CALCULATING CROP EVAPOTRANSPIRATION USING A DUAL CROP COEFFICIENT – PART 3

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INTRODUCTION

As discussed in part 2, the water used by a crop, or crop evapotranspiration (ET_c) is determined by multiplying the short grass reference evapotranspiration (ET_o) with a growth stage-specific crop coefficient (K_c), which serves as an aggregation of the physical and physiological differences between crops and the reference condition.

Modern ET_c calculation methods recommend splitting K_c into two separate coefficients, one for crop transpiration, known as the basal crop coefficient (K_{cb}), and one for soil evaporation (K_e). The calculation of ET_c now becomes:

$$ET_c = (K_{cb} + K_e) \times ET_o$$

Equation 1a, or

$$ET_c = (K_{cb} \times ET_o) + (K_e \times ET_o)$$

Equation 1b

The first component of Equation 1b ($K_{cb} \times ET_o$) represents primarily the transpiration component (T) of ET_c – a crop will transpire at the potential rate as long as water in the root zone is not a limiting factor (and therefore even when the soil surface is dry).

The second component of the equation ($K_e \times ET_o$) represents the evaporation component (E) of ET_c. Where the topsoil is wet following rain or irrigation, this component will be at a maximum. As the soil surface dries, the component will decrease until no practically measureable evaporation is taking place.

THE EVAPORATIVE CROP COEFFICIENT, K_E

The soil evaporation coefficient, K_e, describes the evaporation component of ET_c. Where the topsoil is wet, following rain or irrigation, K_e is maximal. Where the soil surface is dry, K_e is small and even zero when no water remains near the soil surface for evaporation.

Where the soil is wet, evaporation from the soil occurs at the maximum rate. However, the crop coefficient ($K_c = K_{cb} + K_e$) can never exceed a maximum value, $K_{c\ max}$. This value is determined by the energy available for evapotranspiration at the soil surface - ($K_{cb} + K_e \leq K_{c\ max}$) or $K_e \leq (K_{c\ max} - K_{cb})$.

When the topsoil dries out, less water is available for evaporation and a reduction in evaporation begins to occur in proportion to the amount of water remaining in the surface soil layer, or:

$$K_e = K_r (K_{c\ max} - K_{cb}) \leq f_{ew}\ K_{c\ ma}$$

Equation 2

where

K_e = soil evaporation coefficient,

K_{cb} = basal crop coefficient (discussed in the previous article),

$K_{c\ max}$ = maximum value of K_c following rain or irrigation,

K_r = dimensionless evaporation reduction coefficient dependent on the cumulative depth of water depleted (evaporated) from the topsoil,

f_{ew} = fraction of the soil that is both ex-posed and wetted, i.e., the fraction of soil surface from which most evaporation occurs.

K_e will therefore always be equal to K_r ($K_{c\ max}$ - K_{cb}) but never exceed the value of f_{ew} $K_{c\ max}$.

Following rain or irrigation K_r is 1, and evaporation is only determined by the energy available for evaporation. As the soil surface dries, K_r becomes less than one and evaporation is reduced. K_r becomes zero when no water is left for evaporation in the upper soil layer.

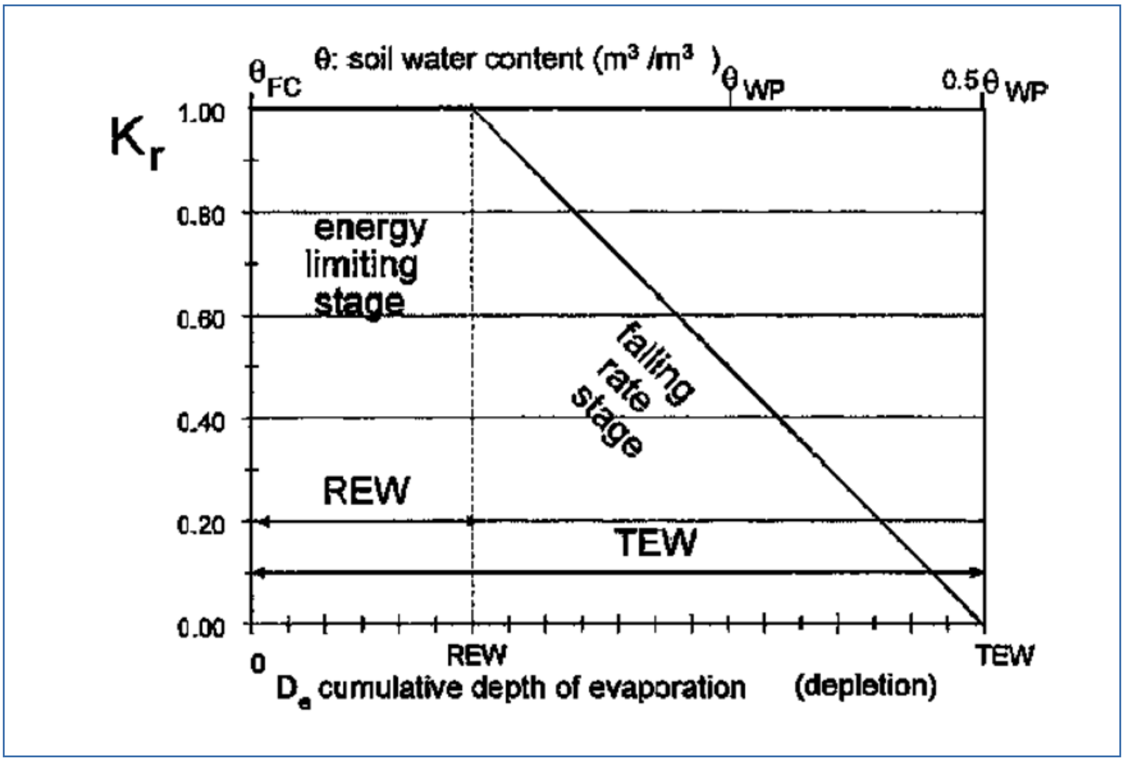
Evaporation occurs predominantly from the exposed soil fraction. Hence, evaporation is restricted at any moment by the energy available at the exposed soil fraction, i.e., K_e cannot exceed f_{ew} $K_{c\ max}$, where f_{ew} is the fraction of soil from which most evaporation occurs, i.e., the fraction of the soil not covered by vegetation and that is wetted by irrigation or precipitation.

THE CALCULATION PROCEDURE CONSISTS OF DETERMINING:

The soil evaporation reduction coefficient Kr; and -

Soil evaporation from the exposed soil can be assumed to take place in two stages: an energy limiting stage, and a falling rate stage. When the soil surface is wet, K_r is 1. When the water content in the upper soil becomes limiting, K_r decreases and becomes zero when the total amount of water that can be evaporated from the topsoil is depleted. The estimation of K_r requires a daily water balance computation for the surface soil layer.

Figure 1 (below) The soil evaporation reduction coefficient, K_r (TEW = Total Evaporable Water, REW = Readily Evaporable Water)



The upper limit Kc max;

$K_{c\ max}$ represents an upper limit on the evaporation and transpiration from any cropped surface and is imposed to reflect the natural constraints placed on available energy represented by the energy balance difference $R_n - G - H$ (see Penman –Monteith equation). $K_{c\ max}$ ranges from about 1.05 to 1.30 when using the grass reference ET_o.

$$K_{cmax} = \max\left(\left\{1.2 + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)]\left(\frac{h}{3}\right)^{0.3}\right\}, \{K_{cb} + 0.05\}\right)$$

Equation 3

where

h = mean maximum plant height during the period of calculation (initial, development, midseason, or late-season)[m],

K_{cb} = basal crop coefficient,

max( ) = maximum value of the parameters in braces {} that are separated by the comma.

The exposed and wetted soil fraction f_{ew}

This aspect of the crop coefficient is of great importance when designing irrigation systems with efficient water use in mind. In crops with incomplete ground cover, evaporation from the soil surface often does not occur uniformly over the entire surface, but is greater between plants where exposure to sunlight occurs and where air ventilation is able to transport vapour from the soil surface to above the canopy. This is especially true when only part of the soil surface is wetted by irrigation.

It is recognised that both the location and the fraction of the soil surface exposed to sunlight changes to some degree with the time of day and depending on row orientation. The procedure presented in FAO56 predicts a general averaged fraction of the soil surface from which the majority of evaporation occurs. Diffusive evaporation from the soil beneath the crop canopy is assumed to be largely included in the basal K_{cb} coefficient.

Where the complete soil surface is wetted, as by precipitation or sprinkler, then the fraction of the soil surface from which most evaporation occurs, f_{ew}, is essentially defined as $(1 - f_c)$ where f_c is the average fraction of soil surface covered by vegetation and $1 - f_c)$ is the approximate fraction of soil surface that is exposed (Figure 2). However, for irrigation systems where only a fraction of the ground surface is wetted, f_{ew} must be limited to f_w, the fraction of soil surface wetted by irrigation. Therefore, f_{ew} is calculated as:

$$f_{ew} = \min(1 - f_c, f_w)$$

Equation 4

Where
$1 - f_c$ = Average exposed soil fraction not covered (or shadowed) by vegetation [0.01 – 1]
f_w = Average fraction of soil surface wetted by irrigation or precipitation [0.01 – 1]

The limitation imposed by equation 4 assumes that the fraction of soil wetted by irrigation occurs within the fraction of soil exposed to sunlight and ventilation. Drip irrigation might be the exception because in most cases the wetted area is under the crop canopy. In this case, it may be necessary to reduce the values to about one-half or one-third of the shown value *(Allen et al., 1998)*.

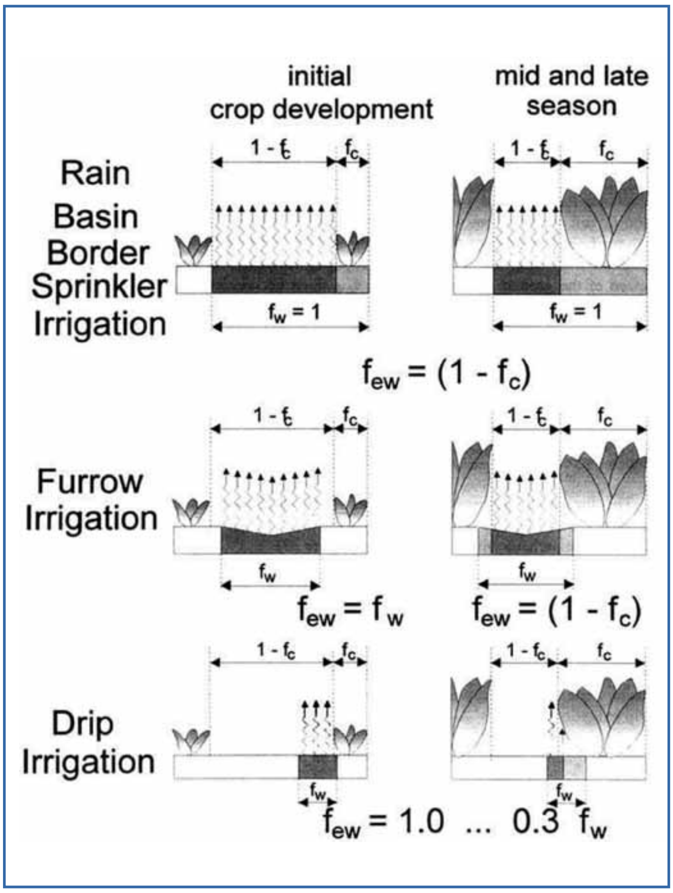


Figure 2: Determination of variable few (cross-hatchet areas) as a function of ground surface coverage (f_c) and the fraction of the surface wetted (f_w) *(Allen et al., 1998).*

FRACTION OF SOIL SURFACE WETTED BY IRRIGATION OR PRECIPITATION

Table 1 presents typical values for f_w. Where a mixture of irrigation and precipitation occur within the same drying period or the same day, the value of f_w should be based on a weighted average of the f_w for precipitation (f_w = 1) and the f_w of the irrigation system. The weighting should be approximately proportional to the infiltration from each water source *(Allen et al., 1998)*.

Table 1: Common values of fraction of soil surface wetted by irrigation or precipitation *(Allen et al., 1998)*

WETTING EVENT	F_w
Precipitation	1.0
Sprinkler irrigation	1.0
Basin irrigation	1.0
Border irrigation	1.0
Furrow irrigation (every furrow), narrow bed	0.6 – 1.0
Furrow irrigation (every furrow), wide bed	0.4 – 0.6
Furrow irrigation (alternated rows)	0.3 – 0.5
Trickle irrigation	0.3 – 0.4

EXPOSED SOIL SURFACE (1 - F_c)

The fraction of soil surface that is covered by vegetation is termed f_c. Therefore, (1 – f_c) represents the fraction of the soil that is exposed to sunlight and air ventilation and which serve as the site for the majority of evaporation from the wet soil. The value for f_c is limited to <0.99. The user should assume appropriate values for the various growth stages. Typical values for f_c and (1 – f_c) are given in Table 2.

Table 2 Common values of fractions covered by vegetation (f_c) and exposed sunlight (1 - f_c) *(Allen et al., 1998)*

CROP GROWTH STAGE	F_c	1 – F_c
Initial stage	0.0 – 0.1	1.0 – 0.9
Crop development stage	0.1 – 0.8	0.9 – 0.2
Mid-season stage	0.8 - 1.0	0.2 – 0.0
Late season stage	0.8 – 0.2	0.2 – 0.8

Application of equation (4) predicts that f_c decreases during the late season period in proportion to K_{cb}, even though the ground cover may remain covered with senescing vegetation. This prediction helps to account for the local transport of sensible heat from senescing leaves to the soil surface below *(Allen et al., 1998)*.

Where f_c is not measured, f_c can be estimated using the relationship:

$$f_c = \left(\frac{K_{cb} - K_{c\,min}}{K_{c\,max} - K_{c\,min}}\right)^{(1+0.5h)}$$

Equation 5

where

f_c = the effective fraction of soil surface covered by vegetation [0 - 0.99],
K_{cb} = the value for the basal crop coefficient for the particular day or period,
$K_{c\,min}$ = the minimum K_c for dry bare soil with no ground cover [≈0.15 - 0.20],
$K_{c\,max}$ = the maximum K_c immediately following wetting (Equation 2),
h = mean plant height [m].

EXAMPLE: CALCULATION OF THE CROP COEFFICIENT (K_{CB} + K_E) UNDER SPRINKLER IRRIGATION

A field of cotton has just been sprinkler irrigated. The K_{cb} for the specific day (during the development period) has been computed as 0.9. The ET_o = 7 mm/day, u_2 = 3 m/s and RH_{min} = 20%. Estimate the crop coefficient (K_{cb} + K_e).

Assuming h = 1 m, from **Equation 2**, $K_{c\,max}$ for this arid climate is:

$$K_{c\,max} = \max\left(\left\{1.2 + [0.04(3-2) - 0.004(20-45)]\left(\frac{1}{3}\right)^{0.3}\right\}, \{0.9 + 0.05\}\right) = 1.30$$

From **Eq. 5**, where $K_{c\,min}$ = 0.15:
f_c = [(K_{cb} - $K_{c\,min}$)/($K_{c\,max}$ - $K_{c\,min}$)] (1 + 0.5h) = [(0.9-0.15)/(1.3-0.15)] (1 +0.5(1)) = 0.53.

As the field was sprinkler irrigated, f_w = 1.0 (100% wetted area) and from **Eq. 4**:
f_{ew} = min(1 - f_c, f_w) = min(1- 0.53, 1.0) = 0.47.

Assuming that the irrigation was sufficient to fill the evaporating layer to field capacity, so that K_r = 1, evaporation would be in stage 1.
From **Eq. 2: K_e = K_r ($K_{c\,max}$ – K_{cb}) = 1.00 (1.30 - 0.90) = 0.40**

The value is compared against the upper limit f_{ew} $K_{c\,max}$ to ensure that it is less than the upper limit: From **Eq. 2: f_{ew} $K_{c\,max}$ = 0.47 (1.30) = 0.61**, which is greater than the value for Ke calculated above. Therefore, the value for K_e can be used with no limitation.

EXAMPLE: CALCULATION OF THE CROP COEFFICIENT (K_{CB} + K_E) UNDER SPRINKLER IRRIGATION (CONTINUED)

The total K_c for the field, assuming no moisture stress due to a dry soil profile, is
$K_c = K_{cb} + K_e = 0.9 + 0.40 = 1.30$.

This value is large because of the very wet soil surface, the relatively tall rough crop as compared to the grass reference, and the arid climate (u_2 = 3 m/s and RH_{min} = 20%). In this situation, K_c happens to equal $K_{c\,max}$, as the field has just been wetted by sprinkler irrigation. Optimal evapotranspiration is therefore occurring.

The dual crop coefficient approach (K_{cb} + K_e) is more complicated and more computationally intensive than the single crop coefficient approach (K_c). As the procedure is conducted on a daily basis, it is intended for applications using computers and has been successfully incorporated into the SAPWAT3 program for calculating irrigation requirements in South Africa.

REFERENCE:

Allen, R.G., Pereira, L.S., Raes, D. and Smith, M. 1998.
Crop evapotranspiration: Guidelines for computing crop water requirements.
Irrigation and Drainage Paper nr 56. FAO, Rome, Italy.

The information provided here was partially abstracted from the recently released Water Research Commission (WRC) report entitled "Integrating and Upgrading SAPWAT and PLANWAT to create a powerful and user-friendly irrigation water planning tool". (WRC report nr TT391/08) in collaboration with report main author Pieter van Heerden. Copies of the report which include a copy of the SAPWAT3 program is available from the WRC at 012 330 0340 or www.wrc.org.za.