Consumptive Use Program + (CUP+) Model

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Introduction

A user-friendly Microsoft Excel application program “Consumptive Use Program +” or “CUP+” was developed to help growers and water agencies determine reference evapotranspiration ($E_{To}$), crop coefficient ($K_c$) values, crop evapotranspiration ($E_{Tc}$), and evapotranspiration of applied water ($E_{Taw}$), which provides an estimate of the net irrigation water diversion needed to produce a crop. The application also can be used to study the impact of climate change on evapotranspiration and irrigation water needs.

CUP+ computes reference evapotranspiration ($E_{To}$) from daily solar radiation, maximum and minimum temperature, dew point temperature, and wind speed using the daily Penman-Monteith equation. In addition, the program uses a curve fitting technique to derive one year of daily weather data from the monthly data and to estimate daily $E_{To}$. It also uses daily rainfall data to estimate bare soil evaporation as a function of mean of $E_{To}$ and wetting frequency in days. A bare soil $K_c$ value is calculated to estimate the off-season evapotranspiration and as a baseline for in-season $K_c$ calculations. CUP+ accounts for the influence of orchard cover crops on $K_c$ values and it accounts for immaturity effects on $K_c$ values for tree and vine crops. Further, the program computes and applies all $E_{To}$ and $K_c$ values on a daily basis to determine crop water requirements by month, by season, by year. The water balance model is similar to that used in the Simulation of ET of Applied Water (SIMETAW) application program, which was also developed as a cooperative effort between the University of California (UC) and the Department of Water Resources (DWR). The application outputs a wide range of tables and charts that are useful for irrigation planning.

Reference Evapotranspiration

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Reference evapotranspiration ($\text{ET}_o$) is estimated from daily weather data using a modified version of the Penman-Monteith equation (Allen et al., 1998; Allen et al., 2005). The equation is:

$$
\text{ET}_o = \frac{0.408 \Delta (R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34 u_2)}
$$

where $\Delta$ is the slope of the saturation vapor pressure as a function of the mean daily air temperature curve (kPa °C$^{-1}$), $R_n$ and $G$ are the net radiation and soil heat flux density in MJ m$^{-2}$d$^{-1}$, $\gamma$ is the psychrometric constant (kPa °C$^{-1}$), $T$ is the daily mean temperature (°C), $u_2$ is the mean wind speed in m s$^{-1}$, $e_s$ is the saturation vapor pressure (kPa) calculated from the mean air temperature (°C) for the day, and $e_a$ is the actual vapor pressure (kPa) calculated from the mean dew point temperature (°C) for the day. The coefficient 0.408 converts the $R_n - G$ term from MJ m$^{-2}$d$^{-1}$ to mm d$^{-1}$ and the coefficient 900 combines together several constants and converts units of the aerodynamic component to mm d$^{-1}$. The product 0.34 $u_2$, in the denominator, is an estimate of the ratio of the 0.12-m tall canopy surface resistance ($r_c=70$ s m$^{-1}$) to the aerodynamic resistance ($r_a=205/u_2^2$ s m$^{-1}$). It is assumed that the temperature, humidity and wind speed are measured between 1.5 and 2.0 m above the grass-covered soil surface. If only temperature data are available, then CUP+ calculates $\text{ET}_o$ using the Hargreaves-Samani equation (Hargreaves and Samani, 1982; Hargreaves and Samani, 1985):

$$
\text{ET}_o = 0.0023 (T_c+17.8) R_a (T_d)^{1/2}
$$

where $T_c$ is the monthly mean temperature (degrees centigrade), $R_a$ is the extraterrestrial solar radiation expressed in mm/month, and $T_d$ is the difference between the mean minimum and mean maximum temperatures for the month (°C). The calculation of extraterrestrial radiation and other parameters in the Penman-Monteith and Hargreaves-Samani equations are described in Allen et al. (1998) and Allen et al. (2005). If pan data are used in CUP+, then the application automatically estimates daily ET$o$ rates using a fetch value (i.e., upwind distance of grass around the pan). The new method
in the CUP+ estimates ET₀ from Epan data without the need for wind speed and relative humidity data.

**Crop Coefficients and Evapotranspiration**

**Field and Row Crops**

Field and row crop Kₑ values are calculated using a method similar to that described by Doorenbos and Pruitt (1977) and Allen et al. (1998). A generalized curve is shown in Fig. 1. In their method, the season is separated into initial (date A-B), rapid (date B-C), midseason (date C-D), and late season (date D-E) growth periods. Kₑ values are denoted KₑA, KₑB, KₑC, KₑD and KₑE at the ends of the A, B, C, D, and E growth dates, respectively. During initial growth, the Kₑ values are at a constant value, so KₑA = KₑB. During the rapid growth period, when the canopy increases from about 10% to 75% ground cover, the Kₑ value increases linearly from KₑB to KₑC. The Kₑ values are also at a constant value during midseason, so KₑC = KₑD. During late-season, the Kₑ values decrease linearly from KₑD to KₑE at the end of the season.
Figure 1. Hypothetical crop coefficient curve for field and row crops using percentage of the season to delineate growth dates. The dashed line is for fresh market crops with no late-season Kc drop (i.e., there is no date D).

Doorenbos and Pruitt (1977) provide estimated number of days for each of the four growth periods to help identify the end dates of growth periods. Because there are climate and varietal differences, however, and because it is difficult for growers to know when the inflection points occur, irrigators often find this confusing. To simplify this problem, percentages of the season from planting to each inflection point rather than days in growth periods are used (Fig. 2). Irrigation planners need only enter the planting and end dates and the intermediate dates are determined from the percentages, which are easily stored in a computer program.
Figure 2. Hypothetical crop coefficient curve for deciduous tree and vine crops using percentage of the season to delineate growth dates. There is no initial growth period, so the season starts at leaf out on date B.

During initial growth of field and row crops, the default $K_c$ value ($K_c1$) is used for $K_cA$ and $K_cB$ unless it is overridden by entering a $K_c$ based on rainfall or irrigation frequency. If a soil wetting based $K_c1$ is desired, the irrigation or rainfall frequency is entered in the ‘Input_Output’ worksheet. The values for $K_cC = K_cD$ depend on the difference in (1) light interception, (2) crop morphology effects on turbulence, and (3) physiological differences between the crop and reference crop. Some field crops are harvested before senescence, and there is no late season drop in $K_c$ (for example, silage corn and fresh market tomatoes). Relatively constant annual $K_c$ values are possible for some crops (for example, turfgrass and pasture) with little loss in accuracy.

Some field crops and landscape plants (type-2 crops) have fixed $K_c$ values all year. However, if the significant rainfall frequency is sufficient to have a higher $K_c$ for bare soil than for the selected crop, then the higher bare soil $K_c$ should be used. CUP permits entry of monthly mean rainfall frequency data. If entered, daily $K_c$ values for bare soil evaporation are computed for the entire year. The higher of the fixed crop $K_c$ or the bare soil $K_c$ is used to estimate $ET_c$ for the crop. If no rainfall frequency data are entered, then the fixed crop $K_c$ is used.

**Tree and Vine Crop $K_c$ Values**
Deciduous Crops
Deciduous tree and vine crops, without a cover crop, have \( K_c \) curves that are similar to field and row crops but without the initial growth period (Fig. 3). Default \( K_cB, K_cC = K_cD = K_c2 \) and \( K_cE = K_c3 \) values are given in the Crop References worksheet of the CUP+. The season begins with rapid growth at leaf out when the \( K_c \) increases from \( K_cB \) to \( K_cC \). The midseason period begins at approximately 70% ground cover. Then, unless the crop is immature, the \( K_c \) is fixed between dates C and D, which corresponds to the onset of senescence. For immature crops, the canopy cover may be less than 70% during the midseason period. If so, the \( K_c \) will increase from \( K_cC \) up to the \( K_cD \) as the canopy cover increases, so the CUP+ program accounts for \( K_c \) changes of immature tree and vine crops. During late season, the \( K_c \) decreases from \( K_cD \) to \( K_cE \), which occurs when the transpiration is near zero.

Initially, the \( K_c \) value for deciduous trees and vines (\( K_cB \)) is selected from a table of default values. However, the ET is mainly soil evaporation at leaf out, so CUP+ contains the methodology to determine a corrected \( K_cB \) based on the bare soil evaporation.

Immature deciduous tree and vine crops use less water than mature crops. The following equation is used to adjust the mature \( K_c \) values (\( K_{cm} \)) as a function of percentage ground cover (\( C_g \)).

\[
\text{If } \sin \left( \frac{C_g \pi}{70} \frac{\pi}{2} \right) \geq 1.0 \quad \text{then } K_c = K_{cm} \quad \text{else } \quad K_c = K_{cm} \left[ \sin \left( \frac{C_g \pi}{70} \frac{\pi}{2} \right) \right] \quad (3)
\]

Subtropical Crops
For mature subtropical orchards (for example, citrus), using a fixed \( K_c \) during the season provides acceptable ET\(_c\) estimates. If higher, however, the bare soil \( K_c \) is used for the orchard \( K_c \). For an immature orchard, the mature \( K_c \) values (\( K_{em} \)) are adjusted for their percentage ground cover (\( C_g \)) using the following criteria.

\[
\text{If } \sqrt{\sin \left( \frac{C_g \pi}{70} \frac{\pi}{2} \right)} \geq 1.0 \quad \text{then } K_c = K_{em} \quad \text{or else } \quad K_c = K_{em} \sqrt{\sin \left( \frac{C_g \pi}{70} \frac{\pi}{2} \right)} \quad (4)
\]
Cover Crop Corrections
With a cover crop, the $K_c$ values for orchards and vines are higher. When a cover crop is present, 0.35 is added to the clean-cultivated $K_c$. However, the $K_c$ is not allowed to exceed 1.20 or to fall below 0.90. CUP+ allows the beginning and end dates to be entered for two periods when a cover crop is present in an orchard or vineyard.

Estimating Bare Soil $K_c$ Values
A soil evaporation $K_c$ value, based on $ET_o$ and rainfall frequency is needed as a minimum (base line) for estimating $ET_c$. It is also useful to determine the $K_c$ value during initial growth of field and row crops ($K_{c1} = K_cA = K_cB$), based on irrigation frequency, and the starting $K_c$ for deciduous tree and vine crops ($K_{c1} = K_cB$). The $K_c$ values used to estimate bare soil evaporation are based on a two-stage soil evaporation method reported by Stroosnjider (1987) and refined by Snyder et al. (2000). The method provides a $K_c$ values as a function of $ET_o$ rate and wetting frequency that are similar to those published in Doorenbos and Pruitt (1977). Figure 3 shows a bare soil $K_c$ curve as a function of the square root of the cumulative reference evapotranspiration ($CET_o$).
The number of days per month of significant rainfall is input into CUP+, and the program computes an estimate of the days between significant rainfall events assuming that the rainfall events are evenly distributed throughout the month. Daily precipitation is considered significant when $P_S > 2 \times E_T$. A smooth curve fit of the monthly values of days between rainfall is computed. CUP+ also computes the monthly mean of daily $E_T$ rate and an annual smooth curve fit of daily $E_T$ values. It uses the daily days between rainfall ($D_{br}$) and daily estimate of $E_T$ to calculate a corresponding

$$\left(CET_{o}\right)^{0.5} = \sqrt{DBR \times ET_{o}}$$  \hspace{1cm} (5)$$

for each day. The equation
\[ K_c = \frac{2.54}{\sqrt{CET_o}} \]  

(6)

is used to estimate the bare soil Kc on each day. During the off-season, the bare-soil Kc value is used to estimate the ETc. During the season, the bigger of the bare-soil Kc or the Kc based on the crop Kc values is used to calculate the crop evapotranspiration as

\[ ET_c = ET_o \times K_c \]  

(7).

Figure 4 presents an example where the bare-soil Kc (dark line) was higher than the crop Kc (colored line) during part of the season. The colored line in Figure 4 shows a Kc curve for a crop that had frequent irrigation between planting that increased the Kc value during initial growth. In all cases, the higher of the bare-soil and crop Kc is used to determine the ETc on each day. Figure 4 shows that the Kc values for the tomatoes have been adjusted for wetting frequency from irrigation and rainfall during that period.

Figure 4. Daily calculated bare soil and crop coefficient values with different colored lines for each growth period for currently entered daily weather and crop/soil information during the growing season and off-season.
Evapotranspiration of Applied Water (ETaw)

ETaw is the sum of the net irrigation applications to a crop during its growing season, where each net irrigation application (NA) is equal to the product of the gross application (GA) and an application efficiency fraction (AE), i.e., NA = GA × AE. The gross application is equivalent to the applied water, and the application efficiency is the fraction of GA that contributes to crop evapotranspiration (ETc). Three possible methods to determine ETaw are explained below using the example of a tomato crop grown in in the Sacramento – San Joaquin River Delta. The ETo, ETc, and Kc values for two sample years are shown in Figure 5.

Figure 5. Crop (ETc) and reference (ETo) evapotranspiration and crop coefficient factors for a tomato crop grown in the Sacramento-San Joaquin Rivers Delta.

For all surfaces except open water and riparian vegetation, daily water balance calculations start with the soil water content on the previous day (SWC0). Then the water losses to ETc are subtracted to determine the soil water content on the current day as SWC1=SWC0 – ETc. This is the soil water depletion adjusted for ETc. Next, any effective
seepage ($E_{spg}$) contribution to the water balance is computed by comparing the seepage ($S_{pg}$) with $SWC_1$. If $S_{pg} < SWC_1$, then $E_{spg} = S_{pg}$, otherwise, $E_{spg} = SWC_1$. Then the soil water content based on $ET_c$ and effective seepage is calculated as $SWC_2 = SWC_1 + E_{spg}$. Then the soil water content is adjusted for effective rainfall by comparing the precipitation ($P$) with $SWC_2$. If $P < SWC_2$, then the effective rainfall is calculated as $E_r = P$. Otherwise, $E_r = SWC_2$. Then the soil water content based on $ET_c$, effective seepage, and effective rainfall is calculated as $SWC_3 = SWC_2 + E_r$. Therefore, the final estimate of soil water content without considering irrigation is given in terms of the daily change in soil water content ($D_{sw}$) as

\[
SWC_3 = SWC_o - D_{sw} = SWC_o - (ET_c - E_{spg} - E_r)
\] (8)

Irrigation is applied whenever the soil water content on a given day would fall below the management allowable depletion (MAD) set for that date. The net application (NA) amount is the depth of water needed to raise the soil water content ($SWC_3$) back to field capacity (FC) on the irrigation date. On each irrigation date, the NA is equal to $SWC_3$, so the actual soil water content on each day of the season is calculated as

\[
SWC = SWC_o - D_{sw} + NA
\] (9),

where $SWC_o$ is the soil water content on the previous day, NA is the net application, which is zero on non-irrigation days, and $D_{sw}$ is the daily change in soil water content expressed as

\[
D_{sw} = ET_c - E_{spg} - E_r
\] (10).

By definition, $ET_{aw}$ is the amount of applied irrigation water that contributes to $ET_c$; therefore, $ET_{aw}$ is the sum of the net irrigation applications during a cropping season. The $ET_{aw}$ for n irrigation events is therefore calculated as
\[ ET_{aw} = N A_1 + N A_2 + \cdots + N A_n \]  

(11).

Alternatively, \( ET_{aw} \) can be calculated as the seasonal total evapotranspiration (\( CET_c \)) minus the cumulative effective seepage contribution (\( CE_{spg} \)) minus the cumulative effective rainfall contribution (\( CE_r \)) minus the difference in soil water content (\( \Delta WC \)) from the beginning to the end of the season (Figure 6). The cumulative \( D_{sw} \) curve (\( CD_{sw} \)) is, by definition, equal to

\[ CD_{sw} = CET_c - CE_{spg} - CE_r \]  

(12).

Therefore, the \( ET_{aw} \) can also be expressed as

\[ ET_{aw} = CD_{sw} - \Delta WC \]  

(13).

Figure 6 illustrates how one can determine \( ET_{aw} \) from \( CET_c, CE_{spg}, CE_r, CD_{sw}, \) and \( \Delta SW \). The \( \Delta SW \) is unknown until the end of the season, however, so it cannot be computed until the end of a cropping season using this method. The \( ET_{aw} \) can be computed from the net applications after the last NA is applied. This is the method used to determine the \( ET_{aw} \) in CUP+.

The other method to estimate \( ET_{aw} \) uses the cumulative daily change in soil water content and the difference between the initial and final soil water content (\( \Delta SW \)) as

\[ ET_{aw} = CD_{sw} - \Delta WC = (CET_c - CE_{spg} - CE_r) - \Delta WC = \sum_{i=1}^{n} N A_i \]  

(14).

Thus, \( ET_{aw} \) can be determined by (1) computing the season accumulation of daily changes in soil water content and subtracting \( \Delta WC \), (2) calculating the seasonal cumulative \( ET_c \) and subtracting the cumulative \( E_s \) and \( E_r \) and the \( \Delta WC \), or (3) summing the net irrigation applications that occur during the season (Figure 6).
Figure 6. A plot of $CET_c$, $CE_{spg}$, $CE_r$, and $CD_{sw}$ versus time for a tomato crop from the Sacramento – San Joaquin Rivers Delta.

$ET_{aw}$ can be calculated as the daily evapotranspiration ($DETC$) minus the estimated daily effective seepage contribution ($DEspg$) minus the daily estimated effective rainfall contribution ($DEr$) minus the difference in soil water content ($DWC$) from the beginning to the end of the season. The figure below shows the comparison of the cumulative daily $ET_{aw}$ values with the cumulative net application (Cum. NA) for tomatoes over the period of one year.
The CUP+ program also plots daily calculated water balance for crops using daily weather data. The plot shows fluctuations in soil water content between field capacity and the maximum depletion during the off-season and between field capacity and maximum soil water content during the growing season. The plot also shows the daily values for crop evapotranspiration ($ET_c$) and rainfall. Irrigation events are given when the maximum soil water depletion exceeds the maximum soil water content (Figure 8).
Figure 8. Fluctuations in soil water content (SWC) between field capacity (FC) and maximum soil water content (SWCx) over the period of one year.

**Literature Cited**


