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Crop evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and drainage paper 56

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Chapter 6 - ET_c - Single crop coefficient (K_c)

This chapter deals with the calculation of crop evapotranspiration (ET_c) under standard conditions. No limitations are placed on crop growth or evapotranspiration from soil water and salinity stress, crop density, pests and diseases, weed infestation or low fertility. ET_c is determined by the crop coefficient approach whereby the effect of the various weather conditions are incorporated into ET_o and the crop characteristics into the K_c coefficient:

$$ET_c = K_c \, ET_o \quad (58)$$

The effect of both crop transpiration and soil evaporation are integrated into a single crop coefficient. The K_c coefficient incorporates crop characteristics and averaged effects of evaporation from the soil. For normal irrigation planning and

management purposes, for the development of basic irrigation schedules, and for most hydrologic water balance studies, average crop coefficients are relevant and more convenient than the K_c computed on a daily time step using a separate crop and soil coefficient (Chapter 7). Only when values for K_c are needed on a daily basis for specific fields of crops and for specific years, must a separate transpiration and evaporation coefficient (K_{cb} + K_e) be considered.
The calculation procedure for crop evapotranspiration, ET_c, consists of:

1. identifying the crop growth stages, determining their lengths, and selecting the corresponding K_c coefficients;

2. adjusting the selected K_c coefficients for frequency of wetting or climatic conditions during the stage;

3. constructing the crop coefficient curve (allowing one to determine K_c values for any period during the growing period); and

4. calculating ET_c as the product of ET_o and K_c.

Length of growth stages

FAO Irrigation and Drainage Paper No. 24 provides general lengths for the four distinct growth stages and the total growing period for various types of climates and locations. This information has been supplemented from other sources and is summarized in Table 11.
In some situations, the time of emergence of vegetation and the time of effective full cover can be predicted using cumulative degree-based regression equations or by more sophisticated plant growth models. These types of models should be verified or validated for the local area or for a specific crop variety using local observations.

TABLE 11. Lengths of crop development stages* for various planting periods and climatic regions (days)

Crop	Init. (L_{ini})	Dev. (L_{dev})	Mid (L_{mid})	Late (L_{late})	Total	Plant Date	Region
a. Small Vegetables							
Broccoli	35	45	40	15	135	Sept	Calif. Desert, USA
Cabbage	40	60	50	15	165	Sept	Calif. Desert, USA
Carrots	20	30	50/30	20	100	Oct/Jan	Arid climate
	30	40	60	20	150	Feb/Mar	Mediterranean
	30	50	90	30	200	Oct	Calif. Desert, USA
Cauliflower	35	50	40	15	140	Sept	Calif. Desert, USA
Celery	25	40	95	20	180	Oct	(Semi) Arid
	25	40	45	15	125	April	Mediterranean

	30	55	105	20	210	Jan	(Semi) Arid
Crucifers[1]	20	30	20	10	80	April	Mediterranean
	25	35	25	10	95	February	Mediterranean
	30	35	90	40	195	Oct/Nov	Mediterranean
Lettuce	20	30	15	10	75	April	Mediterranean
	30	40	25	10	105	Nov/Jan	Mediterranean
	25	35	30	10	100	Oct/Nov	Arid Region
	35	50	45	10	140	Feb	Mediterranean
Onion (dry)	15	25	70	40	150	April	Mediterranean
	20	35	110	45	210	Oct; Jan.	Arid Region; Calif.
Onion (green)	25	30	10	5	70	April/May	Mediterranean
	20	45	20	10	95	October	Arid Region
	30	55	55	40	180	March	Calif., USA
Onion (seed)	20	45	165	45	275	Sept	Calif. Desert, USA
Spinach	20	20	15/25	5	60/70	Apr; Sep/Oct	Mediterranean
	20	30	40	10	100	November	Arid Region
Radish	5	10	15	5	35	Mar/Apr	Medit.; Europe
	10	10	15	5	40	Winter	Arid Region
b. Vegetables - Solanum Family *(Solanaceae)*							
Egg plant	30	40	40	20	130\1	October	Arid Region
	30	45	40	25	40	May/June	Mediterranean
Sweet peppers (bell)	25/30	35	40	20	125	April/June	Europe and Medit.
	30	40	110	30	210	October	Arid Region
Tomato	30	40	40	25	135	January	Arid Region
	35	40	50	30	155	Apr/May	Calif., USA
	25	40	60	30	155	Jan	Calif. Desert, USA
	35	45	70	30	180	Oct/Nov	Arid Region
	30	40	45	30	145	April/May	Mediterranean
c. Vegetables - Cucumber Family *(Cucurbitaceae)*							
Cantaloupe	30	45	35	10	120	Jan	Calif., USA
	10	60	25	25	120	Aug	Calif., USA
Cucumber	20	30	40	15	105	June/Aug	Arid Region
	25	35	50	20	130	Nov; Feb	Arid Region
Pumpkin, Winter squash	20	30	30	20	100	Mar, Aug	Mediterranean
	25	35	35	25	120	June	Europe
Squash, Zucchini	25	35	25	15	100	Apr; Dec.	Medit.; Arid Reg.
	20	30	25	15	90	May/June	Medit.; Europe
Sweet melons	25	35	40	20	120	May	Mediterranean
	30	30	50	30	140	March	Calif., USA
	15	40	65	15	135	Aug	Calif. Desert, USA
	30	45	65	20	160	Dec/Jan	Arid Region
Water melons	20	30	30	30	110	April	Italy

	10	20	20	30	80	Mat/Aug	Near East (desert)
d. Roots and Tubers							
Beets, table	15	25	20	10	70	Apr/May	Mediterranean
	25	30	25	10	90	Feb/Mar	Mediterranean & Arid
Cassava: year 1	20	40	90	60	210	Rainy	Tropical regions
year 2	150	40	110	60	360	season	
Potato	25	30	30/45	30	115/130	Jan/Nov	(Semi) Arid Climate
	25	30	45	30	130	May	Continental Climate
	30	35	50	30	145	April	Europe
	45	30	70	20	165	Apr/May	Idaho, USA
	30	35	50	25	140	Dec	Calif. Desert, USA
Sweet potato	20	30	60	40	150	April	Mediterranean
	15	30	50	30	125	Rainy seas.	Tropical regions
Sugarbeet	30	45	90	15	180	March	Calif., USA
	25	30	90	10	155	June	Calif., USA
	25	65	100	65	255	Sept	Calif. Desert, USA
	50	40	50	40	180	April	Idaho, USA
	25	35	50	50	160	May	Mediterranean
	45	75	80	30	230	November	Mediterranean
	35	60	70	40	205	November	Arid Regions
e. Legumes *(Leguminosae)*							
Beans (green)	20	30	30	10	90	Feb/Mar	Calif., Mediterranean
	15	25	25	10	75	Aug/Sep	Calif., Egypt, Lebanon
Beans (dry)	20	30	40	20	110	May/June	Continental Climates
	15	25	35	20	95	June	Pakistan, Calif.
	25	25	30	20	100	June	Idaho, USA
Faba bean, broad bean	15	25	35	15	90	May	Europe
	20	30	35	15	100	Mar/Apr	Mediterranean
- dry	90	45	40	60	235	Nov	Europe
- green	90	45	40	0	175	Nov	Europe
Green gram, cowpeas	20	30	30	20	110	March	Mediterranean
Groundnut	25	35	45	25	130	Dry	West Africa
	35	35	35	35	140	season	High Latitudes
	35	45	35	25	140	May May/June	Mediterranean
Lentil	20	30	60	40	150	April	Europe
	25	35	70	40	170	Oct/Nov	Arid Region
Peas	15	25	35	15	90	May	Europe

	20	30	35	15	100	Mar/Apr	Mediterranean
	35	25	30	20	110	April	Idaho, USA
Soybeans	15	15	40	15	85	Dec	Tropics
	20	30/35	60	25	140	May	Central USA
	20	25	75	30	150	June	Japan
f. Perennial Vegetables (with winter dormancy and initially bare or mulched soil)							
Artichoke	40	40	250	30	360	Apr (1st yr)	California
	20	25	250	30	325	May (2nd yr)	(cut in May)
Asparagus	50	30	100	50	230	Feb	Warm Winter
	90	30	200	45	365	Feb	Mediterranean
g. Fibre Crops							
Cotton	30	50	60	55	195	Mar-May	Egypt; Pakistan; Calif.
	45	90	45	45	225	Mar	Calif. Desert, USA
	30	50	60	55	195	Sept	Yemen
	30	50	55	45	180	April	Texas
Flax	25	35	50	40	150	April	Europe
	30	40	100	50	220	October	Arizona
h. Oil Crops							
Castor beans	25	40	65	50	180	March	(Semi) Arid Climates
	20	40	50	25	135	Nov.	Indonesia
Safflower	20	35	45	25	125	April	California, USA
	25	35	55	30	145	Mar	High Latitudes
	35	55	60	40	190	Oct/Nov	Arid Region
Sesame	20	30	40	20	100	June	China
Sunflower	25	35	45	25	130	April/May	Medit.; California
i. Cereals							
Barley/Oats/Wheat	15	25	50	30	120	November	Central India
	20	25	60	30	135	March/Apr	35-45 °L
	15	30	65	40	150	July	East Africa
	40	30	40	20	130	Apr	
	40	60	60	40	200	Nov	
	20	50	60	30	160	Dec	Calif. Desert, USA
Winter Wheat	20[2]	60[2]	70	30	180	December	Calif., USA
	30	140	40	30	240	November	Mediterranean
	160	75	75	25	335	October	Idaho, USA
Grains (small)	20	30	60	40	150	April	Mediterranean
	25	35	65	40	165	Oct/Nov	Pakistan; Arid Reg.
Maize (grain)	30	50	60	40	180	April	East Africa (alt.)
	25	40	45	30	140	Dec/Jan	Arid Climate
	20	35	40	30	125	June	Nigeria (humid)

	20	35	40	30	125	October	India (dry, cool)
	30	40	50	30	150	April	Spain (spr, sum.); Calif.
	30	40	50	50	170	April	Idaho, USA
Maize (sweet)	20	20	30	10	80	March	Philippines
	20	25	25	10	80	May/June	Mediterranean
	20	30	50/30	10	90	Oct/Dec	Arid Climate
	30	30	30	103	110	April	Idaho, USA
	20	40	70	10	140	Jan	Calif. Desert, USA
Millet	15	25	40	25	105	June	Pakistan
	20	30	55	35	140	April	Central USA
Sorghum	20	35	40	30	130	May/June	USA, Pakis., Med.
	20	35	45	30	140	Mar/April	Arid Region
Rice	30	30	60	30	150	Dec; May	Tropics; Mediterranean
	30	30.	80	40	180	May	Tropics
j. Forages							
Alfalfa, total season [4]	10	30	var.	var.	var.		last -4°C in spring until first -4°C in fall
Alfalfa [4] 1st cutting cycle	10	20	20	10	60	Jan Apr (last - 4°C)	Calif., USA.
	10	30	25	10	75		Idaho, USA.
Alfalfa [4], other cutting cycles	5	10	10	5	30	Mar	Calif., USA.
	5	20	10	10	45	Jun	Idaho, USA.
Bermuda for seed	10	25	35	35	105	March	Calif. Desert, USA
Bermuda for hay (several cuttings)	10	15	75	35	135	---	Calif. Desert, USA
Grass Pasture [4]	10	20	--	--	--		7 days before last -4°C in spring until 7 days after first -4°C in fall
Sudan, 1st cutting cycle	25	25	15	10	75	Apr	Calif. Desert, USA
Sudan, other cutting cycles	3	15	12	7	37	June	Calif. Desert, USA
k. Sugar Cane							
Sugarcane, virgin	35	60	190	120	405		Low Latitudes
	50	70	220	140	480		Tropics
	75	105	330	210	720		Hawaii, USA
Sugarcane, ratoon	25	70	135	50	280		Low Latitudes
	30	50	180	60	320		Tropics
	35	105	210	70	420		Hawaii, USA
l. Tropical Fruits and Trees							
Banana, 1st yr	120	90	120	60	390	Mar	Mediterranean
Banana, 2nd yr	120	60	180	5	365	Feb	Mediterranean

Pineapple	60	120	600	10	790		Hawaii, USA
m. Grapes and Berries							
Grapes	20	40	120	60	240	April	Low Latitudes
	20	50	75	60	205	Mar	Calif., USA
	20	50	90	20	180	May	High Latitudes
	30	60	40	80	210	April	Mid Latitudes (wine)
Hops	25	40	80	10	155	April	Idaho, USA
n. Fruit Trees							
Citrus	60	90	120	95	365	Jan	Mediterranean
Deciduous Orchard	20	70	90	30	210	March	High Latitudes
	20	70	120	60	270	March	Low Latitudes
	30	50	130	30	240	March	Calif., USA
Olives	30	90	*60*	90	2705	March	Mediterranean
Pistachios	20	60	30	40	150	Feb	Mediterranean
Walnuts	20	10	130	30	190	April	Utah, USA
o. Wetlands - Temperate Climate							
Wetlands (Cattails, Bulrush)	10	30	80	20	140	May	Utah, USA; killing frost
	180	60	90	35	365	November	Florida, USA
Wetlands (short veg.)	180	60	90	35	365	November	frost-free climate

* Lengths of crop development stages provided in this table are indicative of general conditions, but may vary substantially from region to region, with climate and cropping conditions, and with crop variety. The user is strongly encouraged to obtain appropriate local information.

[1] Crucifers include cabbage, cauliflower, broccoli, and Brussel sprouts. The wide range in lengths of seasons is due to varietal and species differences.

[2] These periods for winter wheat will lengthen in frozen climates according to days having zero growth potential and wheat dormancy. Under general conditions and in the absence of local data, fall planting of winter wheat can be presumed to occur in northern temperate climates when the 10-day running average of mean daily air temperature decreases to 17° C or December 1, whichever comes first. Planting of spring wheat can be presumed to occur when the 10-day running average of mean daily air temperature increases to 5° C. Spring planting of maize-grain can be presumed to

occur when the 10-day running average of mean daily air temperature increases to 13° C.

[3] The late season for sweet maize will be about 35 days if the grain is allowed to mature and dry.

[4] In climates having killing frosts, growing seasons can be estimated for alfalfa and grass as:

> alfalfa: last -4° C in spring until first -4° C in fall (Everson, D. O., M. Faubion and D. E. Amos 1978. "Freezing temperatures and growing seasons in Idaho." Univ. Idaho Agric. Exp. station bulletin 494. 18 p.)
>
> grass: 7 days before last -4° C in spring and 7 days after last -4° C in fall (Kruse E. G. and Haise, H. R. 1974. "Water use by native grasses in high altitude Colorado meadows." USDA Agric. Res. Service, Western Region report ARS-W-6-1974. 60 pages)

[5] Olive trees gain new leaves in March. See footnote 24 of Table 12 for additional information, where the K_c continues outside of the "growing period".

Primary source: FAO Irrigation and Drainage Paper 24 (Doorenbos and Pruitt, 1977), Table 22.

The lengths of the initial and development periods may be relatively short for deciduous trees and shrubs that can develop new leaves in the spring at relatively fast rates (Figure 23).

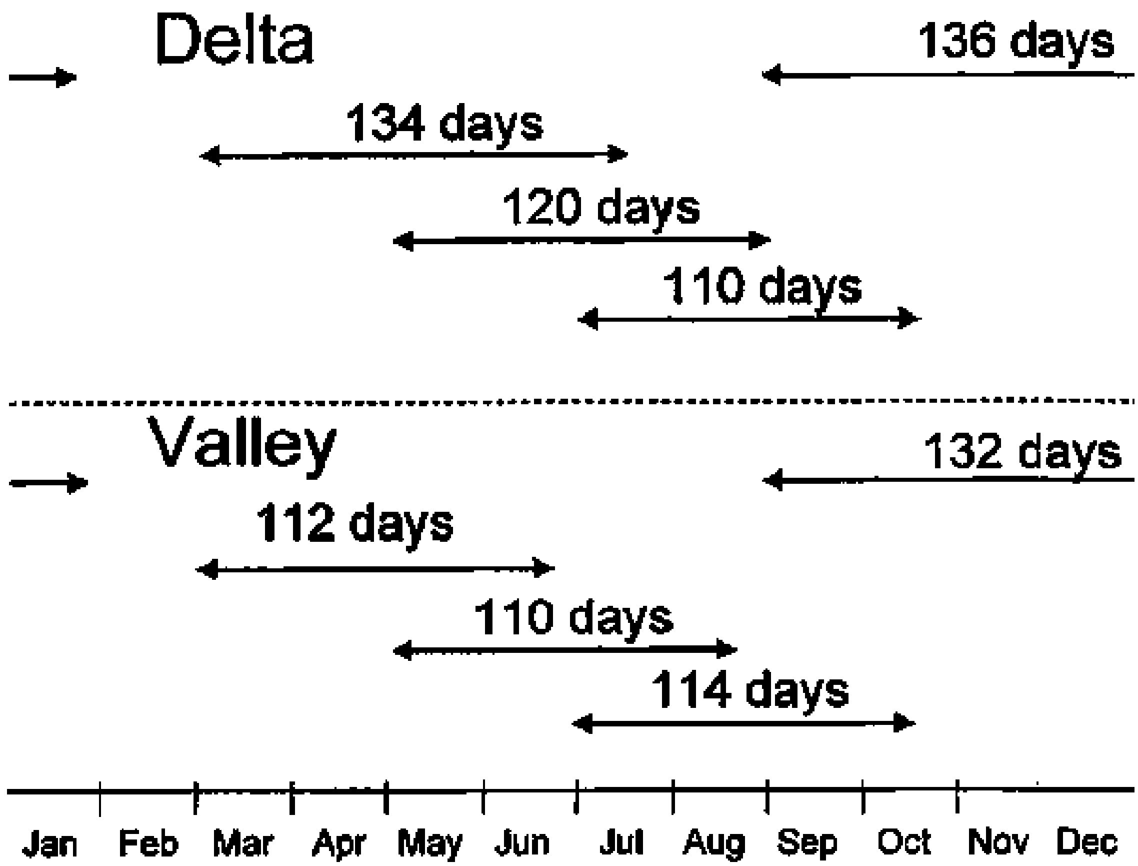
The rate at which vegetation cover develops and the time at which it attains effective full cover are affected by weather conditions in general and by mean daily air temperature in particular. Therefore, the length of time between planting and effective full cover will vary with climate, latitude, elevation and planting date. It will also vary with cultivar (crop variety). Generally, once the effective full cover for a plant canopy has been reached, the rate of further phenological development (flowering, seed development, ripening, and senescence) is more dependent on plant genotype and less dependent on weather. As an example, Figure 28 presents the variation in length of the growing period for one cultivar of rice for one region and for various planting dates.

The end of the mid-season and beginning of the late season is usually marked by senescence of leaves, often beginning with the lower leaves of plants. The length of the late season period may be relatively short (less than 10 days) for vegetation killed by frost (for example, maize at high elevations in latitudes > 40°N) or for agricultural crops that are harvested fresh (for example, table beets and small vegetables).

High temperatures may accelerate the ripening and senescence of crops. Long duration of high air temperature (> 35°C) can cause some crops such as turf grass to go into dormancy. If severely high air temperatures are coupled with moisture stress, the dormancy of grass can be permanent for the remainder of the growing season. Moisture stress or other environmental stresses will usually accelerate the rate of crop maturation and can shorten the mid and late season growing periods.

The values in Table 11 are useful only as a general guide and for comparison purposes. The listed lengths of growth stages are average lengths for the regions and periods specified and are intended to serve only as examples. Local observations of the specific plant stage development should be used, wherever possible, to incorporate effects of plant variety, climate and cultural practices. Local information can be obtained by interviewing farmers, ranchers, agricultural extension agents and local researchers, by conducting local surveys, or by remote sensing. When determining stage dates from local observations, the guidelines and visual descriptions may be helpful.

FIGURE 28. Variation in the length of the growing period of rice (cultivar: Jaya) sown during various months of the year at different locations along the Senegal River (Africa)



Crop coefficients

- Tabulated K_c values
- Crop coefficient for the initial stage ($K_{c\ ini}$)
- Crop coefficient for the mid-season stage ($K_{c\ mid}$)
- Crop coefficient for the end of the late season stage ($K_{c\ end}$)

Changes in vegetation and ground cover mean that the crop coefficient K_c varies during the growing period. The trends in K_c during the growing period are represented in the crop coefficient curve. Only three values for K_c are required to describe and construct the crop coefficient curve: those during the initial stage ($K_{c\ ini}$), the mid-season stage ($K_{c\ mid}$) and at the end of the late season stage ($K_{c\ end}$).

Tabulated K_c values

Table 12 lists typical values for $K_{c\ ini}$, Kc_{mid} and $K_{c\ end}$ for various agricultural crops. The coefficients presented are organized by group type (i.e., small vegetables, legumes, cereals, etc.) to assist in locating the crop in the table and to aid in comparing crops within the same group. There is usually close similarity in the coefficients among the members of the same crop group, as the plant height, leaf area, ground coverage and water management are normally similar.

The coefficients in Table 12 integrate the effects of both transpiration and evaporation over time. The effects of the integration over time represent an average wetting frequency for a 'standard' crop under typical growing conditions in an irrigated setting. The values for K_c during the initial and crop development stages are subject to the effects of large variations in wetting frequencies and therefore refinements to the value used for $K_{c\ ini}$ should always be made. For frequent wettings such as with high frequency sprinkler irrigation or rainfall, the values for $K_{c\ ini}$ may increase substantially.

TABLE 12. Single (time-averaged) crop coefficients, K_c, and mean maximum plant heights for non stressed, well-managed crops in subhumid climates ($RH_{min} \approx 45\%$, $u_2 \approx 2$ m/s) for use with the FAO Penman-Monteith ET_o.

Crop	$K_{c\ ini}$[1]	$K_{c\ mid}$	$K_{c\ end}$	Maximum Crop Height (h) (m)
a. Small Vegetables	**0.7**	**1.05**	**0.95**	
Broccoli		1.05	0.95	0.3
Brussel Sprouts		1.05	0.95	0.4
Cabbage		1.05	0.95	0.4
Carrots		1.05	0.95	0.3
Cauliflower		1.05	0.95	0.4
Celery		1.05	1.00	0.6
Garlic		1.00	0.70	0.3
Lettuce		1.00	0.95	0.3
Onions				
- dry		1.05	0.75	0.4
- green		1.00	1.00	0.3
- seed		1.05	0.80	0.5
Spinach		1.00	0.95	0.3
Radish		0.90	0.85	0.3
b. Vegetables - Solanum Family *(Solanaceae)*	**0.6**	**1.15**	**0.80**	
Egg Plant		1.05	0.90	0.8
Sweet Peppers (bell)		1.05[2]	0.90	0.7
Tomato		1.15[2]	0.70-0.90	0.6
c. Vegetables - Cucumber Family *(Cucurbitaceae)*	**0.5**	**1.00**	**0.80**	
Cantaloupe	0.5	0.85	0.60	0.3
Cucumber				
- Fresh Market	0.6	1.00[2]	0.75	0.3
- Machine harvest	0.5	1.00	0.90	0.3
Pumpkin, Winter Squash		1.00	0.80	0.4

Squash, Zucchini		0.95	0.75	0.3
Sweet Melons		1.05	0.75	0.4
Watermelon	0.4	1.00	0.75	0.4
d. Roots and Tubers	**0.5**	**1.10**	**0.95**	
Beets, table		1.05	0.95	0.4
Cassava				
- year 1	0.3	0.80[3]	0.30	1.0
- year 2	0.3	1.10	0.50	1.5
Parsnip	0.5	1.05	0.95	0.4
Potato		1.15	0.75[4]	0.6
Sweet Potato		1.15	0.65	0.4
Turnip (and Rutabaga)		1.10	0.95	0.6
Sugar Beet	0.35	1.20	0.70[5]	0.5
e. Legumes *(Leguminosae)*	**0.4**	**1.15**	**0.55**	
Beans, green	0.5	1.05[2]	0.90	0.4
Beans, dry and Pulses	0.4	1.15[2]	0.35	0.4
Chick pea		1.00	0.35	0.4
Fababean (broad bean)				
- Fresh	0.5	1.15[2]	1.10	0.8
- Dry/Seed	0.5	1.15[2]	0.30	0.8
Grabanzo	0.4	1.15	0.35	0.8
Green Gram and Cowpeas		1.05	0.60-0.35[6]	0.4
Groundnut (Peanut)		1.15	0.60	0.4
Lentil		1.10	0.30	0.5
Peas				
- Fresh	0.5	1.15[2]	1.10	0.5
- Dry/Seed		1.15	0.30	0.5
Soybeans		1.15	0.50	0.5-1.0
f. Perennial Vegetables (with winter dormancy and initially bare or mulched soil)	**0.5**	**1.00**	**0.80**	
Artichokes	0.5	1.00	0.95	0.7
Asparagus	0.5	0.95[7]	0.30	0.2-0.8
Mint	0.60	1.15	1.10	0.6-0.8
Strawberries	0.40	0.85	0.75	0.2
g. Fibre Crops	**0.35**			
Cotton		1.15-1.20	0.70-0.50	1.2-1.5
Flax		1.10	0.25	1.2
Sisal [8]		0.4-0.7	0.4-0.7	1.5
h. Oil Crops	**0.35**	**1.15**	**0.35**	
Castorbean (*Ricinus*)		1.15	0.55	0.3
Rapeseed, Canola		1.0-1.15[9]	0.35	0.6

Safflower		1.0-1.15[9]	0.25	0.8
Sesame		1.10	0.25	1.0
Sunflower		1.0-1.15[9]	0.35	2.0
i. Cereals	**0.3**	**1.15**	**0.4**	
Barley		1.15	0.25	1
Oats		1.15	0.25	1
Spring Wheat		1.15	0.25-0.4[10]	1
Winter Wheat				
- with frozen soils	0.4	1.15	0.25-0.4[10]	1
- with non-frozen soils	0.7	1.15	0.25-0.4[10]	
Maize, Field (grain) *(field corn)*		1.20	0.60-0.35[11]	2
Maize, Sweet *(sweet corn)*		1.15	1.05[12]	1.5
Millet		1.00	0.30	1.5
Sorghum				
- grain		1.00-1.10	0.55	1-2
- sweet		1.20	1.05	2-4
Rice	1.05	1.20	0.90-0.60	1
j. Forages				
Alfalfa Hay				
- averaged cutting effects	0.40	0.95[13]	0.90	0.7
- individual cutting periods	0.40[14]	1.20[14]	1.15[14]	0.7
- for seed	0.40	0.50	0.50	0.7
Bermuda hay				
- averaged cutting effects	0.55	1.00[13]	0.85	0.35
- Spring crop for seed	0.35	0.90	0.65	0.4
Clover hay, Berseem				
- averaged cutting effects	0.40	0.90[13]	0.85	0.6
- individual cutting periods	0.40[14]	1.15[14]	1.10[14]	0.6
Rye Grass hay				
- averaged cutting effects	0.95	1.05	1.00	0.3
Sudan Grass hay (annual)				
- averaged cutting effects	0.50	0.90[14]	0.85	1.2
- individual cutting periods	0.50[14]	1.15[14]	1.10[14]	1.2
Grazing Pasture				
- Rotated Grazing	0.40	0.85-1.05	0.85	0.15-0.30
- Extensive Grazing	0.30	0.75	0.75	0.10
Turf grass				

- cool season [15]	0.90	0.95	0.95	0.10
- warm season [15]	0.80	0.85	0.85	0.10
k. Sugar Cane	**0.40**	**1.25**	**0.75**	**3**
l. Tropical Fruits and Trees				
Banana				
- 1st year	0.50	1.10	1.00	3
- 2nd year	1.00	1.20	1.10	4
Cacao	1.00	1.05	1.05	3
Coffee				
- bare ground cover	0.90	0.95	0.95	2-3
- with weeds	1.05	1.10	1.10	2-3
Date Palms	0.90	0.95	0.95	8
Palm Trees	0.95	1.00	1.00	8
Pineapple [16]				
- bare soil	0.50	0.30	0.30	0.6-1.2
- with grass cover	0.50	0.50	0.50	0.6-1.2
Rubber Trees	0.95	1.00	1.00	10
Tea				
- non-shaded	0.95	1.00	1.00	1.5
- shaded [17]	1.10	1.15	1.15	2
m. Grapes and Berries				
Berries (bushes)	0.30	1.05	0.50	1.5
Grapes				
- Table or Raisin	0.30	0.85	0.45	2
- Wine	0.30	0.70	0.45	1.5-2
Hops	0.3	1.05	0.85	5
n. Fruit Trees				
Almonds, no ground cover	0.40	0.90	0.65 [18]	5
Apples, Cherries, Pears [19]				
- no ground cover, killing frost	0.45	0.95	0.70 [18]	4
- no ground cover, no frosts	0.60	0.95	0.75 [18]	4
- active ground cover, killing frost	0.50	1.20	0.95 [18]	4
- active ground cover, no frosts	0.80	1.20	0.85 [18]	4
Apricots, Peaches, Stone Fruit [19, 20]				
- no ground cover, killing frost	0.45	0.90	0.65 [18]	3
- no ground cover, no frosts	0.55	0.90	0.65 [18]	3
- active ground cover, killing frost	0.50	1.15	0.90 [18]	3
- active ground cover, no frosts	0.80	1.15	0.85 [18]	3
Avocado, no ground cover	0.60	0.85	0.75	3
Citrus, no ground cover [21]				
- 70% canopy	0.70	0.65	0.70	4
- 50% canopy	0.65	0.60	0.65	3
- 20% canopy	0.50	0.45	0.55	2

Citrus, with active ground cover or weeds [22]				
- 70% canopy	0.75	0.70	0.75	4
- 50% canopy	0.80	0.80	0.80	3
- 20% canopy	0.85	0.85	0.85	2
Conifer Trees [23]	1.00	1.00	1.00	10
Kiwi	0.40	1.05	1.05	3
Olives (40 to 60% ground coverage by canopy) [24]	0.65	0.70	0.70	3-5
Pistachios, no ground cover	0.40	1.10	0.45	3-5
Walnut Orchard [19]	0.50	1.10	0.6518	4-5
o. Wetlands - temperate climate				
Cattails, Bulrushes, killing frost	0.30	1.20	0.30	2
Cattails, Bulrushes, no frost	0.60	1.20	0.60	2
Short Veg., no frost	1.05	1.10	1.10	0.3
Reed Swamp, standing water	1.00	1.20	1.00	1-3
Reed Swamp, moist soil	0.90	1.20	0.70	1-3
p. Special				
Open Water, < 2 m depth or in subhumid climates or tropics		1.05	1.05	
Open Water, > 5 m depth, clear of turbidity, temperate climate		0.6525	1.2525	

[1] These are general values for $K_{c\ ini}$ under typical irrigation management and soil wetting. For frequent wettings such as with high frequency sprinkle irrigation or daily rainfall, these values may increase substantially and may approach 1.0 to 1.2. $K_{c\ ini}$ is a function of wetting interval and potential evaporation rate during the initial and development periods and is more accurately estimated using Figures 29 and 30, or Equation 7-3 in Annex 7, or using the dual $K_{cb\ ini} + K_e$.

[2] Beans, Peas, Legumes, Tomatoes, Peppers and Cucumbers are sometimes grown on stalks reaching 1.5 to 2 meters in height. In such cases, increased K_c values need to be taken. For green beans, peppers and cucumbers, 1.15 can be taken, and for tomatoes, dry beans and peas, 1.20. Under these conditions h should be increased also.

[3] The midseason values for cassava assume non-stressed conditions during or following the rainy season. The $K_{c\ end}$ values account for dormancy during the dry season.

[4] The $K_{c\ end}$ value for potatoes is about 0.40 for long season potatoes with vine kill.

[5] This $K_{c\ end}$ value is for no irrigation during the last month of the growing season. The $K_{c\ end}$ value for sugar beets is higher, up to 1.0, when irrigation or significant rain occurs during the last month.

[6] The first $K_{c\ end}$ is for harvested fresh. The second value is for harvested dry.

[7] The K_c for asparagus usually remains at $K_{c\ ini}$ during harvest of the spears, due to sparse ground cover. The $K_{c\ mid}$ value is for following regrowth of plant vegetation following termination of harvest of spears.

[8] K_c for sisal depends on the planting density and water management (e.g., intentional moisture stress).

[9] The lower values are for rainfed crops having less dense plant populations.

[10] The higher value is for hand-harvested crops.

[11] The first $K_{c\ end}$ value is for harvest at high grain moisture. The second $K_{c\ end}$ value is for harvest after complete field drying of the grain (to about 18% moisture, wet mass basis).

[12] If harvested fresh for human consumption. Use $K_{c\ end}$ for field maize if the sweet maize is allowed to mature and dry in the field.

[13] This $K_{c\ mid}$ coefficient for hay crops is an overall average $K_{c\ mid}$ coefficient that averages K_c for both before and following cuttings. It is applied to the period following the first development period until the beginning of the last late season period of the growing season.

[14] These K_c coefficients for hay crops represent immediately following cutting; at full cover; and immediately before cutting, respectively. The growing season is described as a series of individual cutting periods (Figure 35).

[15] Cool season grass varieties include dense stands of bluegrass, ryegrass, and fescue. Warm season varieties include bermuda grass and St. Augustine grass. The 0.95 values for cool season grass represent a 0.06 to 0.08 m mowing height under general turf conditions. Where careful water management is practiced

and rapid growth is not required, K_c's for turf can be reduced by 0.10.

[16] The pineapple plant has very low transpiration because it closes its stomates during the day and opens them during the night. Therefore, the majority of ET_c from pineapple is evaporation from the soil. The $K_{c\ mid} < K_{c\ ini}$ since $K_{c\ mid}$ occurs during full ground cover so that soil evaporation is less. Values given assume that 50% of the ground surface is covered by black plastic mulch and that irrigation is by sprinkler. For drip irrigation beneath the plastic mulch, K_c's given can be reduced by 0.10.

[17] Includes the water requirements of the shade trees.

[18] These $K_{c\ end}$ values represent K_c prior to leaf drop. After leaf drop, $K_{c\ end} \approx 0.20$ for bare, dry soil or dead ground cover and $K_{c\ end} \approx 0.50$ to 0.80 for actively growing ground cover (consult Chapter 11).

[19] Refer to Eq. 94, 97 or 98 and footnotes 21 and 22 for estimating K_c for immature stands.

[20] Stone fruit category applies to peaches, apricots, pears, plums and pecans.

[21] These K_c values can be calculated from Eq. 98 for $K_{c\ min} = 0.15$ and $K_{c\ full} = 0.75$, 0.70 and 0.75 for the initial, mid season and end of season periods, and $f_{c\ eff} = f_c$ where f_c = fraction of ground covered by tree canopy (e.g., the sun is presumed to be directly overhead). The values listed correspond with those in Doorenbos and Pruitt (1977) and with more recent measurements. The midseason value is lower than initial and ending values due to the effects of stomatal closure during periods of peak ET. For humid and subhumid climates where there is less stomatal control by citrus, values for $K_{c\ ini}$, $K_{c\ mid}$, and $K_{c\ end}$ can be increased by 0.1 - 0.2, following Rogers et al. (1983).

[22] These K_c values can be calculated as $K_c = f_c K_{c\ ngc} + (1 - f_c) K_{c\ cover}$ where $K_{c\ ngc}$ is the K_c of citrus with no active ground cover (calculated as in footnote 21), $K_{c\ cover}$ is the K_c, for the active ground cover (0.95), and f_c is defined in footnote 21. The values listed correspond with

those in Doorenbos and Pruitt (1977) and with more recent measurements. Alternatively, K_c for citrus with active ground cover can be estimated directly from Eq. 98 by setting $K_{c\ min}$ = $K_{c\ cover}$. For humid and subhumid climates where there is less stomatal control by citrus, values for $K_{c\ ini}$, $K_{c\ mid}$, and $K_{c\ end}$ can be increased by 0.1 - 0.2, following Rogers et al. (1983).

For non-active or only moderately active ground cover (active indicates green and growing ground cover with LAI > about 2 to 3), K_c should be weighted between K_c for no ground cover and K_c for active ground cover, with the weighting based on the "greenness" and approximate leaf area of the ground cover.

[23] Confers exhibit substantial stomatal control due to reduced aerodynamic resistance. The K_c, can easily reduce below the values presented, which represent well-watered conditions for large forests.

[24] These coefficients represent about 40 to 60% ground cover. Refer to Eq. 98 and footnotes 21 and 22 for estimating K_c for immature stands. In Spain, Pastor and Orgaz (1994) have found the following monthly K_c's for olive orchards having 60% ground cover: 0.50, 0.50, 0.65, 0.60, 0.55, 0.50, 0.45, 0.45, 0.55, 0.60, 0.65, 0.50 for months January through December. These coefficients can be invoked by using $K_{c\ ini}$ = 0.65, $K_{c\ mid}$ = 0.45, and $K_{c\ end}$ = 0.65, with stage lengths = 30, 90, 60 and 90 days, respectively for initial, development, midseason and late season periods, and using K_c during the winter ("off season") in December to February = 0.50.

[25] These K_c's are for deep water in temperate latitudes where large temperature changes in the water body occur during the year, and initial and peak period evaporation is low as radiation energy is absorbed into the deep water body. During fall and winter periods ($K_{c\ end}$), heat is released from the water body that increases the evaporation above that for grass. Therefore, $K_{c\ mid}$ corresponds to the period when the water body is gaining thermal energy and $K_{c\ end}$ when releasing thermal energy. These K_c's should be used with caution.

Primary sources:

$K_{c\ ini}$: Doorenbos and Kassam (1979)
$K_{c\ mid}$ and $K_{c\ end}$: Doorenbos and Pruitt (1977); Pruitt (1986); Wright (1981, 1982). Snyder et al., (1989)

The values for $K_{c\ mid}$ and $K_{c\ end}$ in Table 12 represent those for a sub-humid climate with an average daytime minimum relative humidity (RH_{min}) of about 45% and with calm to moderate wind speeds averaging 2 m/s. For more humid or arid conditions, or for more or less windy conditions, the K_c coefficients for the mid-season and end of late season stage should be modified as described in this chapter.
The values for K_c in Table 12 are values for non-stressed crops cultivated under excellent agronomic and water management conditions and achieving maximum crop yield (standard conditions). Where stand density, height or leaf area are less than that attained under such conditions, the value for $K_{c\ mid}$ and, for most crops, for $K_{c\ end}$ will need to be modified (Part C, Chapters 8, 9 and 10).

Crop coefficient for the initial stage ($K_{c\ ini}$)

Calculation procedure
The values for $K_{c\ ini}$ in Table 12 are only approximations and should only be used for estimating ET_c during preliminary or planning studies. For several group types only one value for $K_{c\ ini}$ is listed and it is considered to be representative of the whole group for a typical irrigation water management. More accurate estimates of $K_{c\ ini}$ can be obtained by considering:

Time interval between wetting events

Evapotranspiration during the initial stage for annual crops is predominately in the form of evaporation. Therefore, accurate estimates for $K_{c\ ini}$ should consider the frequency with which the soil surface is wetted during the initial period. Where the soil is frequently wet from irrigation or rain, the evaporation from the soil surface can be considerable and $K_{c\ ini}$ will be large. On the other hand, where the soil surface is dry, evaporation is restricted and the $K_{c\ ini}$ will be small (Table 9).

Evaporation power of the atmosphere

The value of $K_{c\ ini}$ is affected by the evaporating power of the atmosphere, i.e., ET_o. The higher the evaporation power of the atmosphere, the quicker the soil will dry between water applications and the smaller the time-averaged K_c will be for any particular period.

Magnitude of the wetting event

As the amount of water available in the topsoil for evaporation and hence the time for the soil surface to dry is a function of the magnitude of the wetting event, $K_{c\ ini}$ will be smaller for light wetting events than for large wettings.

Depending on the time interval between wetting events, the magnitude of the wetting event, and the evaporation power of the atmosphere, $K_{c\ ini}$ can vary between 0.1 and 1.15. A numerical procedure to compute $K_{c\ ini}$ is provided in Annex 7.

Time interval between wetting events

In general, the mean time interval between wetting events is estimated by counting all rainfall and irrigation events occurring during the initial period that are greater than a few millimetres. Wetting events occurring on adjacent days can be counted as one event. The mean wetting interval is estimated by dividing the length of the initial period by the number of events.

Where only monthly rainfall values are available without any information on the number of rainy days, the number of events within the month can be estimated by dividing the monthly rainfall depth by the depth of a typical rain event. The typical depth, if it exists, can vary widely from climate to climate, region to region and from season to season. Table 13 presents some information on the range of rainfall depths. After deciding what rainfall is typical for the region and time of the year, the number of rainy days and the mean wetting interval can be estimated.

TABLE 13. Classification of rainfall depths

rain event	depth
Very light (drizzle)	≤ 3 mm
Light (light showers)	5 mm
Medium (showers)	≥ 10 mm
Heavy (rainstorms)	≥ 40 mm

Where rainfall is insufficient, irrigation is needed to keep the crop well watered. Even where irrigation is not yet developed, the mean interval between the future irrigations should be estimated to obtain the required frequency of wetting necessary to keep the crop stress free. The interval might be as small as a few days for small vegetables, but up to a week or longer for cereals depending on the climatic conditions. Where no estimate of the interval can be made, the user may refer to the values for $K_{c\,ini}$ of Table 12.

EXAMPLE 23. Estimation of interval between wetting events

Estimate, from mean monthly rainfall data, the interval between rains during the rainy season for a station in a temperate climate (Paris, France: 50 mm/month), dry climate (Gafsa, Tunisia: 20 mm/month) and tropical climate (Calcutta, India: 300 mm/month).

Station	monthly rain (mm/month)	typical rainfall (mm)	number of rainy days	interval between rains
Paris	50	3	17	~ 2 days
Gafsa	20	5	4	weekly
Calcutta	300	20	15	~ 2 days

Determination of $K_{c\,ini}$

The crop coefficient for the initial growth stage can be derived from Figures 29 and 30 which provide estimates for $K_{c\,ini}$ as a function of the average interval between wetting events, the evaporation power ET_o, and the importance of the wetting event.

Light wetting events (infiltration depths of 10 mm or less): rainfall and high frequency irrigation systems

Figure 29 is used for all soil types when wetting events are light. When wetting during the initial period is only by precipitation, one will usually use Figure 29 to determine $K_{c\,ini}$. The graph can also be used when irrigation is by high frequency systems such as microirrigation and centre pivot and light applications of about 10 mm or less per wetting event are applied.

EXAMPLE 24. Graphical determination of $K_{c\,ini}$

A silt loam soil receives irrigation every two days during the initial growth stage via a centre pivot irrigation system. The average depth applied by the centre pivot system is about 12 mm per event and the average ET_o during the initial stage is 4 mm/day. Estimate the crop evapotranspiration during that stage.

From Fig. 29 using the 2-day interval curve:	$K_{c\,ini}$ =	0.85	-
	$ET_c = K_c\, ET_o = 0.85\,(4.0) =$	3.4	mm/day

The average crop evapotranspiration during the initial growth stage is 3.4 mm/day

Heavy wetting events (infiltration depths of 40 mm or more): surface and sprinkler irrigation

Figure 30 is used for heavy wetting events when infiltration depths are greater than 40 mm, such as for when wetting is primarily by periodic irrigation such as by sprinkler or surface irrigation. Following a wetting event, the amount of water available in the topsoil for evaporation is considerable, and the time for the soil surface to dry might be significantly increased. Consequently, the average K_c factor is larger than for light wetting events. As the time for the soil surface to dry is, apart from the evaporation power and the frequency of wetting, also determined by the water storage capacity of the topsoil, a distinction is made between soil types.

FIGURE 29. Average $K_{c\ ini}$ as related to the level of ET_o and the interval between irrigations and/or significant rain during the initial growth stage for all soil types when wetting events are light to medium (3-10 mm per event)

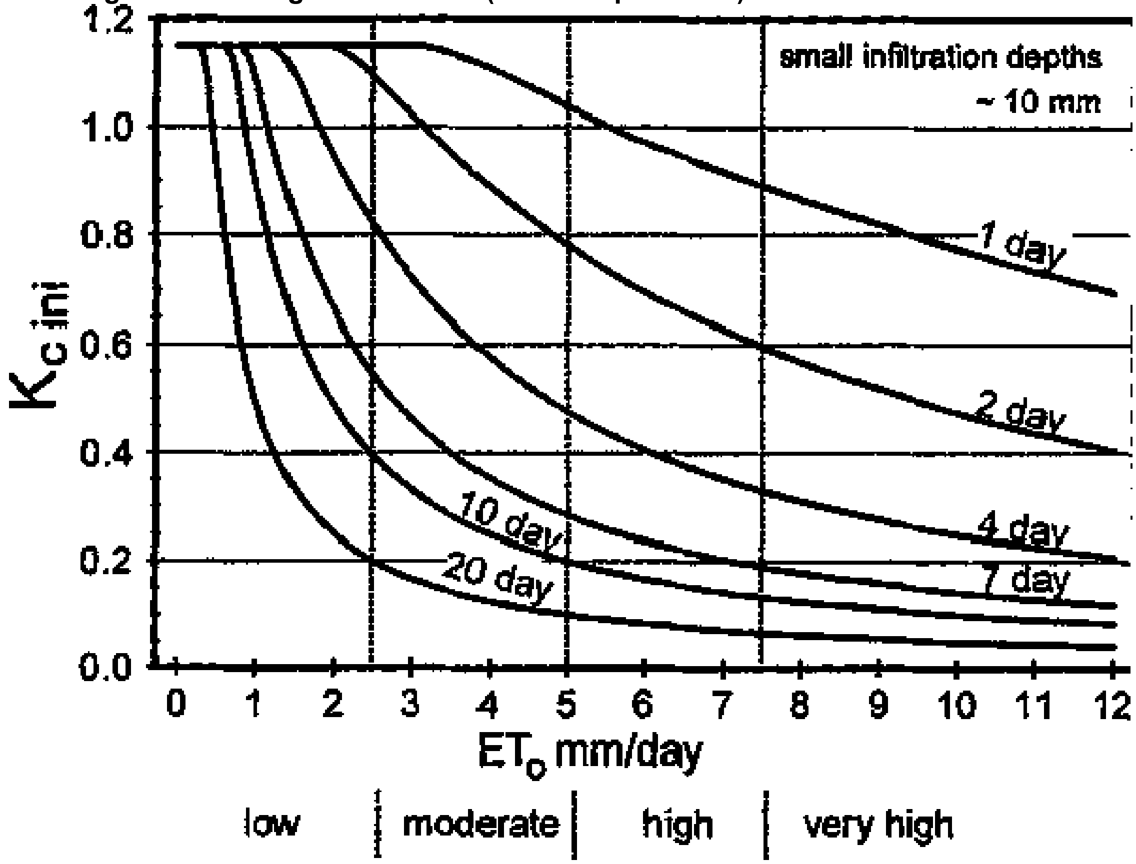


Figure 30a is used for coarse textured soils and Figure 30b is used for fine and medium textured soils. Coarse textured soils include sands and loamy sand textured soils. Medium textured soils include sandy loam, loam, silt loam and silt textured soils. Pine textured soils include silty clay loam, silty clay and clay textured soils.

Average wetting events (*infiltration depths between 10 and 40 mm*):

Where average infiltration depths are between 10 and 40 mm, the value for $K_{c\ ini}$ can be estimated from Figures 29 and 30:

$$K_{c\ ini} = K_{c\ ini(Fig29)} + \frac{(I-10)}{(40-10)}\left[K_{c\ ini(Fig30)} - K_{c\ ini(Fig29)}\right]$$

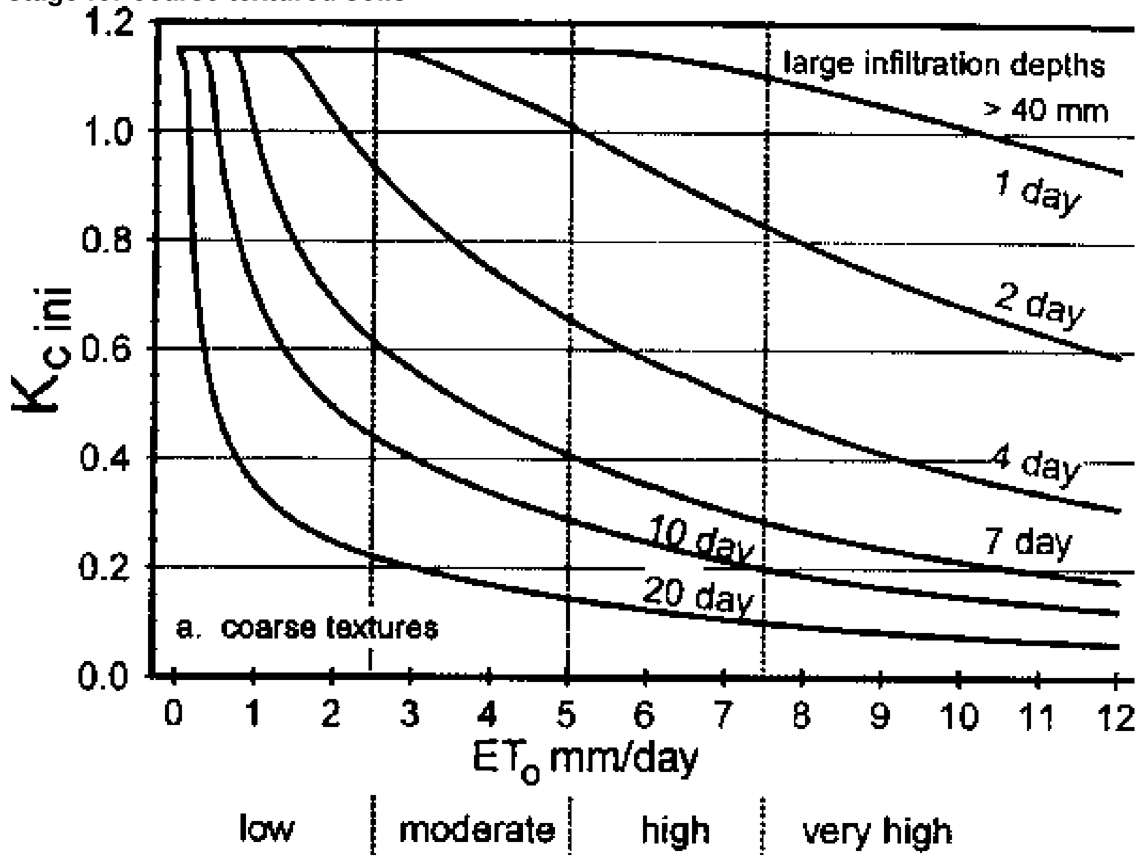
(59)

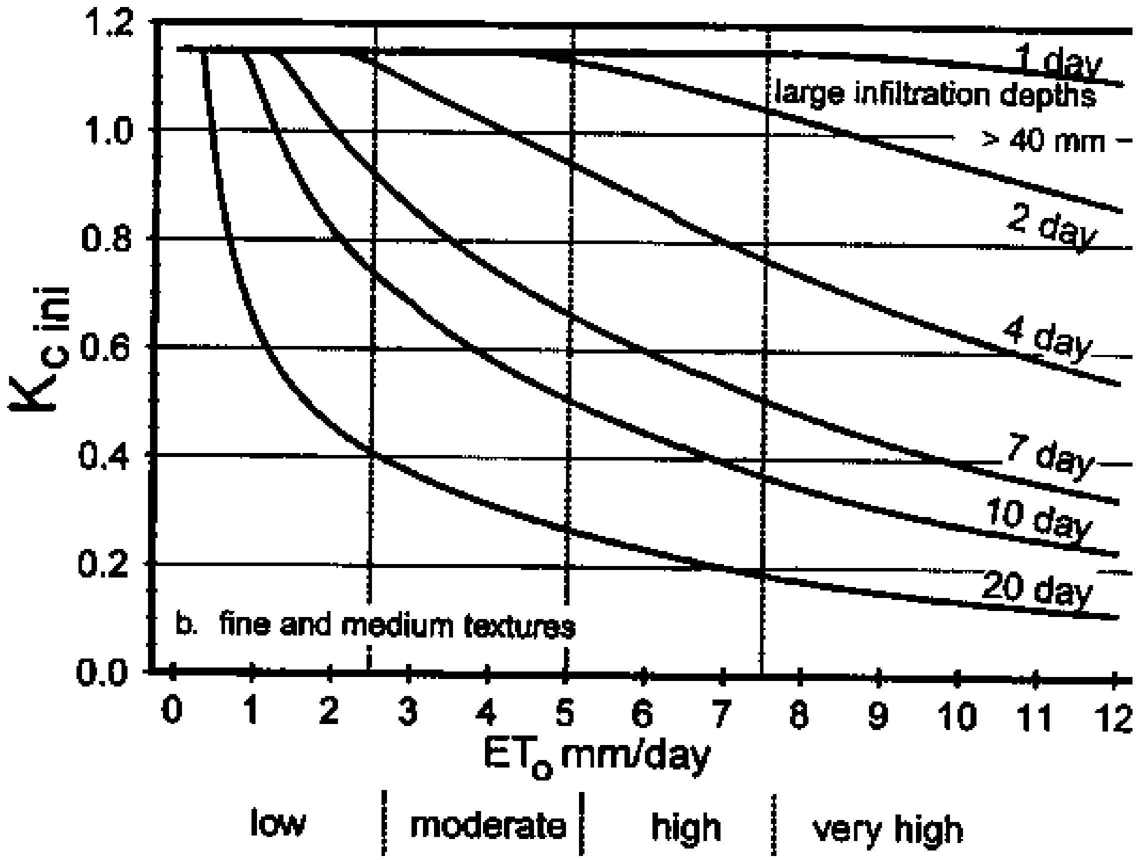
where

$K_{c\ ini}$ (Fig.29) value for $K_{c\ ini}$ from Figure 29,
$K_{c\ ini}$ (Fig.30) value for $K_{c\ ini}$ from Figure 30,
I average infiltration depth [mm].

The values 10 and 40 in Equation 59 are the average depths of infiltration (millimetres) upon which Figures 29 and 30 are based.

FIGURE 30. Average $K_{c\ ini}$ as related to the level of ET_o and the interval between irrigations greater than or equal to 40 mm per wetting event, during the initial growth stage for coarse textured soils





EXAMPLE 25. Interpolation between light and heavy wetting events

Small vegetables cultivated in a dry area on a coarse textured soil receive 20 mm of water twice a week by means of a sprinkler irrigation system. The average ET_o during the initial stage is 5 mm/day. Estimate the crop evapotranspiration during that stage.			
For:	7/2=	3.5	day interval
	ET_o = and a coarse textured soil	5	mm/day
From Fig. 29:	$K_{c\ ini\ (Fig.\ 29)} \approx$	0.55	-
From Fig. 30. a:	$K_{c\ ini\ (Fig.\ 30a)} \approx$	0.7	-
For:	I =	20	mm
From Eq. 59:	$K_{c\ ini}$ = 0.55 + [(20 - 10)/(40 - 10)] (0.7 - 0.55) = 0.55 + 0.33(0.15) =	0.60	
From Eq. 58:	ET_c = 0.60 (5) =	3.0	mm/day
The average crop evapotranspiration during the initial growth stage for the small vegetables is 3.0 mm/day.			

Adjustment for partial wetting by irrigation

Many types of irrigation systems wet only a fraction of the soil surface. For example, for a trickle irrigation system, the fraction of the surface wetted, f_w, may be only 0.4. For furrow irrigation systems, the fraction of the surface wetted may range from 0.3 to 0.8. Common values for the fraction of the soil surface wetted by irrigation or precipitation are given in Table 20. When only a fraction of the soil surface is wetted, the value for $K_{c\ ini}$ obtained from Table 12 or from Figures 29 or 30 should be multiplied by the fraction of the surface wetted to adjust for the partial wetting:

$$K_{c\ ini} = f_w\ K_{c\ ini\ (Tab,\ Fig)} \quad (60)$$

where

f_w the fraction of surfaced wetted by irrigation or rain [0 - 1],
$K_{c\ ini\ (Tab\ Fig)}$ the value for $K_{c\ ini}$ from Table 12 or Figure 29 or 30.

In addition, in selecting which figure to use (i.e., Figure 29 or 30), the average infiltrated depth, expressed in millimetres over the entire field surface, should be divided by f_w to represent the true infiltrated depth of water for the part of the surface that is wetted (Figure 31):

$$I_w = \frac{I}{f_w} \quad (61)$$

where

I_w irrigation depth for the part of the surface that is wetted [mm],
f_w fraction of surface wetted by irrigation,
I the irrigation depth for the field [mm].

When irrigation of part of the soil surface and precipitation over the entire soil surface both occur during the initial period, f_w should represent the average of f_w for each type of wetting, weighted according to the total infiltration depth received by each type.

FIGURE 31. Partial wetting by irrigation

EXAMPLE 26. Determination of $K_{c\ ini}$ for partial wetting of the soil surface

Determine the evapotranspiration of the crop in Example 24 if it had been irrigated using a trickle system every two days (with 12 mm each application expressed as an equivalent depth over the field area), and where the average fraction of surface wet was 0.4, and where little or no precipitation occurred during the initial period.			
The average depth of infiltration per event in the wetted fraction of the surface:			
From Eq. 61;	$Iw = I/f_w = 12$ mm/0.4 =	30	mm
Therefore, one can interpolate between Fig. 29 representing light wetting events (~10 mm per event) and Fig. 30.b representing medium textured soil and large wetting events (~40 mm per event).			
For:	$ET_o = 4$ mm/day	4	mm/day
and:	a 2 day wetting interval:	-	-
Fig. 29 produces:	$K_{c\ ini} = 0.85$	0.85	-
Fig. 30.b produces	$K_{c\ ini} = 1.15$	1.15	-
From Eq. 59:	$K_{c\ ini} = 0.85 + [(30-10)/(40-10)]\ (1.15 - 0.85) =$	1.05	-
Because the fraction of soil surface wetted by the trickle system is 0.4, the actual $K_{c\ ini}$ for			

the trickle irrigation is calculated as:			
From Eq. 60:	$K_{c\ ini} = f_w\ K_{c\ ini\ Fig} = 0.4\ (1.05) =$	0.42	-
	This value (0.42) represents the $K_{c\ ini}$ as applied over the entire field area.		
-	$ET_c = K_{c\ ini}\ ET_o = 0.42(4) =$	1.7	mm/day
The average crop evapotranspiration during the initial growth stage for this trickle irrigated crop is 1.7 mm/day.			

$K_{c\ ini}$ for trees and shrubs

$K_{c\ ini}$ for trees and shrubs should reflect the ground condition prior to leaf emergence or initiation in case of deciduous trees or shrubs, and the ground condition during the dormancy or low active period for evergreen trees and shrubs. The $K_{c\ ini}$ depends upon the amount of grass or weed cover, frequency of soil wetting, tree density and mulch density. For a deciduous orchard in frost-free climates, the $K_{c\ ini}$ can be as high as 0.8 or 0.9, where grass ground cover exists, and as low as 0.3 or 0.4 when the soil surface is kept bare and wetting is infrequent. The $K_{c\ ini}$ for an evergreen orchard (having no concerted leaf drop) with a dormant period has less variation from $K_{c\ mid}$, as exemplified for citrus in Table 12, footnotes 21 and 22. For 50% canopy or less, the $K_{c\ ini}$ also reflects ground cover conditions (bare soil, mulch or active grass or weed cover).

$K_{c\ ini}$ for paddy rice

For rice growing in paddy fields with a water depth of 0.10-0.20 m, the ET_c during the initial stage mainly consists of evaporation from the standing water. The $K_{c\ ini}$ in Table 12 is 1.05 for a sub-humid climate with calm to moderate wind speeds. The $K_{c\ ini}$ should be adjusted for the local climate as indicated in Table 14.

TABLE 14. $K_{c\ ini}$ for rice for various climatic conditions

Humidity	Wind speed		
	light	**moderate**	**strong**
arid - semi-arid	1.10	1.15	1.20
sub-humid - humid	1.05	1.10	1.15
very humid	1.00	1.05	1.10

Crop coefficient for the mid-season stage ($K_{c\ mid}$)

Illustration of the climatic effect

Typical values for the crop coefficient for the mid-season growth stage, $K_{c\ mid}$, are listed in Table 12 for various agricultural crops.

As discussed in Chapter 5, the effect of the difference in aerodynamic properties between the grass reference surface and agricultural crops is not only crop specific but also varies with the climatic conditions and crop height (Figure 21). More arid climates and conditions of greater wind speed will have higher values for $K_{c\ mid}$. More humid climates and conditions of lower wind speed will have lower values for $K_{c\ mid}$.

The relative impact of climate on $K_{c\ mid}$ is illustrated in Figure 32 where the adjustments to the values from Table 12 are shown for various types of climates, mean daily wind speeds and various crop heights. As an example, expected variations for $K_{c\ mid}$ for tomatoes in response to regional climatic conditions are presented in Box 14.

Determination of $K_{c\ mid}$

For specific adjustment in climates where RH_{min} differs from 45% or where u_2 is larger or smaller than 2.0 m/s, the $K_{c\ mid}$ values from Table 12 are adjusted as:

$$K_{c\,mid} = K_{c\,mid(Tab)} + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)]\left(\frac{h}{3}\right)^{0.3} \quad (62)$$

where

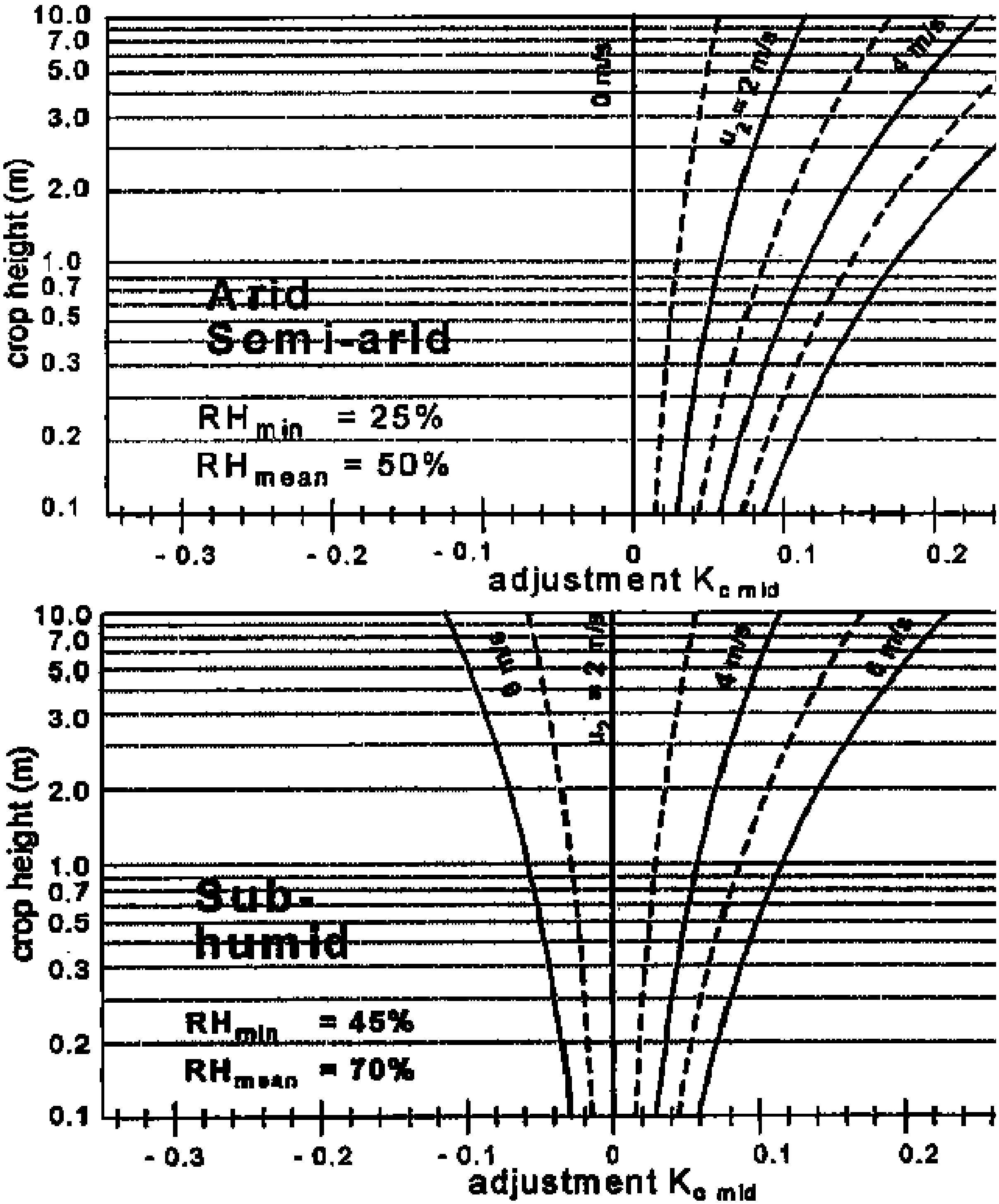
$K_{c\ mid\ (Tab)}$ value for $K_{c\ mid}$ taken from Table 12,

u_2 mean value for daily wind speed at 2 m height over grass during the mid-season growth stage [m s^{-1}], for 1 m $s^{-1} \le u_2 \le$ 6 m s^{-1},

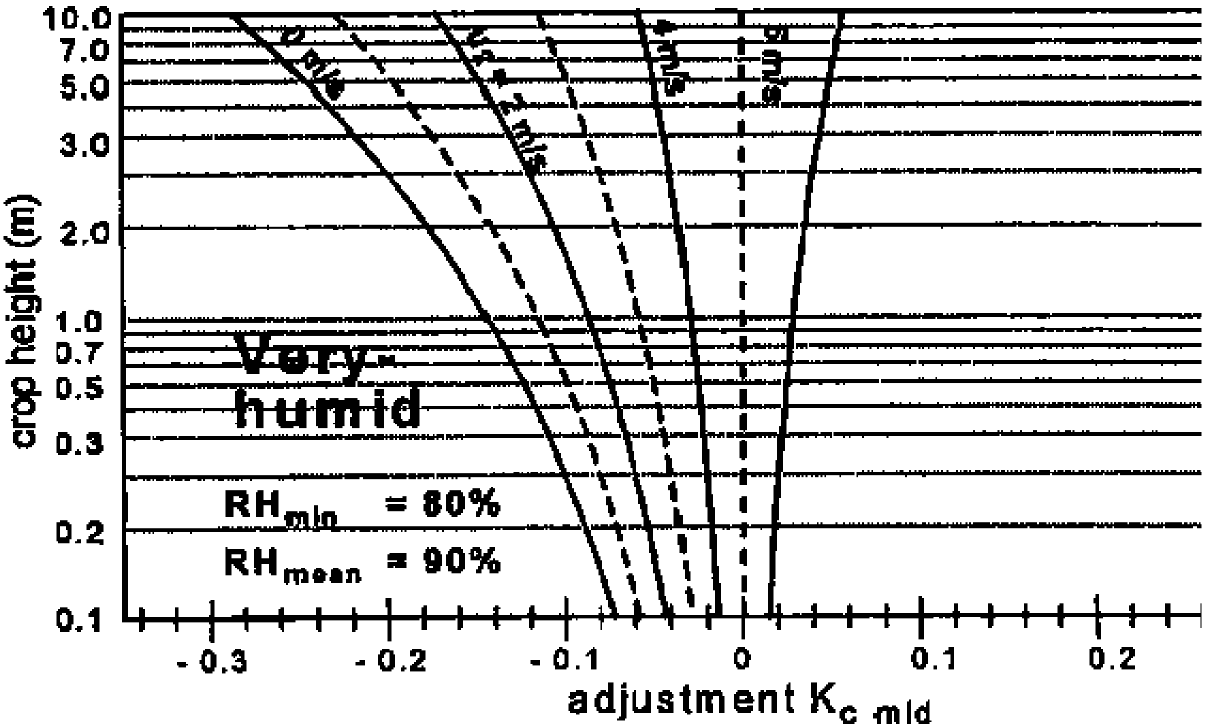
RH_{min} mean value for daily minimum relative humidity during the mid-season growth stage [%], for 20% $\le RH_{min} \le$ 80%,

h mean plant height during the mid-season stage [m] for 0.1 m < h < 10 m.

FIGURE 32. Adjustment (additive) to the $K_{c\ mid}$ values from Table 12 for different crop heights and mean daily wind speeds (u_2) for different humidity conditions



crop height (m)
Arid
Semi-arid
RH min = 25%
RH mean = 50%
0 m/s
u2 = 2 m/s
4 m/s
adjustment Kc mid
crop height (m)
Sub-
humid
RH min = 45%
RH mean = 70%
6 m/s
u2 = 2 m/s
4 m/s
6 m/s
adjustment Kc mid



The $K_{c\ mid}$ values determined with equations 62 and 65 are average adjustments for the midseason and late season periods. The values for parameters u_2 and RH_{min} should be accordingly taken as averages for these periods (see example, Annex 8). The limits expressed for parameters u_2, RH_{min} and h should be observed.

BOX 14. Demonstration of effect of climate on $K_{c\ mid}$ for wheat crop grown under field conditions	
From Table 12 for wheat: $K_{c\ mid}$ = 1.15 and h = 1.0 m	
For semi-arid to arid conditions	
- for strong wind (4 m/s)	$K_{c\ mid}$ = 1.15 + 0.10 = 1.25
- for moderate wind (2 m/s)	$K_{c\ mid}$ = 1.15 + 0.05 = 1.20
- for calm wind (1 m/s)	$K_{c\ mid}$ = 1.15 + 0.00 = 1.17
For sub-humid conditions	
- for strong wind (4 m/s)	$K_{c\ mid}$ = 1.15 + 0.05 = 1.20
- for moderate wind (2 m/s)	$K_{c\ mid}$ = 1.15 + 0.00 = 1.15
- for calm wind (1 m/s)	$K_{c\ mid}$ = 1.15 - 0.05 = 1.12
For humid and very humid conditions	
- for strong wind (4 m/s)	$K_{c\ mid}$ = 1.15 - 0.05 = 1.10
- for moderate wind (2 m/s)	$K_{c\ mid}$ = 1.15 - 0.10 = 1.05
- for calm wind (1 m/s)	$K_{c\ mid}$ = 1.15 - 0.15 = 1.02
Depending on the aridity of the climate and the wind conditions, the crop coefficient for wheat during the mid-season stage ranges from 1.02 (humid and calm wind) to 1.25 (arid and strong wind).	

Where the user does not have access to a calculator with an exponential function, the solution of the $(h/3)^{0.3}$ expression can be approximated as $[(h/3)^{0.5}]^{0.5}$ where the square root key is used.

RH_{min} is used rather than RH_{mean} because it is easier to approximate RH_{min} from T_{max} where relative humidity data are unavailable. Moreover, under the common condition where T_{min} approaches T_{dew} (i.e., $RH_{max} \approx 100\%$), the vapour pressure deficit (e_s - e_a), with e_s from Equation 12 and e_a from Equation 17, becomes $[(100 - RH_{min})/200]\ e°(T_{max})$, where $e°(T_{max})$ is saturation vapour pressure at maximum daily air temperature. This indicates that RH_{min} better reflects the impact of vapour pressure deficit on K_c than does RH_{mean}. RH_{min} is calculated on a daily or average monthly basis as:

$$RH_{min} = \frac{e°(T_{dew})}{e°(T_{max})} 100 \quad (63)$$

where T_{dew} is mean dewpoint temperature and T_{max} is mean daily maximum air temperature during the mid-season growth stage. Where dewpoint temperature or other hygrométrie data are not available or are of questionable quality, RH_{min} can be estimated by substituting mean daily minimum air temperature, T_{min}, for T_{dew}[1]. Then:

$$RH_{min} = \frac{e°(T_{min})}{e°(T_{max})} 100 \quad (64)$$

[1] In the case of arid and semi-arid climates, T_{min} in equation (64) should be adjusted as indicated in Annex 6 (equation 6-6) by subtracting 2°C from the average value of T_{min} to better approximate T_{dew}.

The values for u_2 and RH_{min} need only be approximate for the mid-season growth stage. This is because Equation 62 is not strongly sensitive to these values, changing 0.04 per 1 m/s change in u_2 and per 10% change in RH_{min} for a 3 m tall crop. Measurements, calculation, and estimation of missing wind and humidity data are provided in Chapter 3. Wind speed measured at other than 2 m height should be adjusted to reflect values for wind speed at 2 m over grass using Equation 47. Where no data on u_2 or RH_{min} are available, the general classification for wind speed and humidity data given in Tables 15 and 16 can be used.

TABLE 15. Empirical estimates of monthly wind speed data

description	mean monthly wind speed at 2 m
light wind	...≤ 1.0 m/s
light to moderate wind	2.0 m/s
moderate to strong wind	4.0 m/s
strong wind	... ≥ 5.0 m/s
general global conditions	**2 m/s**

TABLE 16. Typical values for RH_{min} compared with RH_{mean} for general climatic classifications

Climatic classification	RH_{min} (%)	RH_{mean} (%)
Arid	20	45
Semi-arid	30	55
Sub-humid	45	70
Humid	70	85
Very humid	80	90

Equation 62 is valid for mean plant heights up to 10 m. For plant heights smaller than 0.1 m, vegetation will behave aerodynamically similar to grass reference and eq. 62 should not be applied. Example values for h are listed in Table 12 for various crops. However, the mean plant height will greatly vary with crop variety and with cultural practices. Therefore, wherever possible, h should be obtained from general field observations. However, the presence of the 0.3 exponent in Equation 62 makes these equations relatively insensitive to small errors in the value used for h. Generally, a single value for h is used to represent me mid-season period.

Adjustment for frequency of wetting

$K_{c\ mid}$ is less affected by wetting frequency than is $K_{c\ ini}$, as vegetation during this stage is generally near full ground cover so that the effects of surface evaporation on K_c are smaller. For frequent irrigation of crops (more frequently than every 3 days) and where the $K_{c\ mid}$ of Table 12 is less than 1.0, the value can be replaced by approximately 1.1-1.3 to account for the combined effects of continuously wet soil, evaporation due to interception (sprinkler irrigation) and roughness of the vegetation, especially where the irrigation system moistens an important fraction of the soil surface ($f_w > 0.3$).

EXAMPLE 27. Determination of $K_{c\ mid}$

Calculate $K_{c\ mid}$ for maize crops near Taipei, Taiwan and near Mocha, Yemen. The average mean daily wind speed (u_2) during the mid-season stage at Taipei is about 1.3 m/s and the minimum relative humidity (RH_{min}) during this stage averages 75%. The average u_2 during the mid-season near Mocha is 4.6 m/s and the RH_{min} during this stage averages 44%.

From Table 12, the value for $K_{c\ mid}$ is 1.20 for maize. The value for h from Table 12 is 2 m. Using Eq. 62

For Taipei (humid climate):

$$K_{cmid} = 1.20 + [0.04(1.3 - 2) - 0.004(75 - 45)]\left(\frac{2}{3}\right)^{0.3} = 1.07$$

For Mocha (arid climate):

$$K_{cmid} = 1.20 + [0.04(4.6 - 2) - 0.004(44 - 45)]\left(\frac{2}{3}\right)^{0.3} = 1.30$$

The average crop coefficient predicted during the mid-season stage is 1.07 for Taipei and 1.30 for Mocha.

Crop coefficient for the end of the late season stage ($K_{c\ end}$)

Typical values for the crop coefficient at the end of the late season growth stage, $K_{c\ end}$, and listed in Table 12 for various agricultural crops. The values given for $K_{c\ end}$ reflect crop and water management practices particular to those crops. If the crop is irrigated frequently until harvested fresh, the topsoil remains wet and the $K_{c\ end}$ value will be relatively high. On the other hand, crops that are allowed to senesce and dry out in the field before harvest receive less frequent irrigation or no irrigation at all during the late season stage. Consequently, both the soil surface and vegetation are dry and the value for $K_{c\ end}$ will be relatively small (Figure 33).
Where the local water management and harvest timing practices are known to deviate from the typical values presented in Table 12, then the user should make some adjustments to the values for $K_{c\ end}$. Some guidance on adjustment of K_c values for wetting frequency is provided in Chapter 7. For premature harvest, the user can construct a K_c curve using the $K_{c\ end}$ value provided in Table 12 and a late season length typical of a normal harvest date; but can then terminate the application of the constructed curve early, corresponding to the time of the early harvest.
The $K_{c\ end}$ values in Table 12 are typical values expected for average $K_{c\ end}$ under the standard climatic conditions. More arid climates and conditions of greater wind speed will have higher values for $K_{c\ end}$. More humid climates and conditions of lower wind speed will have lower values for $K_{c\ end}$. For specific adjustment in climates where RH_{min} differs from 45% or where u_2 is larger or smaller than 2.0 m/s, Equation 65 can be used:

$$K_{c\,end} = K_{c\,end(Tab)} + \left[0.04(u_2 - 2) - 0.004(RH_{min} - 45)\right]\left(\frac{h}{3}\right)^{0.3}$$

(65)

where

$K_{c\ end\ (Tab)}$ value for $K_{c\ end}$ taken from Table 12,

u_2 mean value for daily wind speed at 2 m height over grass during the late season growth stage [m s^{-1}], for 1 m s^{-1} $\leq u_2 \leq$ 6 m s^{-1},

RH_{min} mean value for daily minimum relative humidity during the late season stage [%], for 20% $\leq RH_{min} \leq$ 80%,

h mean plant height during the late season stage [m], for 0.1 m $\leq$ h $\leq$ 10 m.

FIGURE 33. Ranges expected for $K_{c\ end}$

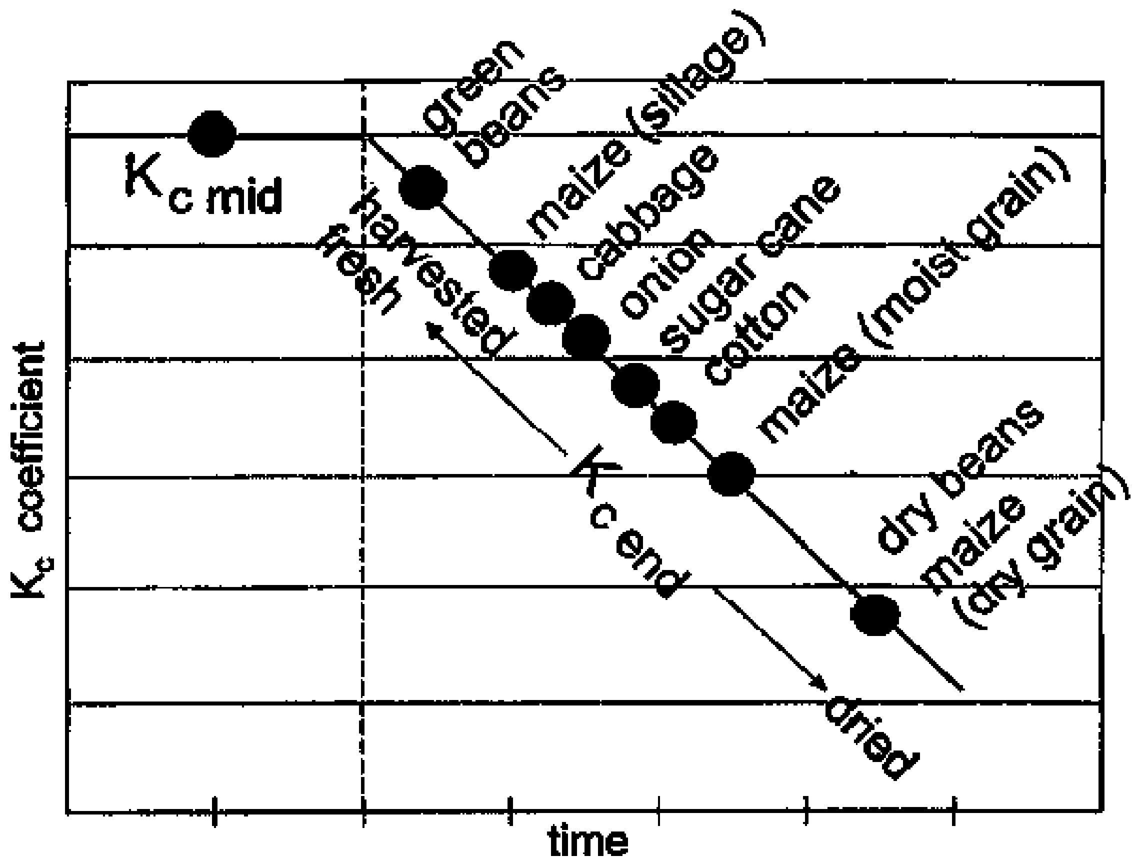
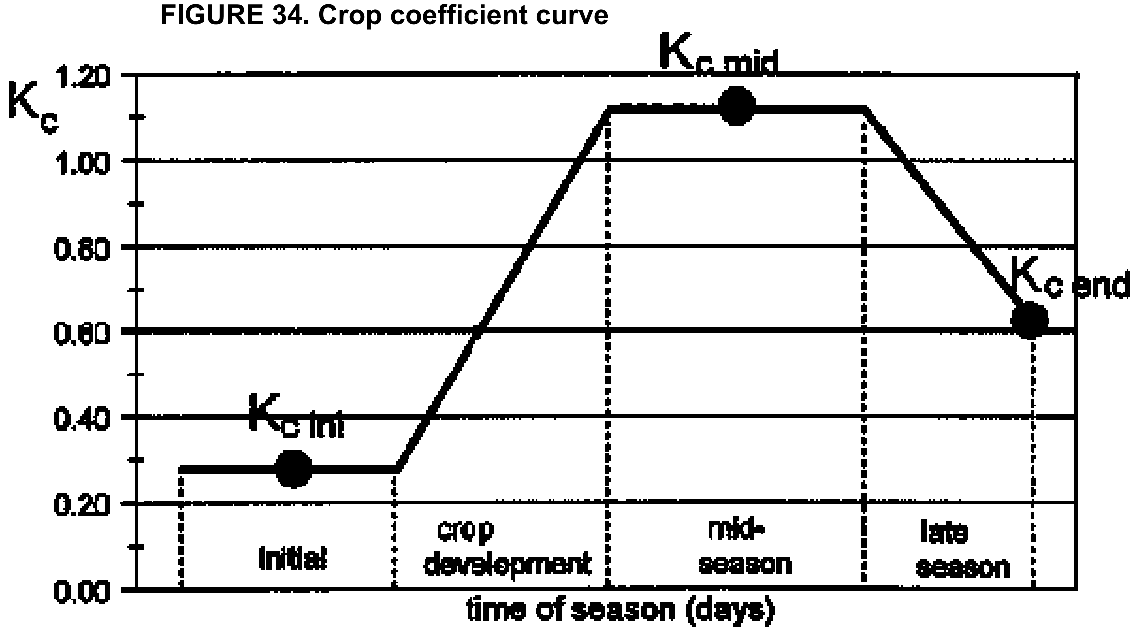


FIGURE 34. Crop coefficient curve



Equation 65 is only applied when the tabulated values for $K_{c\ end}$ exceed 0.45. The equation reduces the $K_{c\ end}$ with increasing RH_{min}. This reduction in $K_{c\ end}$ is characteristic of crops that are harvested 'green' or before becoming completely dead and dry (i.e., $K_{c\ end} \geq 0.45$).
No adjustment is made when $K_{c\ end\ (Table)} < 0.45$ (i.e., $K_{c\ end} = K_{c\ end\ (Tab)}$). When crops are allowed to senesce and dry in the field (as evidenced by $K_{c\ end} < 0.45$), u_2 and RH_{min} have less

effect on $K_{c\ end}$ and no adjustment is necessary. In fact, $K_{c\ end}$ may decrease with decreasing RH_{min} for crops that are ripe and dry at the time of harvest, as lower relative humidity accelerates the drying process.

Construction of the K_c curve

Annual crops

Only three point values for K_c are required to describe and to construct the K_c curve. The curve such as that shown in Figure 34 is constructed using the following three steps:

1. Divide the growing period into four general growth stages that describe crop phenology or development (initial, crop development, mid-season, and late season stage), determine the lengths of the growth stages, and identify the three K_c values that correspond to $K_{c\ ini}$, $K_{c\ mid}$ and $K_{c\ end}$ from Table 12.

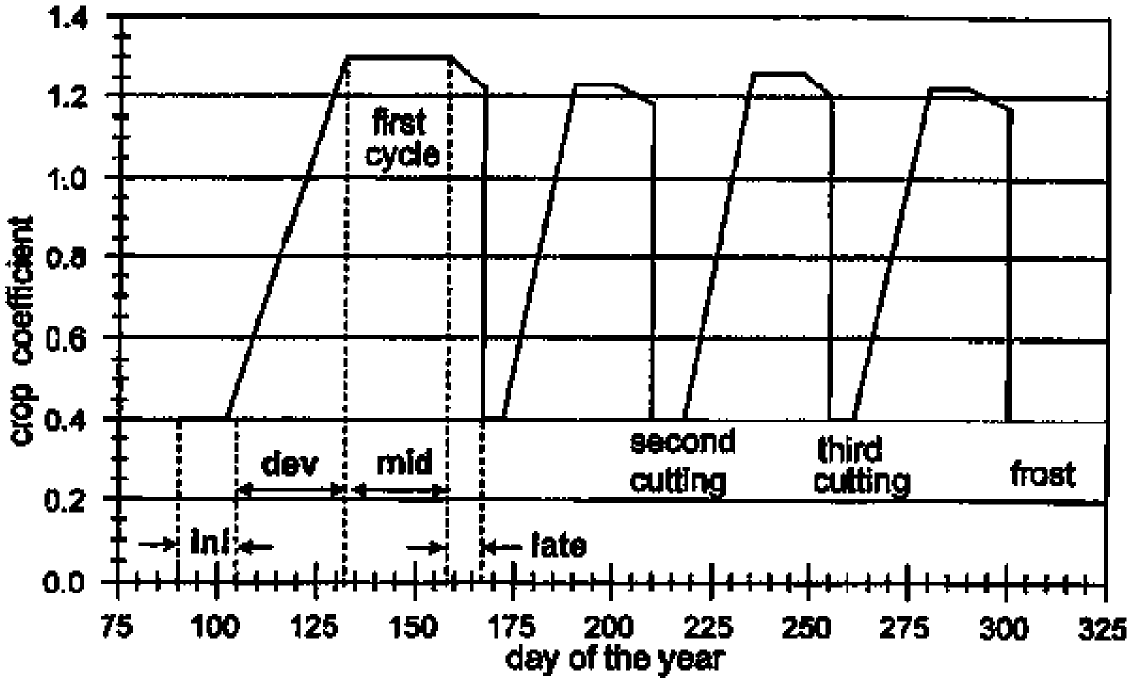
2. Adjust the K_c values to the frequency of wetting and/or climatic conditions of the growth stages as outlined in the previous section.

3. Construct a curve by connecting straight line segments through each of the four growth stages. Horizontal lines are drawn through $K_{c\ ini}$ in the initial stage and through $K_{c\ mid}$ in the mid-season stage. Diagonal lines are drawn from $K_{c\ ini}$ to $K_{c\ mid}$ within the course of the crop development stage and from $K_{c\ mid}$ to $K_{c\ end}$ within the course of the late season stage.

K_c curves for forage crops

Many crops grown for forage or hay are harvested several times during the growing season. Each harvest essentially terminates a 'sub' growing season and associated K_c curve and initiates a new 'sub' growing season and associated K_c curve. The resulting K_c curve for the entire growing season is the aggregation of a series of K_c curves associated with each sub-cycle. Figure 35 presents a K_c curve for the entire growing season constructed for alfalfa grown for hay in southern Idaho.

FIGURE 35. Constructed curve for K_c for alfalfa hay in southern Idaho, the United States using values from Tables 11 and 12 and adjusted using Equations 62 and 65 (data from Wright, 1990)



In the southern Idaho climate, greenup (leaf initiation) begins in the spring on about day 90 of the year. The crop is usually harvested (cut) for hay three or four times during the growing season. Therefore, Figure 35 shows four K_c sub-cycles or cutting cycles: sub-cycle 1 follows greenup in the spring and the three additional K_c sub-cycles follow cuttings. Cuttings create a ground surface with less than 10% vegetation cover. Cutting cycle 1 is longer in duration than cycles 2, 3 and 4 due to lower air and soil temperatures during this period that reduce crop growth rates. The lengths for cutting cycle 1 were taken from the first entry for alfalfa (" 1st cutting cycle") in Table 11 for Idaho, the United States (10/30/25/10). The lengths for cutting cycles 2, 3 and 4 were taken from the entry for alfalfa in Table 11 for "individual cutting periods" for Idaho, the United States (5/20/10/10). These lengths were based on observations. In the southern Idaho climate, frosts terminate the growing season sometime in the fall, usually around day 280-290 of the year (early to mid-October).

The magnitudes of the K_c values during the mid-season periods of each cutting cycle shown in Figure 35 vary from cycle to cycle due to the effects of adjusting the values for $K_{c\ mid}$ and $K_{c\ end}$ for each cutting cycle period using Equations 62 and 65. In applying these two adjustment equations, the u_2 and RH_{min} values were averages for the mid-season and late season stages within each cutting cycle. Basal K_{cb} curves similar to Figure 35 can be constructed for forage or hay crops, following procedures presented in Chapter 7.

$K_{c\ mid}$ when effects of individual cutting periods are averaged

Under some conditions, the user may wish to average the effects of cuttings for a forage crop over the course of the growing season. When cutting effects are averaged, then only a single value for $K_{c\ mid}$ and a only single K_c curve need to be employed for the whole growing season. When this is the case, a "normal" K_c curve is constructed as in Figure 25, where only one midseason period is shown for the forage crop. The $K_{c\ mid}$ for this total midseason period must average the effects of occasional cuttings or harvesting. The value that is used for $K_{c\ mid}$ is therefore an average of the K_c curve for the time period starting at the first attainment of full cover and ending at the beginning of the final late season period near dormancy or frost. The value used for $K_{c\ mid}$ under these averaged conditions may be only about 80% of the K_c value that represents full ground cover. These averaged, full-season $K_{c\ mid}$ values are listed in Table 12. For example, for alfalfa hay, the averaged, full-season $K_{c\ mid}$ is 1.05, whereas, the $K_{c\ mid}$ for an individual cutting period is 1.20.

Fruit trees

Values for the crop coefficient during the mid-season and end of late season stages are given in Table 12. As mentioned before, the K_c values listed are typical values for standard climatic conditions and need to be adjusted by using Equations 62 and 65 where RH_{min} or u_2 differ. As the mid and late season stages of deciduous trees are quite long, the specific adjustment of K_c to RH_{min} and u_2 should take into account the varying climatic conditions throughout the season. Therefore, several adjustments of K_c are often required if the mid and late seasons cover several climatic seasons, e.g., spring, summer and autumn or wet and dry seasons. The $K_{c\ ini}$ and $K_{c\ end}$ for evergreen non dormant trees and shrubs are often not different, where climatic conditions do not vary much, as happens in tropical climates. Under these conditions, seasonal adjustments for climate may therefore not be required since variations in ET_c depend mostly on variations in ET_o.

Calculating ET_c

Graphical determination of K_c
Numerical determination of K_c

From the crop coefficient curve the K_c value for any period during the growing period can be graphically or numerically determined. Once the K_c values have been derived, the crop evapotranspiration, ET_c, can be calculated by multiplying the K_c values by the corresponding ET_o values.

Graphical determination of K_c

Weekly, ten-day or monthly values for K_c are necessary when ET_c calculations are made on weekly, ten-day or monthly time steps. A general procedure is to construct the K_c curve, overlay the curve with the lengths of the weeks, decade or months, and to derive graphically from the curve the K_c value for the period under consideration (Figure 36). Assuming that all decades have a duration of 10 days facilitates the derivation of K_c and introduces little error into the calculation of ET_c.

The constructed K_c curve in Box 15 was used to construct the curve in Figure 36. This curve has been overlaid with the lengths of the decades. K_c values of 0.15, 1.19 and 0.35 and the actual lengths for growth stages equal to 25, 25, 30 and 20 days were used. The crop was planted at the beginning of the last decade of May and was harvested 100 days later at the end of August.

For all decades the K_c values can be derived directly from the curve. The value at the middle of the decade is considered to be the average K_c of that 10 day period. Only the second decade of June, where the K_c value changes abruptly, requires some calculation.

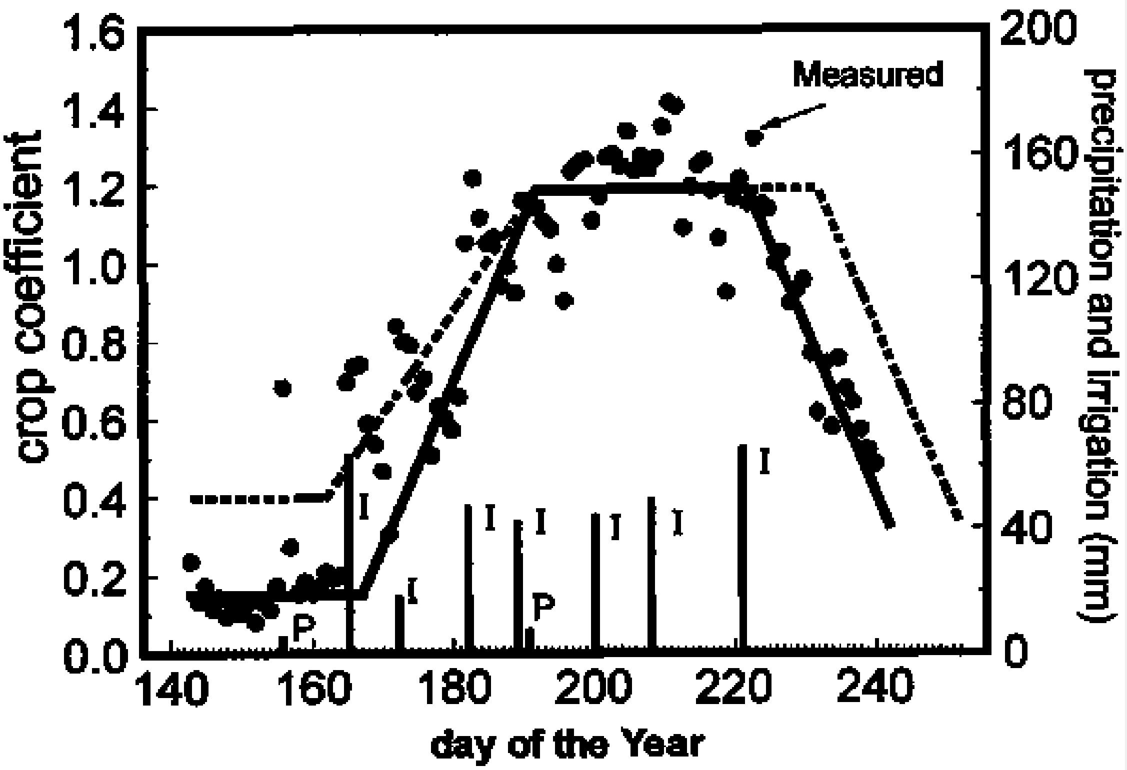
BOX 15. Case study of a dry bean crop at Kimberly, Idaho, the United States (single crop coefficient)

An example application for using the K_c procedure under average soil wetness conditions is presented for a dry bean crop planted on 23 May 1974 at Kimberly, Idaho, the United States (latitude = 42.4°N). The initial, development, mid-season and late season stage lengths are taken from Table 11 for a continental climate as 20, 30, 40 and 20 days (the stage lengths listed for southern Idaho were not used in this example in order to demonstrate the only approximate accuracy of values provided in Table 11 when values for the specific location are not available). Initial values for $K_{c\ ini}$, $K_{c\ mid}$ and $K_{c\ end}$ are selected from Table 12 as 0.4, 1.15, and 0.35.

The mean RH_{min} and u_2 during both the mid-season and late season growth stages were 30% and 2.2 m/s. The maximum height suggested in Table 12 for dry beans is 0.4 m. Therefore, $K_{c\ mid}$ is adjusted using Eq. 62 as:

$$K_{cmid} = 1.15 + [0.04(2.2-2) - 0.004(30-45)]\left(\frac{0.4}{3}\right)^{0.3} = 1.19$$

As $K_{c\ end}$ = 0.35 is less than 0.45, no adjustment is made to $K_{c\ end}$. The value for $K_{c\ mid}$ is not significantly different from that in Table 12 as $u_2 \approx 2$ m/s, RH_{min} is just 15% lower than the 45% represented in Table 12, and the height of the beans is relatively short. The initial K_c curve for dry beans in Idaho can be drawn, for initial, planning purposes, as shown in the graph (dotted line), where $K_{c\ ini}$, $K_{c\ mid}$ and $K_{c\ end}$ are 0.4, 1.19 and 0.35 and the four lengths of growth stages are 20, 30, 40 and 20 days. Note that the $K_{c\ ini}$ = 0.4 taken from Table 12 serves only as an initial, approximate estimate for $K_{c\ ini}$.



Constructed K_c curves using values from Tables 11 and 12 directly (dotted line) and modified using $K_{c\ ini}$ from Fig. 29 and L_{ini} = 25, L_{dev} = 25, L_{mid} = 30, and L_{late} = 20 days (heavy line) for dry beans at Kimberly, Idaho. Also shown are daily measured K_c (lysimeter data from Wright, 1990).

$K_{c\ ini}$ can be more accurately estimated using the approach described in this chapter. ET_o during the initial period at Kimberly (late May - early June, 1974) averaged 5.3 mm/day, and the wetting interval during this period was approximately 14 days (2 rainfall events occurred averaging 5 mm per event). Therefore, as the wetting events were light (< 10 mm each), Fig. 29 is used. The soil texture at Kimberly, Idaho is silt loam. From Fig. 29, $K_{c\ ini}$ for the 14 day wetting interval and ET_o = 5.3 mm/day is about 0.15. This value is substantially less than the general 0.4 value suggested by Table 12, and emphasizes the need to utilize local, actual precipitation and irrigation data when determining $K_{c\ ini}$.

Comparison of constructed curves with measurements

Because the ET_c data for the dry bean crop at Kimberly, Idaho were measured using a precision lysimeter system during 1974 by Wright (1990), the actual K_c measurements can be compared with the constructed K_c curves, where actual K_c was calculated by dividing lysimeter measurements of ET_c by daily ET_o estimated using the FAO Penman-Monteith equation.

As illustrated in the graph, the mid-season length as taken from Table 11 for the general, continental climate overestimated the true mid-season length for dry beans in southern Idaho, which averaged only about 30 days rather than 40 days as suggested by Table 11. This illustrates the importance of using the local observation of 30 days for mid-season period length rather than the general value from Table 11.

The final, best estimate for the K_c curve for the dry bean crop in southern Idaho is plotted (lower curve in graph) using K_c values of 0.15, 1.19, and 0.35 and the actual observed lengths of growth stages equal to 25, 25, 30 and 20 days. Note the impact that the error in estimating mid-season length has on the area under the K_c curve. This supports the need to obtain local observations of

growth stage dates and lengths. The value calculated for $K_{c\ mid}$ (1.19) appears to have underestimated the measured value for K_c during portions of the mid-season period at Kimberly. Some of this effect was due to effects of increased soil water evaporation following four irrigations during the 1974 mid-season which increased the effective K_c. This is illustrated in Box 16, where the basal K_{cb} + K_e approach is introduced and demonstrated for this same example. The 0.15 value calculated for $K_{c\ ini}$ using Fig. 29 agrees closely with measured K_c during the initial period. Measured K_c during the development period exceeded the final K_c curve during days on or following wetting events. The day to day variation in the lysimeter measured K_c is normal and is caused by day to day variations in weather, in wind direction, by errors in prediction of R_n and ET_o, and by some random errors in the lysimeter measurements and weather measurements.

FIGURE 36. K_c curve and ten-day values for K_c and ET_c derived from the graph for the dry bean crop example (Box 15)

first five days of that decade, K_c = 0.15, while during the second part of the decade K_c varies from 0.15 to 0.36 at the end of day 10. The K_c for that decade is consequently: 5/10 (0.15) + 5/10(0.15+0.36)/2 = 0.20.

Numerical determination of K_c

The K_c coefficient for any period of the growing season can be derived by considering that during the initial and mid-season stages K_c is constant and equal to the K_c value of the growth stage under consideration. During the crop development and late season stage, K_c varies linearly between the K_c at the end of the previous stage ($K_{c\ prev}$) and the K_c at the beginning of the next stage ($K_{c\ next}$), which is $K_{c\ end}$ in the case of the late season stage:

$$K_{c\ i} = K_{c\ prev} + \left[\frac{i - \Sigma(L_{prev})}{L_{stage}}\right](K_{c\ next} - K_{c\ prev}) \quad (66)$$

where

i day number within the growing season [1.. length of the growing season],
$K_{c\ i}$ crop coefficient on day i,
L_{stage} length of the stage under consideration [days],
Σ (L_{prev}) sum of the lengths of all previous stages [days].

Equation 66 applies to all four stages.

EXAMPLE 28. Numerical determination of K_c

Determine K_c at day 20, 40, 70 and 95 for the dry bean crop (Figure 36).

Crop growth stage	Length (days)	K_c
initial	25	$K_{c\ ini}$ = 0.15
crop development	25	0.15... 1.19
mid-season	30	$K_{c\ mid}$ = 1.19

late season	20	1.19 .. $K_{c\ end}$ = 0.35

At i = 20:	initial stage, $K_c = K_{c\ ini}$ =	0.15	-
At i = 40	Crop development stage,		
For:	$\Sigma (L_{prev}) = L_{ini}$ =	25	days
and:	$L_{stage} = L_{dev}$ =	25	days
From Eq. 66:	K_c = 0.15 + [(40 - 25)/25](1.19 - 0.15) =	0.77	-
At i = 70:	mid-season stage, $K_c = K_{c\ mid}$ =	1.19	-
At i = 95	late season stage,		
For:	$\Sigma (L_{prev}) = L_{ini} + L_{dev} + L_{mid}$ = (25 + 25 + 30) =	80	days
and:	$L_{stage} = L_{late}$ =	20	days
From Eq. 66:	K_c = 1.19 + [(95-80)/20](0.35-1.19) =	0.56	-
The crop coefficients at day 20, 40, 70 and 95 for the dry bean crop are 0.15, 0.77, 1.19 and 0.56 respectively.			

Alfalfa-based crop coefficients

As two reference crop definitions (grass and alfalfa) are in use in various parts of the world, two families of K_c curves for agricultural crops have been developed. These are the alfalfa-based K_c curves by Wright (1981; 1982) and grass-based curves by Pruitt (Doorenbos and Pruitt 1977; Jensen *et al.* 1990) and those reported in this paper. The user must exercise caution to avoid mixing grass-based K_c values with alfalfa reference ET and vice versa. Usually, a K_c based on the alfalfa reference can be 'converted' for use with a grass reference by multiplying by a factor ranging from about 1.0 to 1.3, depending on the climate (1.05 for humid, calm conditions, and 1.2 for semi-arid, moderately windy conditions, and 1.35 for arid, windy conditions):

$$K_{c\ (grass)} = K_{ratio}\ K_{c\ (alfalfa)} \quad (67)$$

where

$K_{c\ (grass)}$ grass-based K_c (this handbook),
$K_{c\ (alfalfa)}$ alfalfa-based K_c,
K_{ratio} conversion factor (1.0... 1.3).

A reference conversion ratio can be established for any climate by using the $K_{c\ mid}$ = 1.20 listed for alfalfa in Table 12 and then adjusting this $K_{c\ mid}$ for the climate using Equation 62. For example, at Kimberly, Idaho, the United States, where RH_{min} = 30% and u_2 = 2.2 m/s are average values during the summer months, a reference conversion ratio between alfalfa and grass references using Equation 62 is approximately:

$$K_{ratio} = 1.2 + [0.04(2.2-2) - 0.004(30-45)]\left(\frac{0.5}{3}\right)^{0.3} = 1.24$$

(68)

where

> h = 0.5 m is the standard height for the alfalfa reference.

Transferability of previous K_c values

The values for $K_{c\ mid}$ and $K_{c\ end}$ listed in Table 12 are for a large part based on the original values presented in FAO Irrigation and Drainage Papers No. 24 and 33 (FAO-24 and FAO-33), with some adjustment and revisions to reflect recent findings. Similarly adjustments in $K_{c\ mid}$ to compensate for differences in aerodynamic roughness and leaf area, as introduced in Equation 62 are derived from the K_c values given for different wind and RH_{min} conditions in the concerned K_c table in FAO-24, with some upward adjustment to better reflect increased ET_{crop} values under high wind and low RH_{min} when applied with the FAO Penman-Monteith equation.
The K_c's from FAO-24 were based primarily on a living grass reference crop. The FAO Penman-Monteith equation presented in this publication similarly represents the same standardized grass reference. For that reason K_c values are in general not very different between these publications except under high wind and low RH_{min}.
The No. 24 modified Penman was found frequently to overestimate ET_o even up to 25 % under high wind and low evaporative conditions and required often substantial local calibration (see chapter 2). K_c values derived from crop water use studies which used the FAO-24 Penman equation to compute grass reference crop evapotranspiration, can therefore not be used and need to be adjusted using ET_o values estimated from the FAO Penman-Monteith equation. Similarly crop water requirement estimates based on the FAO-24 Modified Penman equation will need to be reassessed in view of the found differences between the FAO-24 Penman and the FAO Penman-Monteith reference equations.