Wright, James L. 1990. Estimating crop evapotranspiration, p. 112-131. In: M.E. Jensen, R.D. Burman, and R.G. Allen (eds.). Evapotranspiration and irrigation water requirements. A manual prepared by the Committee on IrrigationWater Requirements of the Irrigation and Drainage Division of the American Society of Civil Engineers. Am. Soc. of Civil Engineers, New York. (No reprints)

ASCE Manuals and Reports on Engineering Practice No. 70

Evapotranspiration and Irrigation Water Requirements

Edited by
M.E. Jensen, R.D. Burman, and R.G. Allen

A manual prepared by the
Committee on Irrigation Water Requirements of the
Irrigation and Drainage Division of the
American Society of Civil Engineers

Contributors

R.G. Allen	E.L. Johns
R.H. Cuenca	J.F. Stone
M.E. Jensen	R.D. Burman
W.O. Pruitt	R.W. Hill
R.K. Blatchley	P.R. Nixon
J.M. Erpenbeck	J.L. Wright[a]
	[a]Nonmember Advisor

Published by the
American Society of Civil Engineers
345 East 47th Street
New York, New York 10017-2398

where T_c is the mean temperature in °C and T_{co} = 20°C.

$$C_{W2} = 1.189 - 0.240\,(W/W_o) + 0.051\,(W/W_o)^2 \qquad [6.58c]$$

where W is the mean wind velocity 2 m above ground level in miles per day or km per hour and W_o = 100 miles per day or 6.7 km per hour.

$$C_{H2} = 0.499 + 0.620\,(H_m/H_{mo}) - 0.119\,(H_m/H_{mo})^2 \qquad [6.58d]$$

where H_m is the mean relative humidity, expressed decimally, and H_{mo} = 0.60

$$C_{S2} = 0.904 + 0.0080\,(S/S_o) + 0.088\,(S/S_o)^2 \qquad [6.58e]$$

where S is the percentage of possible sunshine, expressed decimally, and S_o = 0.80.

The original Christiansen reference referred to potential evapotranspiration, E_{tp}, but E_{tp} may be regarded as grass reference evapotranspiration, E_{to}, because data from grass surfaces were used as calibration input to the method.

6.4. Estimating Crop Evapotranspiration

Dominant crop and environmental conditions need to be considered to obtain accurate estimates of E_t for a specific crop. Meteorological conditions determine the evaporative demand while the crop canopy and soil moisture conditions determine the extent to which that demand will be met. Evapotranspiration for a particular crop can be estimated if measurements or estimates of a potential or reference E_t are available. These measurements or estimates represent the meteorological demand. Crop coefficients represent the crop and soil ability to meet the demand.

Extensive research has been conducted on reference E_t methods and crop coefficients because of their use in irrigation scheduling and water resources allocation, management, and planning. The available methods for estimating reference E_t when properly used with reliable crop curves permit estimating crop E_t within the accuracy of most field-irrigation systems to deliver water (Jensen et al., 1971; Jensen and Wright, 1978; Wright and Jensen, 1978).

Various procedures have been used during the past three decades to obtain the experimental crop and reference E_t data needed to develop E_t crop coefficients. Several sets of curves derived from these data have been published (Burman et al., 1980; Doorenbos and Pruitt, 1977; Jensen, 1974; Pruitt et al., 1972, 1987a; Wright, 1979, 1981, 1982). It is important that empirically derived crop coefficients be used with the appropriate reference E_t. The climatic adequacy of the methods, the necessary data, and the time scale all need to be understood and carefully applied if accurate estimates of crop water requirements are to be obtained.

The nature and origin of several sets of crop coefficients and reference E_t were discussed by Wright (1981). The following discussion summarizes the basic nature of crop coefficients and provides a background of the conditions for which they can be appropriately used.

Crop Coefficients

Crop coefficients are generally empirical ratios of crop E_t to some reference E_t that have been derived from experimental data according to the relationship:

$$K_c = E_{tc}/E_t(\text{reference}) \qquad [6.59]$$

where K_c is a dimensionless crop coefficient for a particular crop at a given growth stage and soil moisture condition, E_{tc} is daily crop E_t, and E_t(reference) is daily reference E_t.

Ideally, reference E_t characterizes the evaporative demand determined by meteorological conditions and a standard crop surface and K_c indicates the relative ability of a specific crop-soil surface to meet that demand. Since reference E_t is affected by many variables, it cannot be simply described for all climate and crop situations because of the effects of the relative leaf area and the morphological and physiological characteristics of the reference crop canopy on the energy exchange and aerodynamic diffusion processes within the atmosphere over a field. Several methods have been developed for estimating reference E_t for either grass or alfalfa with corresponding sets of crop coefficients (Burman et al., 1980, 1983; Doorenbos and Pruitt, 1977; Wright, 1981). The use of a reference E_t and associated crop coefficients is a practical technique because it provides a conservative means of estimating crop E_t at progressive stages of growth.

The general crop coefficient, described by Eq. 6.59, includes the effects of evaporation from both plant and soil surfaces and is dependent upon available soil water within the root zone and the wetness of the exposed soil surface. Most crop coefficient curves or tables are for well-watered crops. A crop curve is the distribution of K_c with time throughout the season. Other time-related parameters, such as growing degree days, solar-thermal units, or accumulative reference E_t may also be used in place of elapsed time. If various reference E_t values are used to develop crop coefficients, the resulting K_c values will vary accordingly.

Soil water depletion data, initially used to determine crop E_t, were obtained by gravimetric sampling or neutron probe methods and represented three- to five-day or longer averages. However, even in carefully planned studies, the effects of upward or downward movement of water and extraction by deep roots caused some uncertainty in the measured E_t. Measurements obtained with sensitive weighing lysimeters with representative fetch conditions over the past 30 years provide daily E_t data that are not subject to errors caused by soil water movement or extraction from below the sampling depth. However, lysimeter data may not be representative of field data unless precautions are taken such as maintaining soil water in the lysimeter essentially the same as in the surrounding field and ensuring that the vegetation in and immediately surrounding the lysimeter is essentially the same. In a good lysimeter installation, the location of the lysimeter within a field should not be apparent.

Reference Crop Evapotranspiration

In the past, various forms of potential E_t, E_{tp}, intended to describe near maximum E_t, were used in developing crop coefficients. However, because of ambiguities in defining potential E_t, particularly in arid climates, the term reference crop evapotranspiration with the reference crop specifically noted, has been recommended (Perrier and Jensen, 1979).

Alfalfa was suggested as a reference crop for arid climates for use in irrigation scheduling procedures (Jensen, 1969; Jensen et al., 1971) and has frequently been used since (Wright, 1979, 1981, 1982; Wright and Jensen, 1972). Alfalfa reference E_t is defined as the daily E_t of an actively growing alfalfa crop covering an extensive area, at least 30 cm tall and standing erect and well watered so that soil water availability does not limit E_t. Wright and Jensen (1972), using lysimeter data, developed procedures for estimating alfalfa E_t from meteorological data. These procedures were later refined by Wright (1982).

Alfalfa reference E_t may be preferable for arid regions because alfalfa is capable of near maximum E_t rates when there is considerable advective sensible heat input from the air. Also, because of an extensive root system, alfalfa E_t is less subject to decreasing soil water effects under high E_t rates compared with a shallow-rooted crop. At high elevations where alfalfa cannot be grown, the estimate of alfalfa reference E_t is for a hypothetical crop.

The E_t of well-watered, actively growing green grass that is clipped to a uniform height of 8–15 cm, completely shading the soil, not short of water, and covering an extensive area, has also been used as a reference E_t (Doorenbos and Pruitt, 1977; Pruitt, 1966). Short grass reference E_t is usually less than alfalfa E_t, particularly under dry, windy conditions. Thus, the K_c values determined with Eq. 6.59 for a given crop would be larger when used with a grass than when used with an alfalfa E_t reference.

Estimating Crop Evapotranspiration

In practice, Eq. 6.59 is rewritten to estimate crop E_t as:

$$E_t = K_c E_t(\text{reference}) \qquad [6.60]$$

where K_c is the experimentally derived crop coefficient and the appropriate reference E_t is estimated or measured. Problems sometimes occur in applying this concept because of misunderstandings or lack of attention to the details of the methods used in deriving K_c. The same reference E_t values should be used to estimate E_t as were used in developing K_c, and the time scale should be similar. When procedures and coefficients developed for a given climatic area are applied elsewhere, testing is advisable along with any adjustment of functional relationships that may be needed. A satisfactory degree of accuracy in estimating E_t, i.e., ± 10 percent for short time periods, generally requires careful adherence to recommended procedures.

Methods available for estimating E_t(reference) for use with Eq. 6.60 depend on data availability and local circumstances. Several suitable methods using climatic data are discussed in other sections of this manual and will not be repeated here. It is important to note, however, that methods based solely on temperature are generally inadequate for arid or semiarid regions. The Blaney-Criddle method described by Doorenbos and Pruitt (1977) involves extensive revisions, and for clarity is referred to as the "FAO-24 Blaney-Criddle method" to distinguish it from the original method of Blaney and Criddle (1950) and the modified method developed by the Soil Conservation Service (USDA, 1970). The original Blaney-Criddle and SCS Modified Blaney-Criddle methods have been used extensively because of the relatively lesser data requirements. However, appropriate calibrations or adjustments have not always been used with these methods. The monthly crop coefficients developed for the original and the SCS versions of the Blaney-Criddle equation are different from the E_t crop coefficient of Eq. 6.59 because a reference E_t is not used and climatic effects are not completely separated from the crop parameters in the equation.

Doorenbos and Pruitt (1977) recommended using the combination equation method for areas where measurements of temperature, humidity, wind and sunshine duration, or radiation are available (see also Chapter 7). While their procedures provide estimates of grass reference E_t, which they call E_{to}, other versions of the combination equation are available for estimating alfalfa E_{tr} (Allen et al., 1989; Wright, 1982; Wright and Jensen, 1972).

In selecting a practical method, it is important to remember that all existing methods of estimating crop E_t from climatic data involve some empirical relationships. Consequently, some local or regional verification or calibration is advisable with any selected method. A method giving the highest precision over the shortest time period is preferred. The extent to which this is possible depends on the availability of data. Verification or calibration of a method involves the simultaneous measurement of crop E_t and corresponding climatic data. If the method is to be used for short-period estimates, comparable data should be used in calibration.

6.5. Use of Crop Coefficients

Generalized crop coefficient curves for estimating E_{tr} are shown in Fig. 6.4. The K_{cb} curve represents basal crop coefficients for conditions

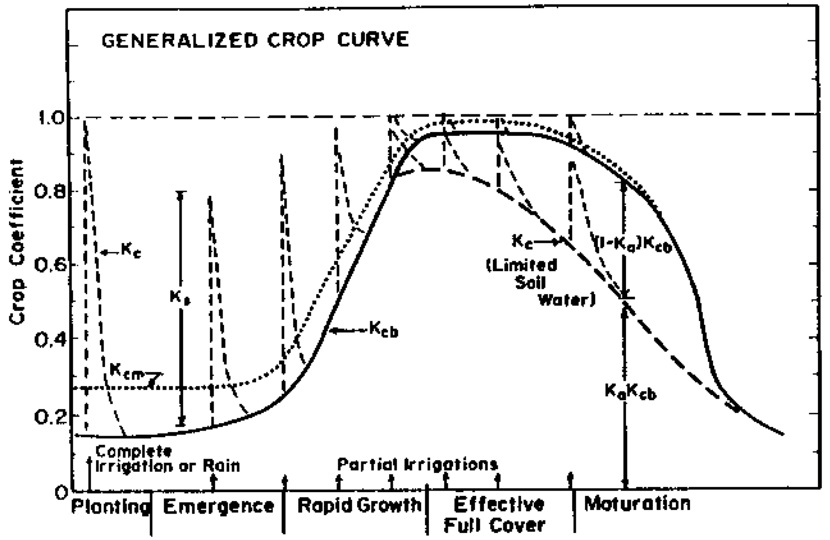

FIG. 6.4. Generalized Crop Curves Showing the Effects of Growth Stage, Wet Surface Soil, and Limited Available Soil Water. K_{cb} = Basal Curve; K_c = Adjusted Curve (Function of K_a and K_s); and K_{cm} = Mean Curve (after Wright, 1982).

when the soil surface is visually dry, so that evaporation is minimal but the availability of soil water does not limit plant growth or transpiration. The K_{cm} line represents the mean crop coefficient, which includes wet soil effects.

Basal Crop Coefficients

In estimating daily crop E_t, as for irrigation scheduling, the use of crop coefficients representing primarily the transpiration component of E_t with adjustment for wet soil effects after rain or irrigation permits finer resolution than that obtained using K_{cm}. Improved procedures for estimating alfalfa E_{tr} and the daily lysimeter E_t data used to develop K_{cb} curves have improved the accuracy of this approach (Burman et al., 1980; Wright 1979, 1981, 1982). The designation K_{cb} is used to emphasize the nature and source of these coefficients and to differentiate these values from previous versions of crop coefficients such as K_{co} (Jensen, 1974; Jensen et al., 1971). Daily values of K_c are obtained using a K_{cb} curve that is adjusted for the effects of surface soil wetness, differences in soil drying properties, and available soil water as follows:

$$K_c = K_{cb}K_a + K_s \qquad [6.61]$$

in which K_a is a dimensionless coefficient dependent on available soil water and K_s is a coefficient to adjust for increased evaporation from wet soil immediately after rain or irrigation. The value of K_a is 1 unless available soil water limits transpiration, in which case it has a value less than 1. When the soil surface is wet, $K_s > 0$ so that $K_c > K_{cb}$. The coefficients K_a and K_s are shown in Fig. 6.4. When the soil surface is dry, so that evaporation is minimal but available soil water does not limit plant growth or transpiration, $K_c = K_{cb}$ because $K_a = 1$ and $K_s = 0$. When available water within the root zone limits growth and E_t, K_a is less than 1 so that K_c is less than K_{cb} when $K_s = 0$. Similar procedures were used in the USDA-ARS Irrigation Scheduling Program (Jensen et al., 1971).

The functional relationship of K_a and available soil water depends on soil properties and crop rooting patterns. An example is:

$$K_a = \ln(A_w + 1)/\ln(101) \qquad [6.62a]$$

in which A_w = the percentage of available soil water (100 when the soil is at field capacity). When $A_w = 100$, $K_a = 1$. K_a goes to 0 as A_w goes to 0. This algorithm, developed for a southern Idaho soil (Jensen et al., 1970), results in little reduction of K_c until A_w is less than 50. Suitable relationships should be used for each soil. Boonyatharokol and Walker (1979) evaluated various relationships for estimating K_a using field measurements obtained at Grand Junction, Colorado. They recommended the following variations of K_a:

$$K_a = 1 \text{ for } A_w > 50\% \qquad [6.62b]$$

$$K_a = A_w/50 \text{ for } A_w \leq 50\% \qquad [6.62c]$$

Jensen et al. (1970, 1971) used the following method to approximate K_s for Kimberly, Idaho:

$$K_s = (K_1 - K_{ci})\, e^{-\xi t} \text{ for } K_1 > K_{ci} \qquad [6.63]$$

in which t is the number of days after a rain or irrigation, ξ represents the combined effects of soil characteristics and evaporative demand, and K_{ci} is the value of K_c at the time the rain or irrigation occurred. The values of K_1 will vary for various soils and locations.

Wright (1981) developed the following general equation for K_c based on K_{cb} and the effects of surface soil wetness, soil drying properties, and irrigation methods:

$$K_c = K_a K_{cb} + (K_1 - K_aK_{cb})[1 - (t/t_d)^{1/2}]\, f_w, \text{ for } t \leq t_d \qquad [6.64]$$

where K_c is the adjusted crop coefficient, K_a is as used in Eq. 6.62, K_1 is the maximum value of K_c normally occurring after rain or irrigation, t is the number of days after major rain or irrigation, t_d is the usual number of days required for the soil surface to visually appear dry, and f_w = the relative proportion of the soil surface originally wetted by furrow irrigation. Normally, under arid conditions, K_1 would have a maximum value of 0.8 to 1 depending on irrigation method, climate, and soil properties. If irrigation is completed before noon, $t = 0$ for that day; otherwise $t = 0$ for the following day. For surface irrigations that wet the entire soil surface $f_w = 1.0$, while for irrigations using every other furrow and wetting only to the plant row, $f_w = 0.5$. For sprinkler irrigations or precipitation, P, equivalent to several days of E_t, $f_w = 1.0$. For precipitation, P, less than $0.35[1.5 + t_d][(K_1 - K_a K_{cb})E_{tr}]$, the value of f_w should be limited to $P/\{[0.35(1.5 + t_d)][K_1 - K_a K_{cb}]E_{tr}\}$.

Kimberly E_t data indicate that with bare silt soil and little crop cover, five or more days elapse after thorough wetting of the soil surface before K_c returns to the basal level, thus t_d is about five days. For sandy soils, t_d is probably three days or less, and for clay loams, probably seven days or more. The total increase in surface evaporation due to an irrigation will be about $\{0.35[t_d + 1.5](K_1 - K_a K_{cb})E_{tr}\}$. Most of the increase occurs in the first few days after the soil is wetted. Eq. 6.64 will produce the upward spikes equivalent to K_s above the K_{cb} curve in Fig. 6.4.

Mean Crop Coefficients

Sometimes a mean crop coefficient may be more useful than a basal coefficient for estimating daily crop E_t because it may be impractical to estimate wet soil effects or it may be necessary to estimate total seasonal water requirements for a general area from historical climatic data. The mean crop curve, K_{cm}, shown in Fig. 6.4, lies above the basal curve by an amount that depends on the frequency of soil wetting. When a mean coefficient is used, usually no adjustment is made for the effects of surface soil wetness on increased evaporation. However, adjustments can be made for the effects of limiting soil moisture using K_a from Eq. 6.62a:

$$K_c = K_{cm} K_a \tag{6.65}$$

Mean crop coefficients can be developed from the lysimeter E_t data that were used to derive the basal coefficients. Also, soil water balance data can be used to develop K_{cm} values for time periods of several days if daily lysimeter data are unavailable. Values of K_{cm} during partial crop cover will be dependent on precipitation and irrigation practices that wet all or part of the soil surface during the sampling interval.

Alfalfa-Related Basal Crop Coefficients Developed in Idaho

Basal crop coefficients developed by Wright (1982) for several crops grown in southern Idaho are given in Table 6.6. These were derived from data obtained with weighing lysimeters and are intended for use in arid

TABLE 6.6. Basal Crop Coefficients, K_{cb}, for Dry Surface Soil for Use with Alfalfa Reference E_t, E_{tr}, for Irrigated Crops Grown in an Arid Region with a Temperate Intermountain Climate (after Wright, 1982[c])

Basal ET Crop Coefficients, K_{cb}

Crop [1]	*PCT*, time from planting to effective cover (%): 0 [2]	10 [3]	20 [4]	30 [5]	40 [6]	50 [7]	60 [8]	70 [9]	80 [10]	90 [11]	100 [12]
Spring grain[a]	0.15	0.15	0.16	0.20	0.25	0.40	0.52	0.65	0.81	0.96	1.00
Peas	0.15	0.15	0.16	0.18	0.20	0.29	0.38	0.47	0.65	0.80	0.90
Sugar beets	0.15	0.15	0.15	0.15	0.15	0.17	0.20	0.27	0.40	0.70	1.00
Potatoes	0.15	0.15	0.15	0.15	0.15	0.20	0.32	0.47	0.62	0.70	0.75
Corn	0.15	0.15	0.15	0.16	0.17	0.18	0.25	0.38	0.55	0.74	0.93
Beans	0.15	0.15	0.16	0.18	0.22	0.34	0.45	0.60	0.75	0.88	0.92
Winter wheat	0.15	0.15	0.15	0.30	0.55	0.80	0.95	1.00	1.00	1.00	1.00

Crop [1]	*DT*, days after effective cover: 0 [2]	10 [3]	20 [4]	30 [5]	40 [6]	50 [7]	60 [8]	70 [9]	80 [10]	90 [11]	100 [12]
Spring grain[a]	1.00	1.00	1.00	1.00	0.90	0.40	0.15	0.07	0.05	—	—
Peas	0.90	0.90	0.72	0.50	0.32	0.15	0.07	0.05	—	—	—
Sugar beets	1.00	1.00	1.00	1.00	0.98	0.91	0.85	0.80	0.75	0.70	0.65
Potatoes	0.75	0.75	0.73	0.70	0.66	0.63	0.59	0.52	0.20	0.10	0.10
Field corn	0.93	0.93	0.93	0.90	0.87	0.83	0.77	0.70	0.30	0.20	0.15
Sweet corn	0.93	0.91	0.90	0.88	0.80	0.70	0.50	0.25	0.15	—	—
Beans	0.92	0.92	0.86	0.65	0.30	0.10	0.05	—	—	—	—
Winter wheat	1.00	1.00	1.00	1.00	0.95	0.50	0.20	0.10	0.05	—	—

Crop [1]	Time from new growth or harvest to harvest (%): 0 [2]	10 [3]	20 [4]	30 [5]	40 [6]	50 [7]	60 [8]	70 [9]	80 [10]	90 [11]	100 [12]
Alfalfa (1st)[b]	0.40	0.50	0.62	0.80	0.90	0.95	1.00	1.00	0.98	0.96	0.94
(Intermediate)	0.25	0.30	0.40	0.70	0.90	0.95	1.00	1.00	0.98	0.96	0.94
(Last)	0.25	0.30	0.40	0.50	0.55	0.50	0.40	0.35	0.30	0.27	0.25

[a]Spring grain includes wheat and barley.
[b]1st denotes first harvest, intermediate harvests may be 1 or more depending on length of season. The last harvest is when crop becomes dormant in cool weather. See text for further discussion. Cultivar used was Ranger.
[c]Minor changes from Wright (1982) reflect additional data for some crops (Wright, 1984, personal communication).

soil shading becomes nearly complete. If shading of the soil does not become complete, the maximum value of K_{cb} should be scaled down accordingly. During the period of crop development just prior to full cover, leaf area expansion is very rapid and the exact day of effective full cover is not critical. Winter wheat, spring cereals, and sugar beets at effective full cover have crop coefficients similar to full-cover alfalfa. The other crops peak at values of about 0.95, except for potatoes, which peak at about 0.75. The K_{cb} values for most of the crops gradually decline after the peak because of lodging or leaf senescence. There normally is rapid decline at maturation.

The low maximum K_{cb} for potatoes in Table 6.6 is assumed to be due to physiological factors, canopy structure, and varietal differences of the crop. The data presented were obtained with an excellent crop of the Russet Burbank variety. Other researchers report higher maximum K_{cb} values for other potato cultivars (Burman et al., 1980; Doorenbos and Pruitt, 1977). Lysimeter and field data presented by California (1975, 1986) indicate similar peak K_{cb} values for potatoes as for rice, sugar beets, and other crops.

The basal crop coefficients for the visually dry soil surface early in the season reflect the combined effects of soil-water carryover from winter precipitation and relatively low evaporative demand. After tillage, with the disruption of the soil capillary channels and the development of stronger drying conditions, the K_{cb} for dry soil generally decreases to about 0.1 or less before irrigation or crop emergence. During the latter part of the season, it averages about 0.05 for crops harvested under dry soil conditions. When potatoes are irrigated after vine kill to facilitate harvesting, the late-season K_{cb} ranges from 0.2 to 0.4. Some crops, like sugar beets, may be irrigated before harvest to facilitate removal of the roots from the soil, which will increase the late-season coefficient.

Grass-Related Basal Crop Coefficients Developed in California

Basal crop coefficients derived from Davis, California, for use with a grass reference evapotranspiration, E_{to}, are given in Table 6.8. These coefficients were based on concurrent lysimeter measurements of E_t for Alta fescue grass and E_t for each of the crops. The coefficients are representative of an arid Mediterranean-type climate (Burman et al., 1980). Typical planting dates, days to full crop cover, harvest dates, and days from full cover to harvest are included in Table 6.9. Because of the manner of assessing full cover, the peak K_c sometimes occurred after indicated full cover. When using grass-based basal crop coefficients, the value of K_1 in Eq. 6.64 is generally in the range of 1.0 to 1.2.

Alfalfa-Related Mean Crop Coefficients Developed in Idaho

Mean daily E_t crop coefficients, K_{cm}, are given in Table 6.9. These were developed from the same E_t data set as the K_{cb} values of Table 6.6.

TABLE 6.8. Basal Crop Coefficient, K_{cb}, for Use with Grass Reference E_t, E_{to}, for Irrigated Crops Grown in an Arid Mediterranean Climate (after Burman et al., 1980; Pruitt, 1986)

Crop (1)	Planting date mo/day (2)	Days to full cover (3)	Time from Planting to Peak k_c (%): 10 (4)	20 (5)	30 (6)	40 (7)	50 (8)	60 (9)	70 (10)	80 (11)	90 (12)	100 (13)
Sorghum	5/17	45	0.12	0.13	0.14	0.16	0.22	0.33	0.50	0.75	1.00	1.07
Beans	6/21	43	0.10	0.12	0.16	0.21	0.28	0.39	0.53	0.75	0.98	1.08
Tomatoes	4/29	80	0.14	0.15	0.17	0.19	0.22	0.33	0.48	0.71	1.04	1.18
Barley	10/31	100	0.18	0.20	0.22	0.24	0.28	0.34	0.47	0.66	0.90	1.07
Corn	5/14	52	0.12	0.13	0.15	0.20	0.29	0.45	0.81	0.99	1.08	1.13
Sugar beets (late)	6/16	55	0.12	0.13	0.16	0.20	0.29	0.45	0.65	0.87	1.04	1.10
Sugar beets (early)	3/25	90	0.14	0.16	0.18	0.22	0.27	0.37	0.53	0.77	1.04	1.10

Crop (1)	Harvest date mo/day (2)	Days from full cover (3)	Days After Peak k_c: 10 (4)	20 (5)	30 (6)	40 (7)	50 (8)	60 (9)	70 (10)	80 (11)	90 (12)	100 (13)
Sorghum	9/13	74	1.08	1.06	1.03	0.99	0.94	0.88	0.79	0.65	—	—
Beans	9/18	46	1.12	1.12	1.10	0.71	0.15	—	—	—	—	—
Tomatoes	9/24	68	1.24	1.21	1.12	1.03	0.90	0.75	0.58	—	—	—
Barley	5/19	100	1.15	1.17	1.19	1.21	1.19	1.12	0.98	0.75	0.50	0.24
Corn	9/20	77	1.17	1.17	1.17	1.14	1.03	0.87	0.67	—	—	—
Sugar beets (late)	11/18	100	1.15	1.16	1.16	1.16	1.15	1.14	1.13	1.12	1.10	1.08
Sugar beets (early)	9/20	90	1.13	1.15	1.15	1.14	1.13	1.11	1.08	1.05	1.01	—

TABLE 6.9. Mean E_t Crop Coefficients, K_{cm}, for Normal Irrigation and Precipitation Conditions, for Use with Alfalfa Reference E_t, E_{tr} (after Wright, 1981[a])

Crop	Mean ET Crop Coefficients, K_{cm}										
	PCT, time from planting to effective cover (%)										
	0[#]	10	20	30	40	50	60	70	80	90	100
Spring grain*	0.20	0.20	0.21	0.26	0.39	0.55	0.66	0.78	0.92	1.00	1.00
Peas	0.20	0.20	0.21	0.26	0.36	0.43	0.51	0.62	0.73	0.85	0.93
Sugar beets	0.20	0.20	0.21	0.22	0.24	0.27	0.33	0.45	0.60	0.80	1.00
Potatoes	0.20	0.20	0.20	0.22	0.31	0.41	0.51	0.62	0.70	0.76	0.78
Corn	0.20	0.20	0.20	0.20	0.23	0.32	0.42	0.55	0.70	0.85	0.95
Beans	0.20	0.20	0.20	0.26	0.35	0.45	0.55	0.66	0.80	0.90	0.95
Winter wheat	0.30	0.30	0.30	0.50	0.75	0.90	0.98	1.00	1.00	1.00	1.00
	DT, days after effective cover										
	0[#]	10	20	30	40	50	60	70	80	90	100
Spring grain*	1.00	1.00	1.00	1.00	0.90	0.50	0.30	0.15	0.10	—	—
Peas	0.93	0.93	0.70	0.53	0.35	0.20	0.12	0.10	—	—	—
Sugar beets	1.00	1.00	1.00	1.00	0.98	0.94	0.89	0.85	0.80	0.75	0.71
Potatoes	0.78	0.78	0.76	0.74	0.71	0.67	0.63	0.59	0.36	0.25	0.20
Field corn	0.95	0.96	0.95	0.94	0.90	0.85	0.79	0.74	0.35	0.25	—
Sweet corn	0.95	0.94	0.93	0.90	0.85	0.75	0.58	0.40	0.20	0.10	—
Beans	0.95	0.95	0.90	0.67	0.33	0.15	0.10	0.05	—	—	—
Winter wheat	1.00	1.00	1.00	1.00	0.95	0.55	0.25	0.15	0.10	—	—
	Time from new growth or harvest to harvest (%)										
	0[#]	10	20	30	40	50	60	70	80	90	100
Alfalfa (1st)[@]	0.55	0.70	0.82	0.91	0.96	0.99	1.00	1.00	0.98	0.96	0.94
(Intermediate)	0.30	0.40	0.50	0.80	0.96	0.99	1.00	1.00	0.98	0.96	0.94
(Last)	0.30	0.40	0.50	0.60	0.65	0.63	0.61	0.59	0.57	0.55	0.50
	Total season (days from beginning of spring growth)										
	0[#]	20	40	60	80	100	120	140	160	180	200
Alfalfa	0.45	0.69	0.87	0.88	0.70	0.75	0.88	0.81	0.88	0.71	0.65
(seasonal)	0.50	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.75	0.60
(overall seasonal mean)						0.82					
Grass (perennial ryegrass) (8–15 cm)	0.60	0.70	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.76	0.75

*Spring grain includes wheat and barley.

[#]The value 0.2 is appropriate for relatively dry surface soil conditions from planting until significant crop development. For moderately wet surface soil, as with preemergence irrigation(s) or some precipitation, use 0.35, and for very wet conditions use 0.50.

[@]1st denotes first harvest, intermediate harvests may be 1 or more depending on length of season. The last harvest is when crop becomes dormant in cool weather. See text for further discussion. Cultivar used was Ranger.

[a]Minor changes from Wright (1981) reflect additional years of data for some crops (Wright, 1987, personal communication).

Corresponding crop development data of Table 6.7 also apply. The K_{cm} values represent crop development and management practices where root zone soil water does not limit crop growth and includes the effects of average rainfall and irrigation patterns typical of the area. At Kimberly, Idaho, light rains or showers usually occur during the spring and summer, averaging about 20, 25, 25, 5, 13, 13, and 16 mm per month for the April–October period, respectively. Five or more irrigations are required throughout the season for most annual crops. The mean crop coefficients in Table 6.9 can be used directly in Eq. 6.60 without adjustment for soil wetness or can be used in Eq. 6.65 if root zone soil water is limiting. A mean coefficient of 0.3 early in the season represents soil evaporation from residual winter-season soil water, spring precipitation, and preplant and preemergence irrigations where applicable. For wetter-than-normal soil conditions throughout the period, a general coefficient of 0.4 is appropriate until the crop emerges and begins rapid growth. For unusually dry conditions, a value of 0.2 is recommended. For unusually wet conditions, such as with daily sprinkler irrigation of a crop like potatoes, a coefficient of 0.9 should be used.

The K_{cm} values for alfalfa in Table 6.9 are for separate cuttings, as in Table 6.6, where the season is considered to be from April 1 until October 31. A general-seasonal K_{cm} data set, which includes normal harvest date effects, for southern Idaho is also presented. The second line of this data set is a smoothed seasonal data set that averages all three harvest effects. For longer growing seasons with more than three harvests, the middle portion of the time period for the second line can be extended. An overall seasonal mean K_{cm} is also listed for alfalfa. The alfalfa K_c values listed in Tables 6.6 and 6.9 are for disease-free, insect-free crops of well-watered Ranger alfalfa harvested without windrow effects or other damage to regrowth. If regrowth of alfalfa is delayed due to irrigation system, disease, insect, fertility, compaction, and windrow effects, then the K_c values should be reduced proportionately.

The K_{cm} values for clipped grass, as obtained with a weighing lysimeter, are listed in the lower portion of Table 6.9 similar to the overall alfalfa data. Basal coefficients were not listed for grass in Table 6.6 since dry soil factors are not as applicable as for other crops.

Grass-Related Mean Crop Coefficients Developed in California

Mean daily crop coefficients, K_{cm}, relating E_t to E_{to} for the San Joaquin Valley are given in Table 6.10 (Pruitt et al., 1987a). Although the format differs from Tables 6.6, 6.7, 6.8, and 6.9, this table provides K_{cm} values for a wide range of crops that are grown in California and similar climates. K_{cm} values for other regions of California with climates ranging from cool coastal areas to hot desert areas are presented by Pruitt et al. (1987a).

TABLE 6.10. Example Mean Crop Coefficients Related to E_{tr}[1] Suggested for Crops Grown in the San Joaquin Valley (adapted from Pruitt et al., 1987a)

Date	Citrus (clean cultivate)	Table grapes	Deciduous orchard (clean cultivate)	Deciduous orchard with cover crop	Beans (dry)	Corn (grain)	Milo	Small grains	Cotton	Sugar beets	Tomato	Onions	Onions	Melons
Jan 1–15	0.83							0.46					0.70	
16–31	0.82							0.67					0.90	
Feb 1–14	0.81							0.95					1.05	
15–28	0.80							1.15					1.10	
Mar 1–15	0.74							1.18				0.32	1.12	
16–31	0.73		0.56	0.96				1.20		0.16		0.34	1.15	0.18
Apr 1–15	0.72		0.62	1.01				1.20		0.22	0.26	0.40	1.15	0.23
16–30	0.72	0.14	0.68	1.06		0.19		1.10	0.17	0.33	0.26	0.55	1.15	0.36
May 1–15	0.72	0.21	0.74	1.10	0.14	0.24		0.81	0.21	0.53	0.31	0.85	1.15	0.72
16–31	0.72	0.50	0.81	1.14	0.40	0.44		0.47	0.29	0.97	0.47	1.06	1.15	1.10
Jun 1–15	0.67	0.64	0.86	1.17	1.10	0.72			0.59	1.14	0.78	1.13	1.14	1.10
16–30	0.67	0.74	0.88	1.19	1.14	1.15	0.14		0.94	1.17	1.10	1.15	1.06	1.10
Jul 1–15	0.67	0.82	0.95	1.21	1.14	1.18	0.21		1.23	1.18	1.19	1.13	0.92	0.96
16–31	0.67	0.85	0.96	1.21	1.01	1.18	0.50		1.25	1.17	1.17	1.04	0.74	0.21
Aug 1–15	0.67	0.85	0.96	1.22	0.52	1.13	1.12		1.25	1.17	1.04	0.91		
16–31	0.67	0.83	0.96	1.21		0.91	1.14		1.22	1.14	0.87	0.74		
Sept 1–15	0.67	0.83	0.96	1.19		0.59	1.10		1.08	1.06				
16–30	0.68	0.78	0.95	1.18			1.00		0.81					
Oct 1–15	0.74	0.67	0.89	1.16			0.80		0.54					
16–31	0.75	0.52	0.84	1.15			0.40							
Nov 1–15	0.76	0.27	0.76	1.11										
16–30	0.77													
Dec 1–15	0.79							0.28						
16–31	0.80							0.34						

[1] Crop coefficients are related to E_{tr} defined as cool-season grass E_t. A constant of $K_c = 1.0$ can be assumed for a well-managed pasture with rotation grazing. A $K_c = 0.95$ to 1.0 is recommended as an average between-cutting value for alfalfa for all but winter months.

Other Sources of Mean Crop Coefficients

Doorenbos and Pruitt (1977) suggested a general format for developing mean crop coefficient curves relating E_t to E_{to}. Their procedure, along with suggested peak and crop maturity K_{cm} values for many crops, have also been presented by Burman et al. (1980, 1983). Snyder et al. (1987a, 1987b) presented a revised and updated version of the FAO approach to crop coefficients. They included additional crops and revised the peak and maturity K_{cm} data based on more recent research. Another recent compilation of crop-coefficient information for California was published in 1986 (California, State of, 1986).

Comparison of Alfalfa and Grass Reference Evapotranspiration

Monthly ratios of reference E_t for alfalfa to estimates of reference E_t by various methods are listed in Table 6.11 to provide a comparison of methods under Kimberly, Idaho, conditions. E_{tr} is the alfalfa reference E_t computed by the combination equation calibrated for Kimberly conditions and is used as a basis for comparison. E_t(method) is the reference E_t measured or calculated by some other method. These ratios provide approximate adjustment factors for converting other references to alfalfa E_{tr} for use with the Kimberly-derived crop coefficients. They should be used with caution, however, since they are monthly averages and the interrelationships of the methods may not be the same at all locations.

The E_{pan} ratios in Table 6.11 are based on 20 years of pan evaporation data obtained with a U.S. Class A pan by the National Weather Service at Kimberly. This pan was located in an irrigated grass plot, about 40 m square, surrounded by irrigated research plots planted to various crops each year. The ratios gradually increase in the spring as the grass around the pan site begins to grow and E_t increases in surrounding fields. The ratio remains fairly constant during the central portion of the growing season. Since a pan and a crop respond differently to daily changes in meteorological conditions, the use of pan factors provides averages that are best suited for periods of five days or longer. Recommendations and procedures for using evaporation pans, as summarized by Doorenbos and Pruitt (1977), should be closely followed if pans are to be used in estimating crop E_t (see also earlier discussions in this chapter).

TABLE 6.11. Ratios of E_{tr}/E_{pan} and E_{tr}/E_t (method) Developed from Kimberly, Idaho, Data

Method (1)	E_{tr}/E_{pan} and E_{tr}/E_t (method) April (2)	May (3)	June (4)	July (5)	Aug (6)	Sept (7)	Oct (8)
E_{pan}	0.75	0.86	0.92	0.94	0.92	0.92	0.91
E_{tr}	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E_{to} (FAO)	1.00	1.09	1.12	1.11	1.08	1.12	1.15
E_{to} (P)	0.98	1.14	1.20	1.20	1.15	1.12	1.12
E_{tr} (JH)	1.33	1.25	1.18	1.08	1.08	1.25	1.37
E_{to} (K)	1.33	1.28	1.28	1.28	1.28	1.30	1.25

E_{pan}: measured Class A pan evaporation.
E_{tr}: reference E_t, alfalfa, by combination equation using the 1982 Kimberly wind function (Wright, 1982).
E_{to} (FAO): reference E_t, grass, FAO-24 Penman method.
E_{to}(P): reference E_t, grass, modified Penman method using $W_f = (1.0 + 0.0062\, u_2)$ with u_2 in km d^{-1} and vapor pressure deficit method 3 (Jensen et al., 1971).
E_{tr} (JH): reference E_t, alfalfa, Jensen-Haise method.
E_{to} (K): measured E_t for clipped ryegrass (8 to 15 cm) at Kimberly.

The estimates of E_{to}(FAO) are based on the data of Allen and Brockway (1983b) who used the combination equation and correction coefficients of FAO-24 (Doorenbos and Pruitt, 1977) to compute a grass reference E_t, E_{to}. The E_{to}(P) estimates were obtained using the modified combination equation with the Penman (1963) wind function and method 3 for vapor saturation deficit as presented by Wright and Jensen (1972). The same meteorological data were used as were used to compute E_{tr}. The E_{tr}(JH) estimates were calculated using the Jensen-Haise method with an elevation correction (Jensen et al., 1970). All of the ratios in Table 6.11 were based on monthly totals of daily values.

E_{to}(K) estimates were based on one year's lysimeter measurements with clipped ryegrass, which was maintained according to the requirements of FAO-24 for a grass reference E_t. Measured grass reference, E_{to}, at Kimberly was 10 to 25 percent less than E_{to}(FAO), and E_{to}(FAO) was 10 to 15 percent less than E_{tr}. The E_{to}(P) calculated with the original Penman wind function, which was developed for clipped grass, but with vapor pressure deficit method 3 exceeded the measured grass E_t. This difference can be attributed to major climatic differences, arid versus humid, between areas where the various methods were developed and the manner of calculating the vapor pressure deficit (method 3). E_{tr} estimates were calculated using the mean of vapor pressure deficits at the maximum and minimum air temperatures. The average ratio of E_{tr} to measured grass E_t of 1.28 compares with a ratio of 1.15 suggested by Doorenbos and Pruitt (1977) for a dry climate with light to moderate wind. Erpenbeck (1981) obtained an average alfalfa-to-grass ratio of 1.21 using grass E_t and pan evaporation data from Davis, California. Allen et al. (1989) estimated alfalfa to grass ratios of 1.2 to 1.35 using the Penman-Monteith equation over a wide range of climates.

Application of Crop Coefficients

Polynomial equations have been fitted by regression analysis to the crop coefficient curves for use in computer computations, such as irrigation scheduling (Jensen et al., 1971; Wright and Jensen, 1978). Good fits have been obtained for some of the curves. However, other curves do not lend themselves to this type of equation. Comparable values can be obtained with tabular data with linear interpolation between the points at intervals of 10 percentage points or 10 days. This procedure provides accuracy as good as, and in some cases better than, that obtained with the polynomial equation and the results are as good as the data and intended use warrant. Errors are easier to detect in tabular data entered into a computer file and adjustments for local conditions are easier to make than adjusting polynomial equations.

The E_t crop coefficients developed from lysimeter data should be usable in estimating crop E_t in areas with a climate similar to that of the area for which they were developed. They should also be usable in other areas if verified procedures are used for the reference E_t, or if correction factors are used to adjust this reference. While there is some variation in the rate of crop development between locations and successive years, the crop curve can be shifted to account for this variation if some crop development characteristics are monitored, such as date of emergence, beginning of rapid growth, bloom, heading, and full canopy indicated by the closing of rows. The general nature of the curves, including the development prior to full cover, the value at full cover, the ripening characteristics of the crop, and irrigation prior to harvest are most important. When soil, disease, insect, and other crop and soil management factors cause unusual crop development, crop coefficient curves should be adjusted accordingly.

It would be desirable to have a means of relating crop coefficients more directly to crop development instead of percentage time or elapsed days as a basis for normalizing the crop coefficients. Some attempts have been made to relate crop coefficients to variables such as accumulated growing degree days, or reference E_t, with mixed results (Buchheim and Brower, 1981). Others have related crop coefficients to light interception. Leaf area index crop models adaptable to irrigation scheduling have been developed for alfalfa, corn, dry beans, potatoes, and wheat (Heilman et al., 1981; Hill et al., 1985; Sammis et al., 1986). These usually work well for the sites for which they were developed.

6.6. Blaney-Criddle Crop Coefficients

Seasonal crop coefficients for use with the Blaney-Criddle equation are presented in Table 6.12. These coefficients should be used directly only with the original Blaney-Criddle equation because they are not independent of meteorological effects. Curves of crop coefficients for use with the SCS version of the Blaney-Criddle equation can be found in SCS Technical Release TR-21 (USDA, 1970).

6.7. Example Calculations

Data for Kimberly, Idaho, are used to illustrate computation procedures for estimating reference evapotranspiration by each of the methods evaluated in Chapter 7 and for estimating expected evapotranspiration for

TABLE 6.12. Seasonal Consumptive Use Coefficients, *K*, for Irrigated Crops In Western United States*

Crop (1)	Length of normal growing season or period** (2)	Consumptive use coefficient (*K*)*** (3)
Alfalfa	Between frosts	0.80 to 0.90
Bananas	Full year	0.80 to 1.00
Beans	3 months	0.60 to 0.70
Cocoa	Full year	0.70 to 0.80
Coffee	Full year	0.70 to 0.80
Corn (maize)	4 months	0.75 to 0.85
Cotton	7 months	0.60 to 0.70
Dates	Full year	0.65 to 0.80
Flax	7 to 8 months	0.70 to 0.80
Grains, small	3 months	0.75 to 0.85
Grains, sorghum	4 to 5 months	0.70 to 0.80
Oil seeds	3 to 5 months	0.65 to 0.75
Orchard crops:		
Avocado	Full year	0.50 to 0.55
Grapefruit	Full year	0.55 to 0.65
Orange and lemon	Full year	0.45 to 0.55
Walnuts	Between frosts	0.60 to 0.70
Deciduous	Between frosts	0.60 to 0.70
Pasture crops:		
Grass	Between frosts	0.75 to 0.85
Ladino white clover	Between frosts	0.80 to 0.85
Potatoes	3 to 5 months	0.65 to 0.75
Rice	3 to 5 months	1.00 to 1.10
Soybeans	140 days	0.65 to 0.70
Sugar beets	6 months	0.65 to 0.75
Sugar cane	Full year	0.80 to 0.90
Tobacco	4 months	0.70 to 0.80
Tomatoes	4 months	0.65 to 0.70
Truck crops, small	2 to 4 months	0.60 to 0.70
Vineyard	5 to 7 months	0.50 to 0.60

*From USDA (1970).
**Length of season depends largely on variety and time of year when the crop is grown. Annual crops grown during the winter period may take much longer than if grown in the summer.
***The lower values of *K* for use in the Blaney-Criddle formula, $U = KF$, are for the more humid areas, the higher values are for the more arid climates.

several well-watered crops. Small differences between example calculations and results presented in Chapter 7 are due to rounding of values in these examples. In these example calculations, estimates of reference E_t for grass, E_{to}, were adjusted upward by a factor of 1.15 for comparison with alfalfa, E_{tr}. Data from Table 6.11 indicate that a factor of 1.25 may have been better for Kimberly site conditions.