes

Class Description	Mean Monthly Wind Speed at 2 m
Light wind	$\leq$ 1.0 m/s
Light to moderate wind	1 to 3 m/s
Moderate to strong wind	3 to 5 m/s
Strong wind	$\geq$ 5.0 m/s
Source: Allen et al. (1998).	

where k_{Rs} (°C$^{-0.5}$) is an adjustment coefficient and varies for coastal or interior areas. For areas located on or near the coast of a large land mass and where the air masses are influenced by a nearby body of water, $k_{Rs} \approx 0.19$. For interior areas where land mass dominates and air masses are not influenced by a nearby body of water, $k_{Rs} \approx$ 0.16 (ASCE, 2005).

Wind Speed. When wind speed data are not available, they may be extrapolated from a nearby agricultural weather station if the airflow conditions are relatively homogeneous. Wind speeds vary throughout the day; however, when averaged over a day or longer the differences between two sites are smaller. If incomplete data are available, a calibration between two sites will improve the accuracy of the estimated speeds. If no data are available, wind speed can be selected from Table 4.3 or a global value of 2 m/s used as a temporary estimate.

Airport wind speeds are typically measured at 10-m heights in the United States. In semiarid and arid areas airport anemometers are generally surrounded by low vegetation. These wind speeds can be adjusted to a 2-m height, but will typically exceed the velocity over an irrigated area because of large differences in vegetative roughness and the damping effect caused by the heat sink as water evaporates (ASCE, 2005).

Crop and Landscape Coefficients

4.10 Crop Coefficients

Examples of the daily evapotranspiration from three crops are given in Figure 15.1. Agricultural crops differ in evaporation and transpiration from reference crops, particularly grass, because of differences in ground cover, canopy characteristics, and aerodynamic resistance. These differences are integrated into a single crop coefficient K_c that includes effects of both crop transpiration and soil evaporation. The evapotranspiration from a specific crop ET_c can be estimated from the reference ET and appropriate single crop coefficient K_c by

$$ET_c = K_c \times ET_{ref} \tag{4.29}$$

It is important to note that the crop coefficients for alfalfa and grass reference crops are different and cannot be interchanged. Also, the crop coefficients may be somewhat different for the same reference crop depending on the location and method used for determining reference ET.

Crop coefficients vary with crop type, climate, and soil evaporation. For a specific crop the coefficient varies with the stage of growth of the plant as shown in Figure 4.4. For annual crops, crop coefficients are lowest at planting, increase as the plants grow, and reach a maximum when the canopy covers the soil surface. As the plants ripen late in the season, the coefficients decrease. In addition to time, crop coefficients also can be expressed as functions of degree-days.

For simplicity, the crop coefficient curve is divided into four straight-line segments for four growth stages (initial, crop development, mid-season, and late season) as shown in Figures 4.4 and 4.5. These segments are defined by three coefficients—$K_{c\ ini}$, $K_{c\ mid}$, and $K_{c\ end}$—and the number of days in each stage (Figure 4.5). Examples of ap-

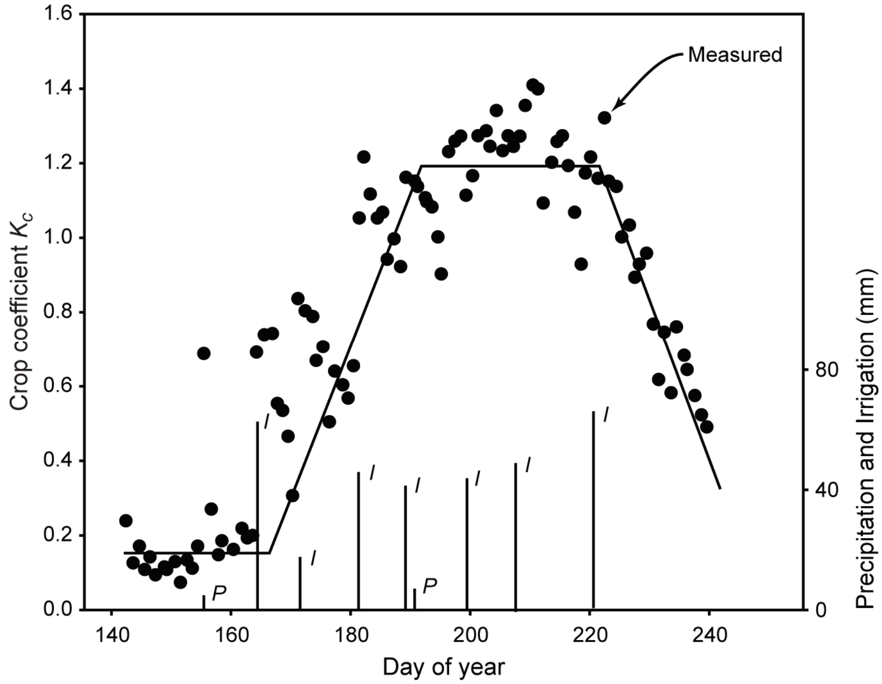


Figure 4.4–Crop coefficients for dry beans at Kimberly, Idaho, as measured by lysimeter, and as represented by four straight-line segments. Precipitation and irrigation events have the symbols P and I, respectively. (Modified from Allen et al., 1998.)

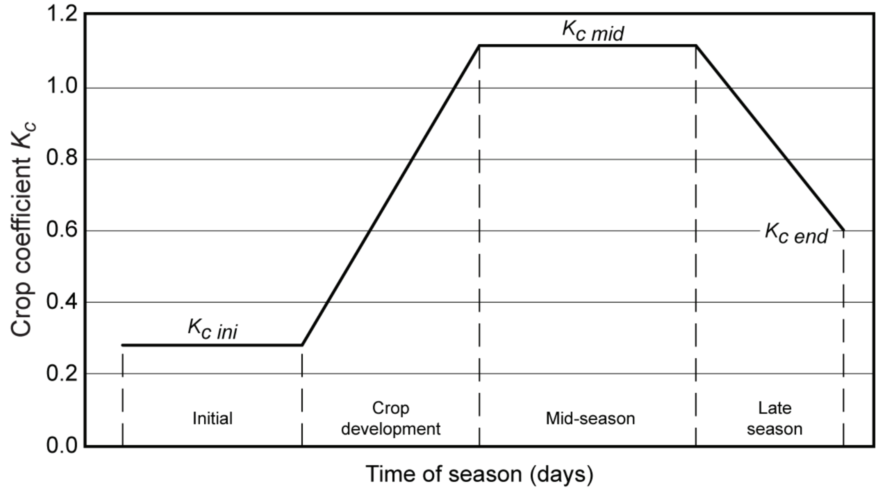


Figure 4.5–Illustration of crop coefficients represented by four line segments for the four major growth stages. (Source: Allen et al., 1998.)

proximate crop coefficients for a grass reference crop and a few crops are given in Table 4.4. Values of $K_{c\ ini}$ in Table 4.4 are for average soil wetting conditions. The corresponding lengths of each stage are given in Table 4.5. Local crop coefficients are preferred, but if they are not available see Allen et al. (1998), Jensen et al. (1990), Doorenbos and Pruitt (1977), or Pruitt et al. (1987).

Example 4.4

Estimate ET_c for cotton on June 20, 2002, near Bakersfield, California. Assume the planting date was April 1.

Solution. From Example 4.3, ET_o for Bakersfield on June 20 is 6.9 mm/day. June 20 is 81 days after planting. From Table 4.5 determine that this is mid-season and from Table 4.4 $K_{c\ mid}$ is 1.2. Substituting into Equation 4.30 yields

$$ET_c = 1.2 \times 6.9 \text{ mm/day} = 8.3 \text{ mm/day}$$

Because $K_{c\ ini}$ represents periods of nearly bare soil and varies widely according to the frequency of wetting of the soil surface, values of $K_{c\ ini}$ from Table 4.4 are approximate and recommended for preliminary planning studies (Allen et al., 1998). Improved values can be obtained by adjusting $K_{c\ ini}$ depending on the frequency of rain-

Table 4.4 Approximate Single Crop Coefficients for a Grass Reference Crop and Mean Maximum Plant Heights for Well Managed, Nonstressed Crops for Subhumid Regions

Crop	$K_{c\ ini}$	$K_{c\ mid}$	$K_{c\ end}$	Maximum Crop Height (m)
Carrots	0.7	1.05	0.95	0.3
Lettuce	0.7	1.00	0.7	0.3
Tomato	0.6	1.15	0.8	0.6
Cantaloupe	0.5	0.85	0.6	0.3
Potato	0.5	1.05	0.95	0.4
Sugar beet	0.35	1.2	0.7	0.5
Soybeans	0.4	1.15	0.5	1.0
Cotton	0.35	1.2	0.7	1.5
Small grain	0.3	1.15	0.4	1
Maize	0.3	1.2	0.5	2
Alfalfa	0.4	0.95	0.9	0.7
Grapes	0.3	0.85	0.45	2
Deciduous orchard	0.5	1.0	0.7	4
Citrus, no ground cover, 50% canopy	0.65	0.6	0.65	3
Turf grass, cool season[a]	0.90	0.95	0.95	[a]
Turf grass, warm season[b]	0.80	0.85	0.85	0.10

[a] Cool season varieties include dense stands of bluegrass, ryegrass, and fescue; the 0.95 values for cool season grass represent 0.06 to 0.08 m mowing height.

[b] Warm season varieties include bermuda and St. Augustine grass.

Source: Selected values from Allen et al. (1998).

Table 4.5 Typical Lengths (days) of the Four Growing Stages for Selected Crops

Crop	Initial (L_{ini})	Developmental (L_{dev})	Mid (L_{mid})	Late (L_{late})
Carrots	30	40	60	25
Lettuce	30	40	30	10
Tomato	30	40	60	30
Cantaloupe	20	50	30	20
Potato	30	30	50	30
Sugar beet	40	50	90	40
Soybeans	20	30	60	25
Cotton	30	50	55	45
Small grain	25	35	60	30
Maize	20	40	50	30
Alfalfa	5	15	10	10
Grapes	20	50	80	60
Deciduous orchard	20	70	120	60
Citrus	60	90	120	95

Source: Selected values from Allen et al. (1998).

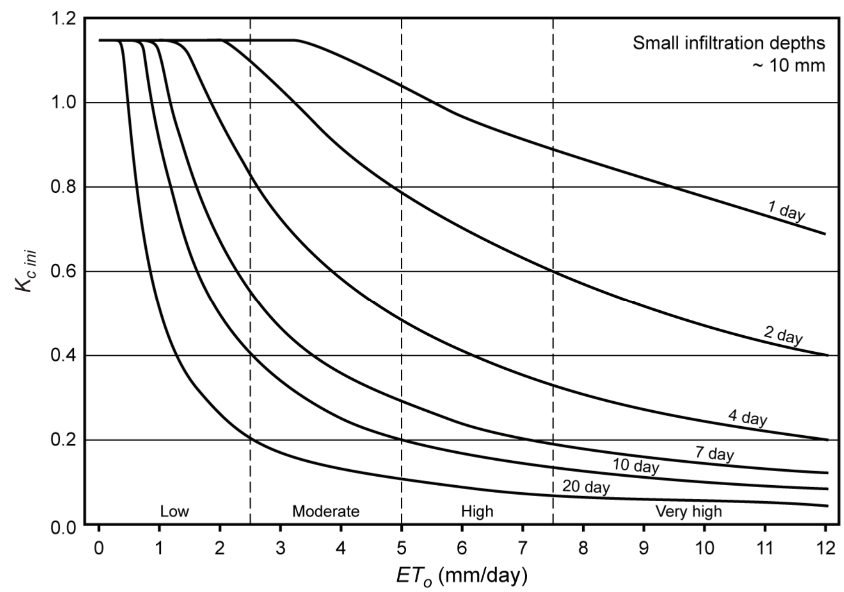
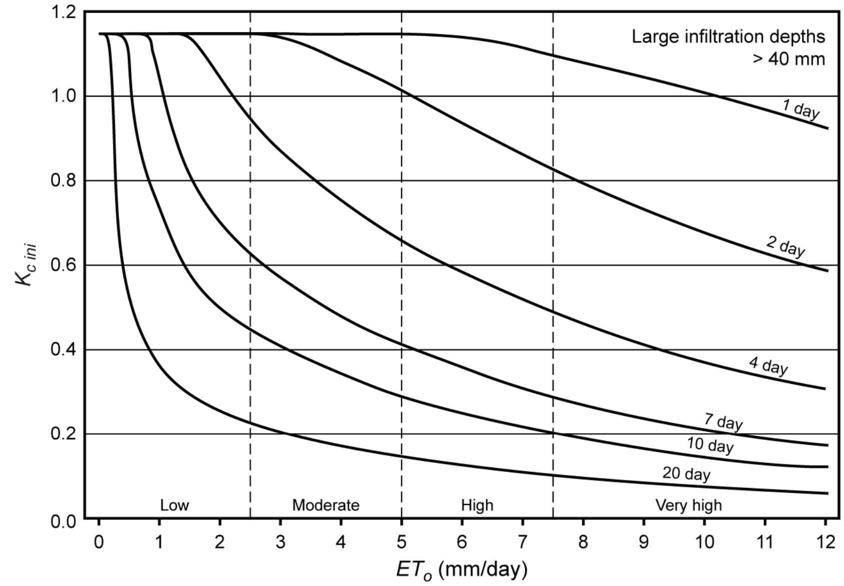
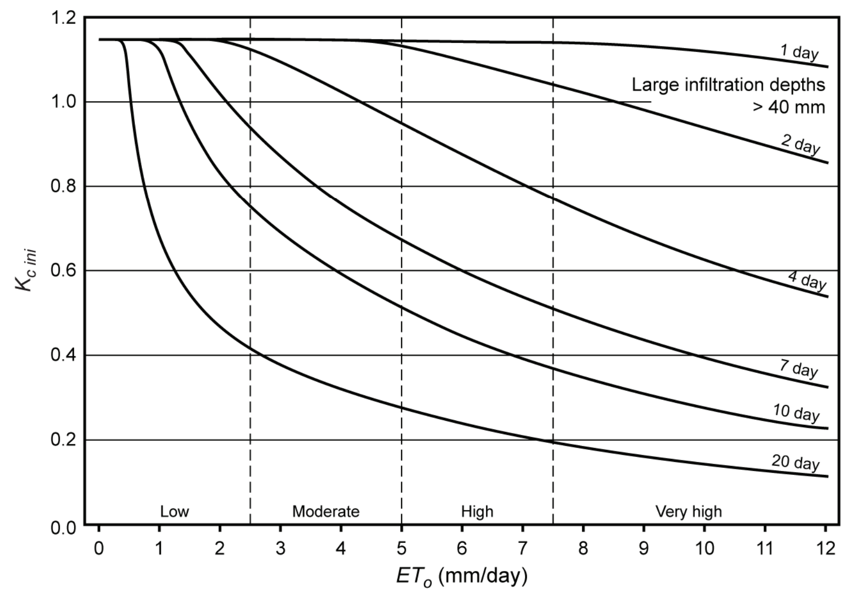


Figure 4.6–Average $K_{c\ ini}$ as related to ET_o and the interval between irrigations and/or significant rain of 3 to 10 mm during the initial growth stage for all soil types. (Source: Allen et al., 1998.)



(a) Coarse textures



(b) Fine and medium textures

Figure 4.7–Average $K_{c\ ini}$ as related to ET_o and the interval between irrigations greater than or equal to 40 mm per wetting event during the initial growth stage for (a) coarse textured soils and (b) fine and medium textured soils. (Source: Allen et al., 1998.)

fall or irrigation and the depth of water infiltrated per event for infiltration depths of 10 mm or less as shown in Figure 4.6. Figure 4.7 shows similar curves for infiltration depths of 40 mm or greater for (a) coarse textured soils and (b) medium and fine textured soils. These curves indicate higher values of $K_{c\ ini}$ for more frequent wetting and larger infiltration depths because soil evaporation is the main component of $K_{c\ ini}$. For average infiltration depths per wetting event between 10 and 40 mm, the value of $K_{c\ ini}$ can be estimated from

$$K_{c\ ini} = K_{c\ ini\ (\text{Fig.4.6})} + \frac{F - 10}{40 - 10}\left[K_{c\ ini\ (\text{Fig. 4.7})} - K_{c\ ini\ (\text{Fig. 4.6})}\right] \quad (4.30)$$

where $K_{c\ ini\ (\text{Fig. 4.6})}$ = value of $K_{c\ ini}$ from Figure 4.6,
$K_{c\ ini\ (\text{Fig. 4.7})}$ = value of $K_{c\ ini}$ from Figure 4.7,
F = average infiltration depth (mm).

Example 4.5

Determine $K_{c\ ini}$ if the average infiltration depth per wetting event is 25 mm and the irrigation is applied every 7 days to a medium textured soil. Estimated ET_o is 5 mm/day.

Solution. From Figure 4.6 read $K_{c\ ini}$ = 0.28 and from Figure 4.7*b* read $K_{c\ ini}$ = 0.67. Substitute into Equation 4.30 as:

$$K_{c\ ini} = 0.28 + \frac{25 - 10}{40 - 10}\left(0.67 - 0.28\right) = 0.48$$

Dual crop coefficients have K_c as the sum of a basal crop coefficient and a soil evaporation coefficient to account for increased evaporation from wet soil surfaces after irrigation or rainfall, or decreased evaporation and transpiration because soil water is limiting. This procedure is more complicated but is recommended when improved estimates of K_c and ET are needed (Allen et al., 1998).

4.11 Landscape Plant Coefficients

The water requirements of landscape plants are handled differently from crop plants because maximum growth is not usually desired. The basic need is to supply sufficient water to maintain appearance, health, and reasonable growth, thus the water requirements are frequently lower than for agricultural crops (Costello and Jones, 2000). Other differences occur because landscape plantings are often composed of more than one species that are irrigated as a unit or zone. The vegetative density may vary from single plants to groups of plants to complete cover. In addition, large trees in some landscape designs will have more leaf area and use more water than a grouping of small plants in the same surface area.

Table 4.6 Estimated Values of Landscape Plant Coefficient Factors

	Very Low	Low	Moderate	High
Species factor, k_s	< 0.1	0.1 to 0.3	0.4 to 0.6	0.7 to 0.9
Density factor, k_d		0.5 to 0.9	1.0	1.1 to 1.3
Microclimate factor, k_{mc}		0.5 to 0.9	1.0	1.1 to 1.4

Source: Costello and Jones (2000).

The water use of landscape plants can be estimated by (Costello and Jones, 2000)

$$ET_L = K_L \times ET_o \tag{4.31}$$

where ET_L is the estimated water requirement of a landscape planting and K_L is the landscape planting coefficient. The landscape coefficient is estimated from (Costello and Jones, 2000)

$$K_L = k_s \times k_d \times k_{mc} \tag{4.32}$$

where K_L = landscape coefficient,
k_s = plant species factor,
k_d = plant density factor,
k_{mc} = microclimate factor.

Estimated values for the plant species, plant density, and microclimate factors are shown in Table 4.6 for California conditions (Costello and Jones, 2000). Until local estimates are available, landscape factors for other geographic locations may be estimated based on evaluation of the values and conditions assumed in developing the values in Table 4.6.

Plants species factors are divided into four categories according to the relative water use of a species and vary from about 0.1 to 0.9. Costello and Jones (2000) assigned categories to over 1800 species based on measurements and observations of plant water needs.

Plant density factors are divided into three categories and vary from 0.5 to 1.3. Immature and sparsely planted landscapes are placed in the Low category because they use less water than mature or full cover plantings. Plantings of one type with full cover are in the Moderate category. Mixed plantings with trees, shrubs, and ground covers use the most water and are placed in the High category.

Plant microclimate factors are divided into three categories and vary from 0.5 to 1.4. The Moderate category is similar to open field conditions with no unusual wind or heat sources for the location. For example, most well vegetated parks, unless exposed to high winds, would fall in the average microclimate category. The High category includes plantings with nearby paved areas, building walls, reflective surfaces, or locations with high winds. Plantings in shade, north facing slopes, or under building overhangs fall in the Low category.

Example 4.6

Estimate the water required for one citrus tree in a bare area in California. The tree is mature with a canopy diameter of 10 m, irrigated every third day, and ET_o is

7 mm/day.

Solution. From Table 4.6 estimate the following values:

k_s = 0.6 for moderate water use,

k_d = 0.7 for large canopy and low density, and

k_{mc} = 1.3 for the bare soil heat source.

Calculate K_L from Equation 4.32:

$$K_L = 0.6 \times 0.7 \times 1.3 = 0.546$$

Calculate ET_L from Equation 4.31:

$$ET_L = 0.546 \times 7 = 3.82 \text{ mm/day}$$

The estimated volume of water to be delivered per irrigation is:

$$\text{Volume} = \frac{3.82 \text{ mm/day}}{1000 \text{ mm/m}} \times 3\,\text{days} \times \pi (5\,\text{m})^2 \times 1000 \text{ L/m}^3 = 900.5 \text{ L/irrigation}$$

Thus the irrigation system should be set to deliver about 900 L of water every three days.

Internet Resources

General reference sites for equipment and information:
- www.clemson.edu/irrig/sites.htm
- www.irrigation-mart.com
- www.irrigation.org
- www.wsi.nrcs.usda.gov/products/W2Q/water_mgt/Irrigation/nrcs_irrigation_page.html

Solar radiation data sources:
- www.nrel.gov/rredc/solar_resource.html
- wrdc-mgo.nrel.gov/

Examples of evapotranspiration data sources:
- www.usbr.gov/pn/agrimet/ETtotals.html
- www.cimis.water.ca.gov
- cropwatch.unl.edu/ Key search term: evapotranspiration
- ag.arizona.edu/AZMET

Landscape water use, California DWR publications:
- www.water.ca.gov/publications/browse.cfm?display=topic&pub=120,127,225

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Problems

4.1 Compute the daily evaporation from a free-water surface if the wind speed is 4 m/s at 0.15 m height, average water and air temperatures are both 25°C, and the average relative humidity of the air is 50%. Atmospheric pressure is

100 kPa. How would your computed value compare with the evaporation from a dry-soil surface? From a Class A Weather Bureau pan?

4.2 For a Class A pan, estimate ET_o for June 1. The measured evaporation from the pan was 11 mm. The wind was 2.5 m/s and the average minimum relative humidity was 75%. The pan is surrounded by 100 m of bare soil.

4.3 Using the Standardized Penman-Monteith equation, estimate ET_o for July 10, 2002, at 40°N. The data were measured over grass and the mean minimum and maximum temperatures are 16°C and 29°C, respectively; maximum and minimum relative humidity are 70 and 40%, respectively; measured solar radiation is 27 MJ m^{-2} day^{-1}; 1.7 m/s wind speed at 3 m height; 300 m elevation; and negligible heat flux to the soil.

4.4 From the data in Problem 4.3 estimate the alfalfa-based reference ET_r.

4.5 Assume the only climatic data available from Problem 4.3 are the maximum and minimum temperatures. Estimate ET_o using the equations from Section 4.9 on missing data.

4.6 Estimate K_c for soybeans for May 15, June 4, July 20, and September 2 from Tables 4.4 and 4.5. Determine $K_{c\ ini}$ using Equation 4.30 for a typical infiltration depth of 20 mm, a 10 day frequency, a silt loam soil, and a planting date of May 1. ET_o is 3 mm/day, 5 mm/day, 6 mm/day, and 4 mm/day for May 15, June 4, July 20, and September 2, respectively.

4.7 Estimate the water requirement for a cluster of small shrubs surrounded by grass in the Central Valley of California in July. ET_o is 10 mm/day, the climate is hot and dry, with light winds, and the plant species factor is 0.5.