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 (ET_o), crop coefficient (K_c) values, crop evapotranspiration (ET_c), and evapotranspiration of applied water (ET_{aw}), 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 (ET_o) 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 ET_o. It also uses daily rainfall data to estimate bare soil evaporation as a function of mean of ET_o 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 ET_o 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 (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:

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

where Δ is the slope of the saturation vapor pressure as a function of the mean daily air temperature curve (kPa $^oC^{-1}$), R_n and G are the net radiation and soil heat flux density in MJ $m^{-2}d^{-1}$, γ is the psychrometric constant (kPa $^oC^{-1}$), T is the daily mean temperature (^oC), 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 (^oC) for the day, and e_a is the actual vapor pressure (kPa) calculated from the mean dew point temperature (^oC) 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 coverts 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 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 ET_o using the Hargreaves-Samani equation (Hargreaves and Samani, 1982; Hargreaves and Samani, 1985):

$$ET_o = 0.0023\ (T_c + 17.8)\ R_a\ (T_d)^{1/2} \quad (2)$$

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 (^oC). 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 ETo rates using a fetch value (i.e., upwind distance of grass around the pan). The new method

in the CUP+ estimates ET_o 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 K_c 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. K_c values are denoted K_cA, K_cB, K_cC, K_cD and K_cE at the ends of the A, B, C, D, and E growth dates, respectively. During initial growth, the K_c values are at a constant value, so $K_cA = K_cB$. During the rapid growth period, when the canopy increases from about 10% to 75% ground cover, the K_c value increases linearly from K_cB to K_cC. The K_c values are also at a constant value during midseason, so $K_cC = K_cD$. During late-season, the K_c values decrease linearly from K_cD to K_cE at the end of the season.

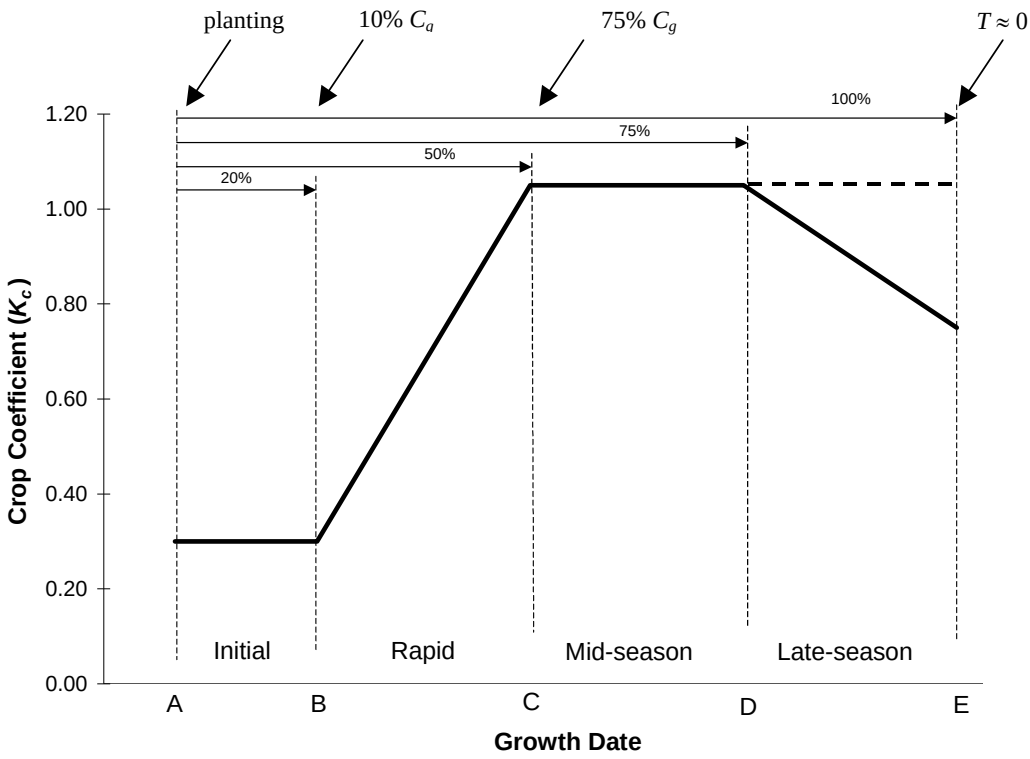

Figure 1. Hypothetical crop coefficient curve for field and row crops using percentage of the season to delineate growth dates. The dashed line is for fresh market crops with no late-season Kc drop (i.e., there is no date D).

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.

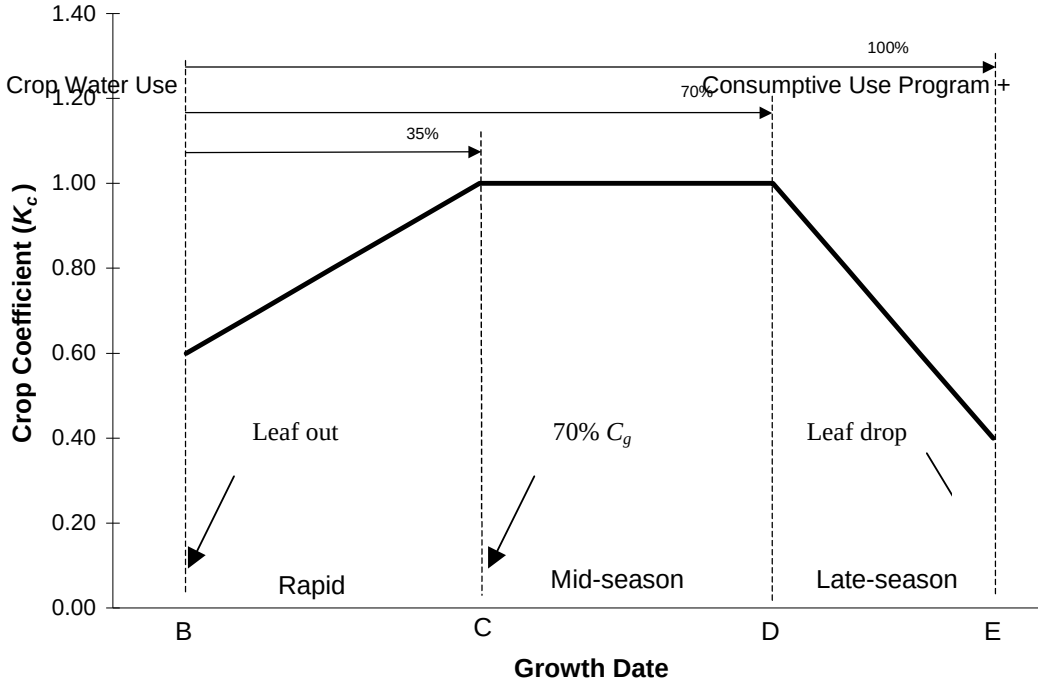

Figure 2. Hypothetical crop coefficient curve for deciduous tree and vine crops using percentage of the season to delineate growth dates. There is no initial growth period, so the season starts at leaf out on date B.

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 Kc values all year. However, if the significant rainfall frequency is sufficient to have a higher Kc 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 Kc 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).

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

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_{cm}) are adjusted for their percentage ground cover (C_g) using the following criteria.

$$\text{If } \sqrt{\sin\left(\frac{C_g}{70}\frac{\pi}{2}\right)} \geq 1.0 \text{ then } K_c = K_{cm} \text{ or else } K_c = K_{cm}\sqrt{\sin\left(\frac{C_g}{70}\frac{\pi}{2}\right)} \quad (4)$$

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).

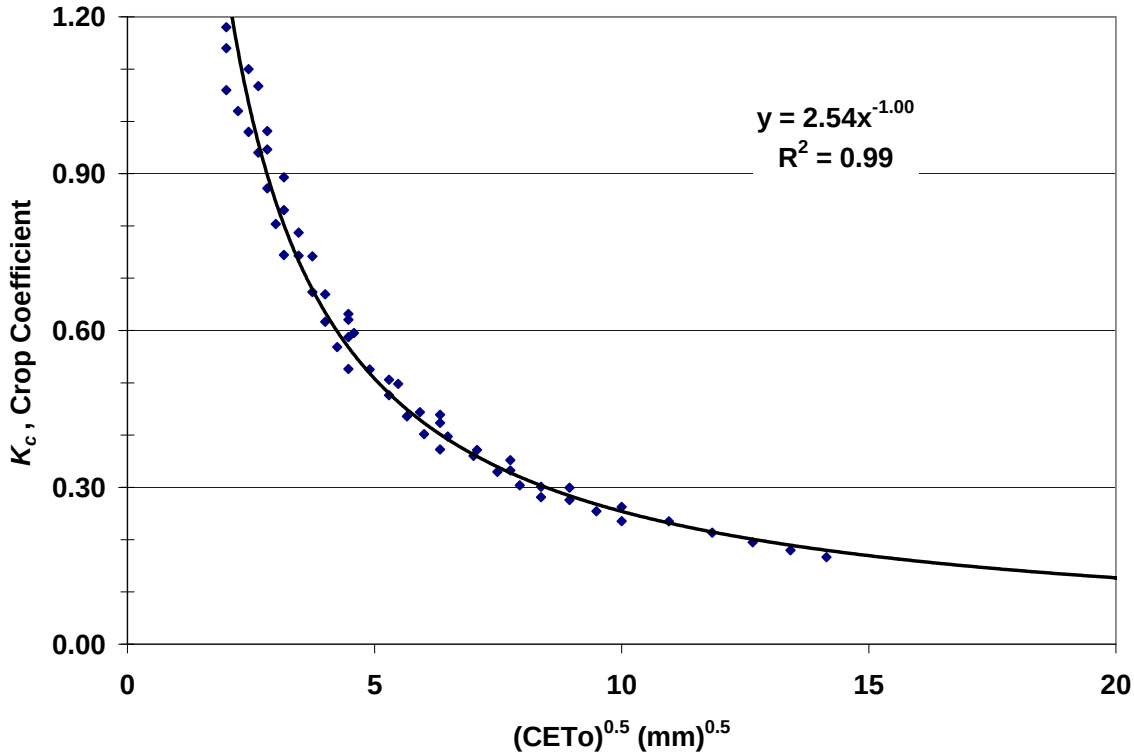

Figure 3. Bare soil crop coeffient curve as a function of the square root of cumulative ET_o (CET_o).

The number of days per month of signiificant 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 through out the month. Daily precipitation is considered significant when $Ps > 2 \times ET_o$. A smooth curve fit of the monthly values of days between rainfall is computed. CUP+ also computes the monthly mean of daily ETo rate and an annual smooth curve fit of daily ETo values. It uses the daily days between rainfall (D_{br}) and daily estimate of ET_o to calculate a corresponding

$$\left(CET_o\right)^{0.5} = \sqrt{DBR \times ET_o} \qquad (5)$$

for each day. The equation

$$K_c = \frac{2.54}{\sqrt{CET_o}} \qquad (6)$$

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 K_c or the K_c based on the crop K_c values is used to calculate the crop evapotranspiration as

$$ET_c = ET_o \times K_c \qquad (7).$$

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

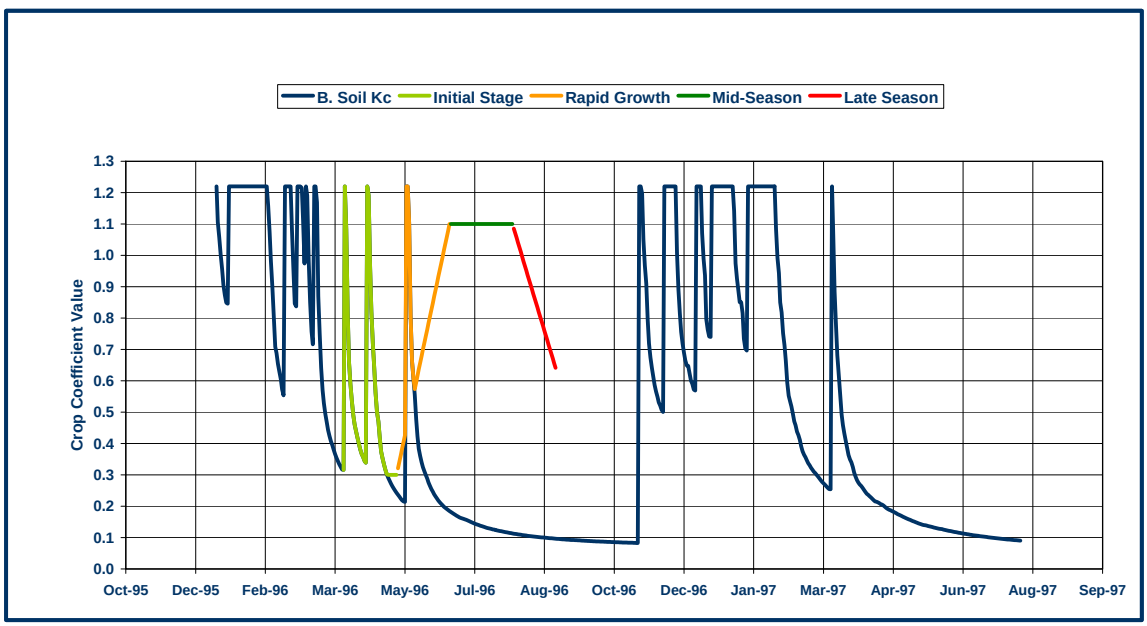

Figure 4. Daily calculated bare soil and crop coefficient values with different colored lines for each growth period for currently entered daily weather and crop/soil information during the growing season and off-season.

Evapotranspiration of Applied Water (ETaw)

ET_{aw} 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 (ET_c). Three possible methods to determine ET_{aw} are explained below using the example of a tomato crop grown in in the Sacramento – San Joaquin River Delta. The ET_o, ET_c, and K_c values for two sample years are shown in Figure 5.

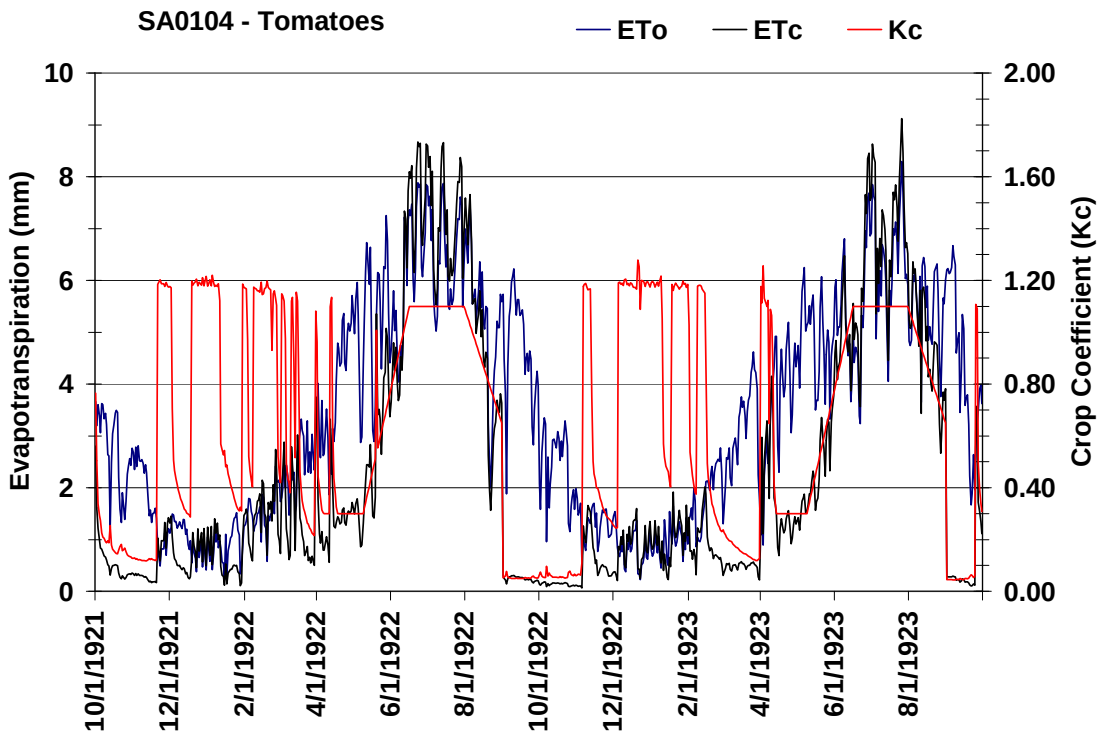

Figure 5. Crop (ET_c) and reference (ET_o) evapotranspiration and crop coefficient factors for a tomato crop grown in the Sacramento-San Joaquin Rivers Delta.

For all surfaces except open water and riparian vegetation, daily water balance calculations start with the soil water content on the previous day (SWC_o). Then the water losses to ET_c are subtracted to determine the soil water content on the current day as $SWC_1=SWC_o – ET_c$. This is the soil water depletion adjusted for ET_c. 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 $SWC_2 = SWC_1 + Espg$. 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

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

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

$$SWC = SWC_o - D_{sw} + NA \qquad (9),$$

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

$$D_{sw} = ET_c - E_{spg} - E_r \qquad (10).$$

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

$$ET_{aw} = NA_1 + NA_2 + \cdots + NA_n \quad (11).$$

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 (ΔWC) from the beginning to the end of the season (Figure 6). The cumulative D_{sw} curve (CD_{sw}) is, by definition, equal to

$$CD_{sw} = CET_c - CE_{spg} - CE_r \quad (12).$$

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

$$ET_{aw} = CD_{sw} - \Delta WC \quad (13).$$

Figure 6 illustrates how one can determine ET_{aw} from CET_c, CE_{spg}, CE_r, CD_{sw}, and ΔSW. The ΔSW 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 (ΔSW) as

$$ET_{aw} = CD_{sw} - \Delta WC = \left(CET_c - CE_{spg} - CE_r\right) - \Delta WC = \sum_{i=1}^{n} NA_i \quad (14).$$

Thus, ET_{aw} can be determined by (1) computing the season accumulation of daily changes in soil water content and subtracting ΔWC, (2) calculating the seasonal cumulative ET_c and subtracting the cumulative E_s and E_r and the ΔWC, or (3) summing the net irrigation applications that occur during the season (Figure 6).

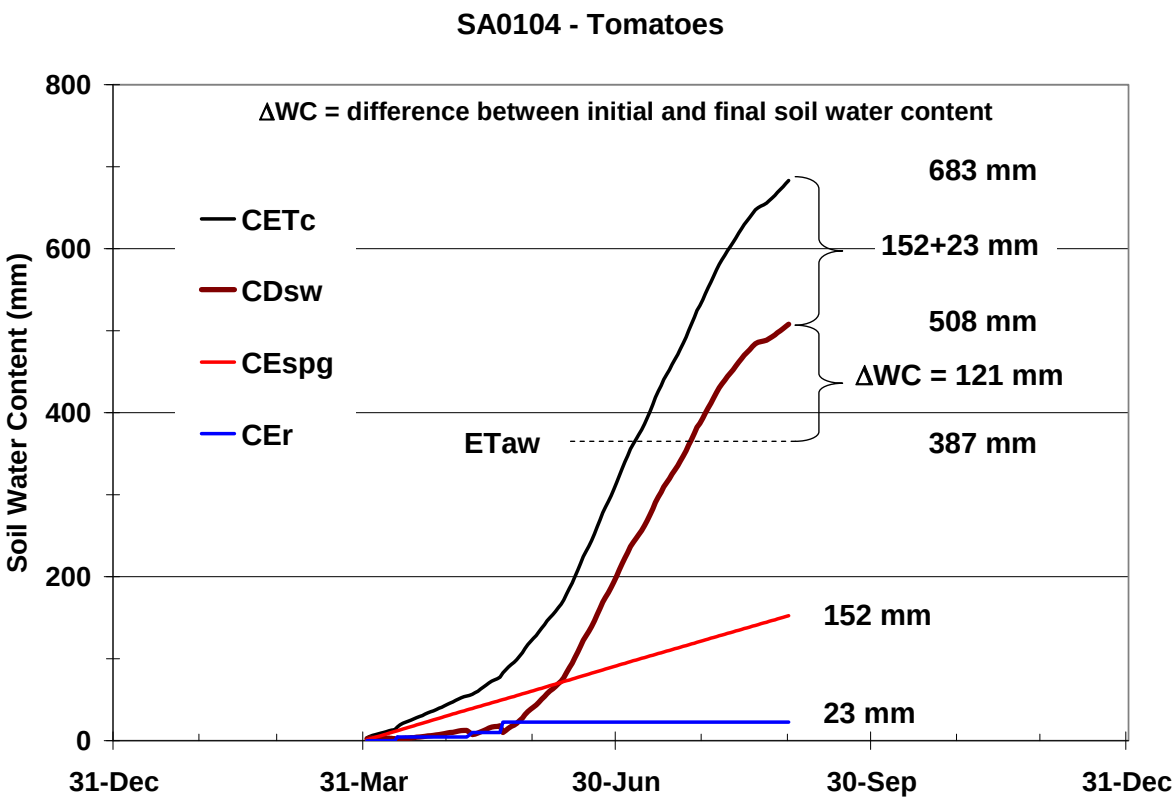

Figure 6. A plot of CET_c, CE_{spg}, CE_r, and CD_{sw} versus time for a tomato crop from the Sacramento – San Joaquin Rivers Delta.

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 ETaw values with the cumulative net application (Cum. NA) for tomatoes over the period of one year.

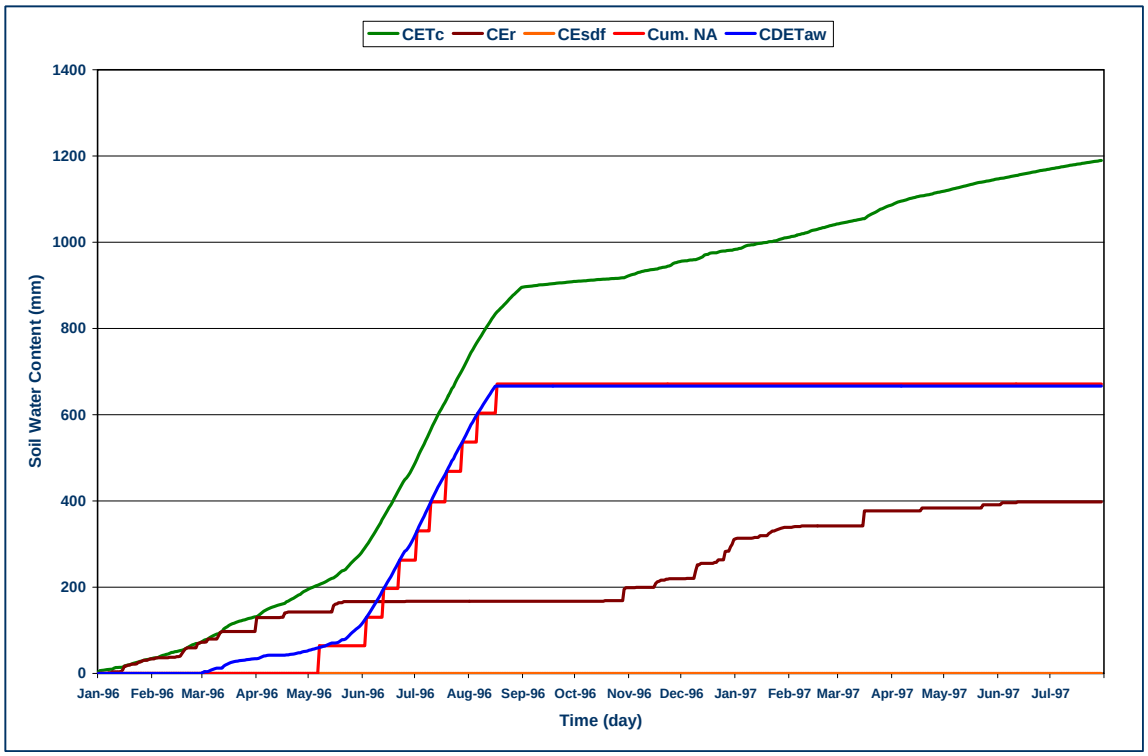

Figure 7. A plot of CETc, CEsdf, CEr, CDsw, Cum. NA, and CETaw Vs time using data from Jan. 1 to Jul. 31 of the following year

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).

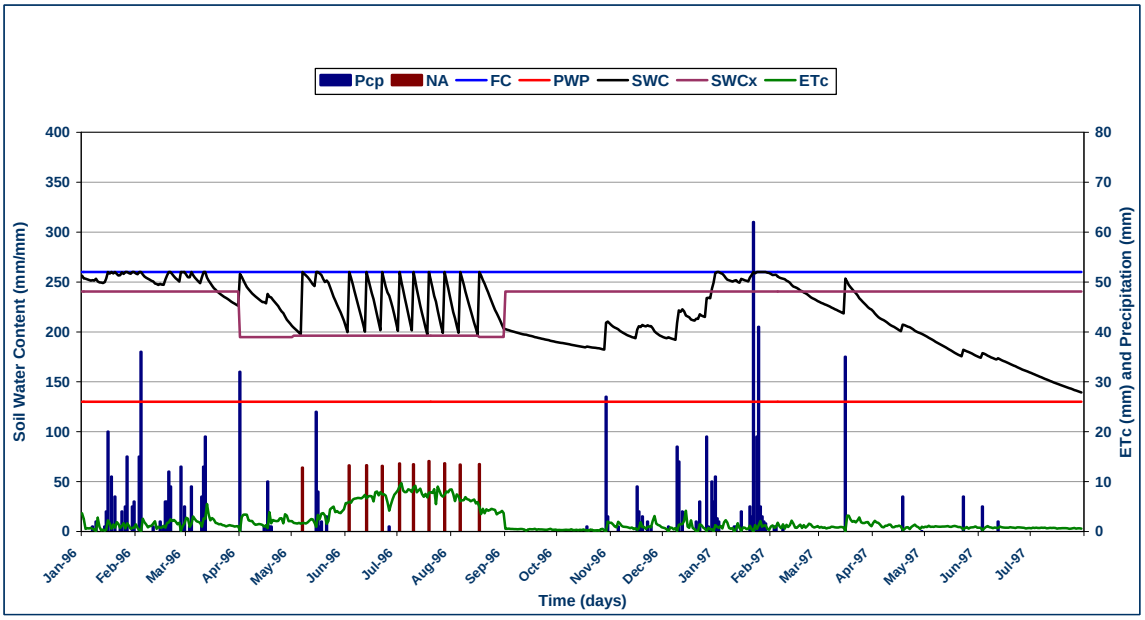

Figure 8. Fluctuations in soil water content (SWC) between field capacity (FC) and maximum soil water content (SWCx) over the period of one year.

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