CUP (Consumptive Use Program) Model

By Morteza Orang, Richard Snyder, and Scott Matyac, DWR and UC Davis

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The California Department of Water Resources (DWR) and the University of California (UC) have developed a user-friendly Excel application program (CUP) to improve the dissemination of K_c and crop evapotranspiration (ET_c) information to California growers and water purveyors. CUP computes reference evapotranspiration (ET_o) from monthly means of solar radiation, maximum and minimum temperature, dew point temperature, and wind speed using the daily Penman-Monteith equation. The program uses a curve fitting technique to derive one year of daily weather and ET_o data from the monthly data. In addition, daily rainfall data are used 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 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, and by year.

Methodology

Reference Evapotranspiration (ET_o) Calculation

Reference evapotranspiration (ET_o) is estimated from daily weather data using a modified version of the Penman-Monteith equation (Walter and others 2000). The equation is:

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

where Δ is the slope of the saturation vapor pressure at mean 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

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between 1.5 m (5 ft) and 2.0 m (6.6 ft) above the grass-covered soil surface. If only temperature data are available, the Hargreaves-Samani equation is used. The equation may be written:

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

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).

If pan data are input into the program, then the program automatically converts monthly pan evaporation data to ET_o estimates using the latest methodology. The new method in the CUP estimates ET_o from Epan data using a fetch value (that is, upwind distance of grass around the pan) without the need for wind speed and relative humidity data.

Validation and Comparison of CUP with Other Methods

Nine years of estimated daily ET_o data from CIMIS (California Irrigation Management Information System) at Davis, Calif., were used to validate our model predictions of ET_o. Figure 1 compares daily mean ET_o estimates of CUP and CIMIS averaged over the period of the data set at Davis, Calif.. The performance of the CUP was further evaluated at a humid location (Port Hueneme) and windy desert site (Bishop). Simulation of Evapotranspiration of Applied Water (SIMETAW) data are included. As seen in figures 1, 2, and 3, a close agreement between CIMIS-based estimates of ET_o and those of the CUP model exists. Davis is in the Central Valley, which is characterized by clear, hot, dry days with strong, cooling southwest winds during afternoons in the summer. Port Hueneme is in Ventura County with coastal cool, humid weather patterns. Bishop is influenced by a windy desert environment on the eastern side of the Sierra Nevada range.

Figure 1
Comparison of Daily ETo Estimates from CUP, SIMETAW, and CIMIS at Davis, Calif.

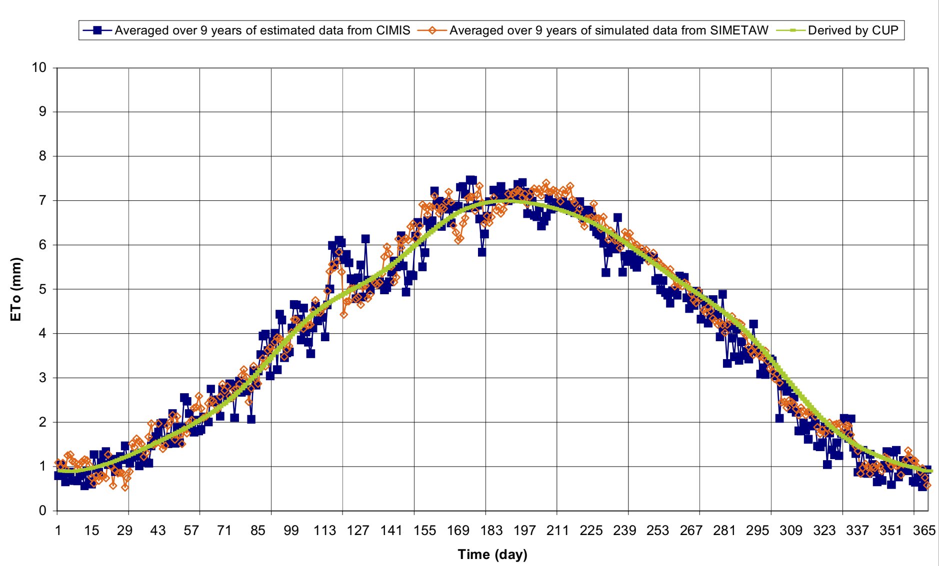

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Figure 2
Comparison of Estimated and Simulated Reference Evapotranspiration Data at Oceanside, California

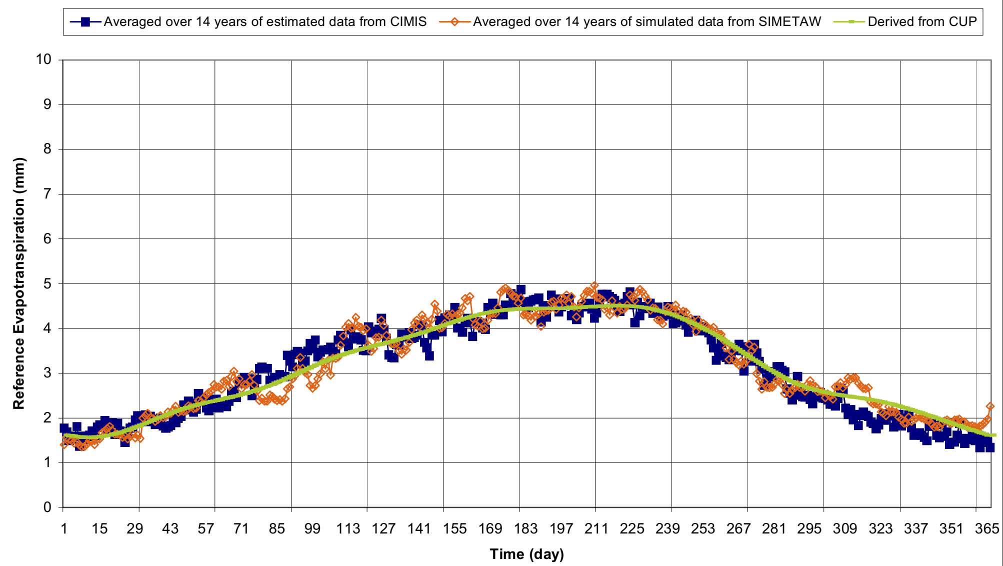
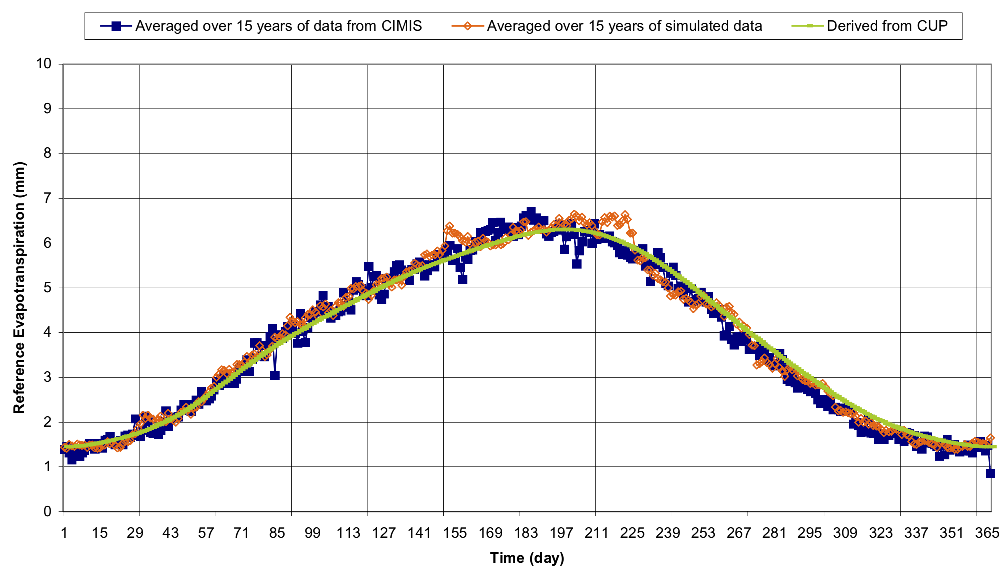


Figure 3
Comparison of Daily ETo Estimates from CUP, SIMETAW, and CIMIS at Bishop, Calif.



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Daily Weather Output Accuracy

One of objectives of the CUP model is to use a curve fitting technique to produce one year of daily weather data from 12 monthly mean values. Monthly mean values of measured weather data averaged over the period of the data set (1990–1998) from CIMIS in Davis were used in the model to derive one year of daily weather data. The weather data consist of R_s, T_{max}, T_{min}, wind speed, T_{dew}, and rainfall. The weather data derived by CUP were compared with the measured and simulated data from CIMIS and SIMETAW, respectively. Results in figures 4, 5, and 6 showed that R_s, T_{max}, and rainfall values predicted from CUP were well correlated with those values obtained from CIMIS and SIMETAW. The performance of the CUP was further evaluated at a humid location and windy desert site. In all locations, CUP correlated very well with CIMIS and SIMETAW. Similar results were also observed for T_{min}, wind speed, and T_{dew} data in other locations.

Figure 4
Comparison of Measured and Predicted Daily Solar Radiation Data at Davis, Calif.

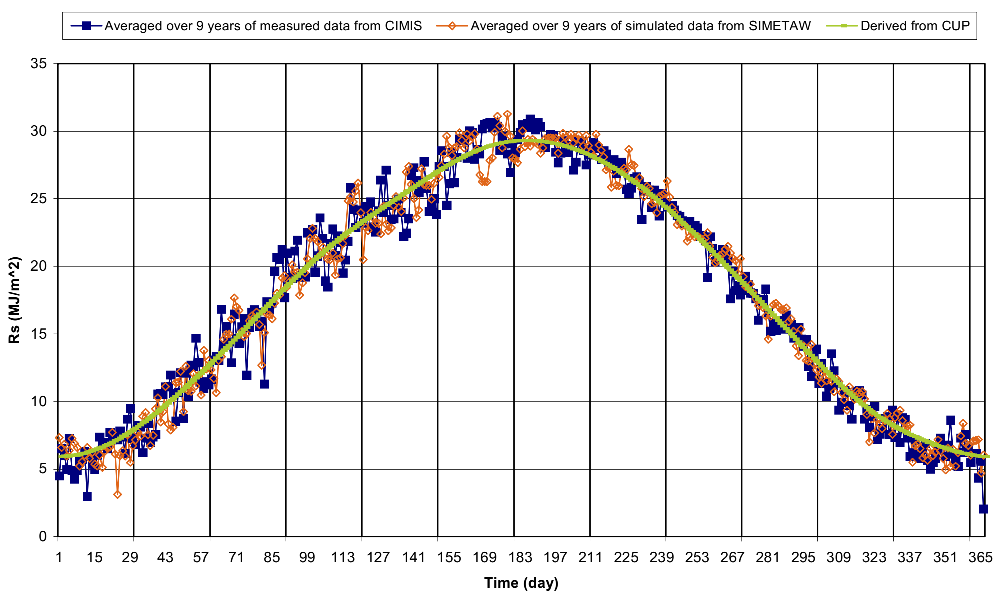


Figure 5
Comparison of Measured and Predicted Daily Air Maximum Temperature Data at Davis, Calif.

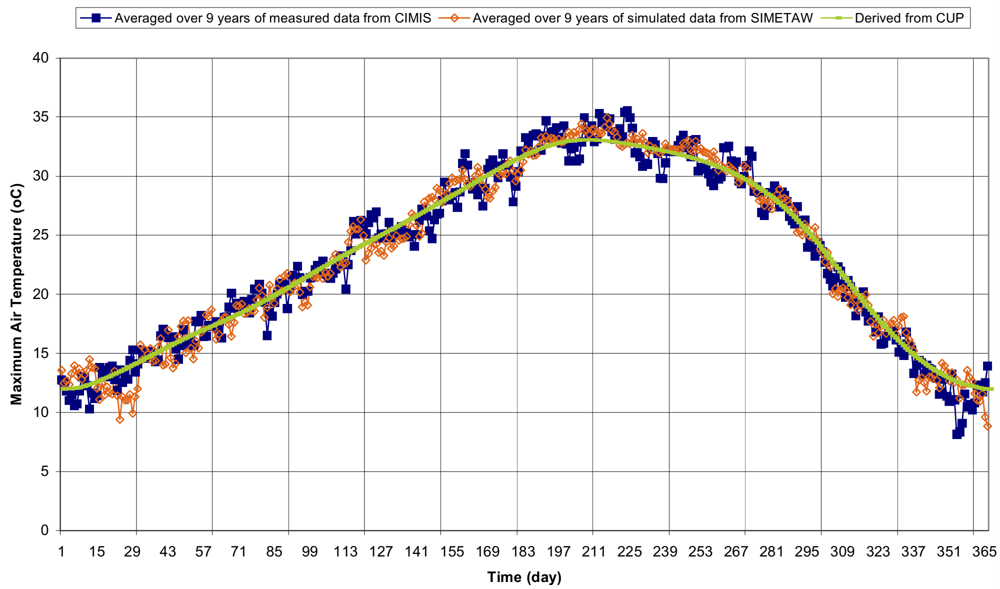
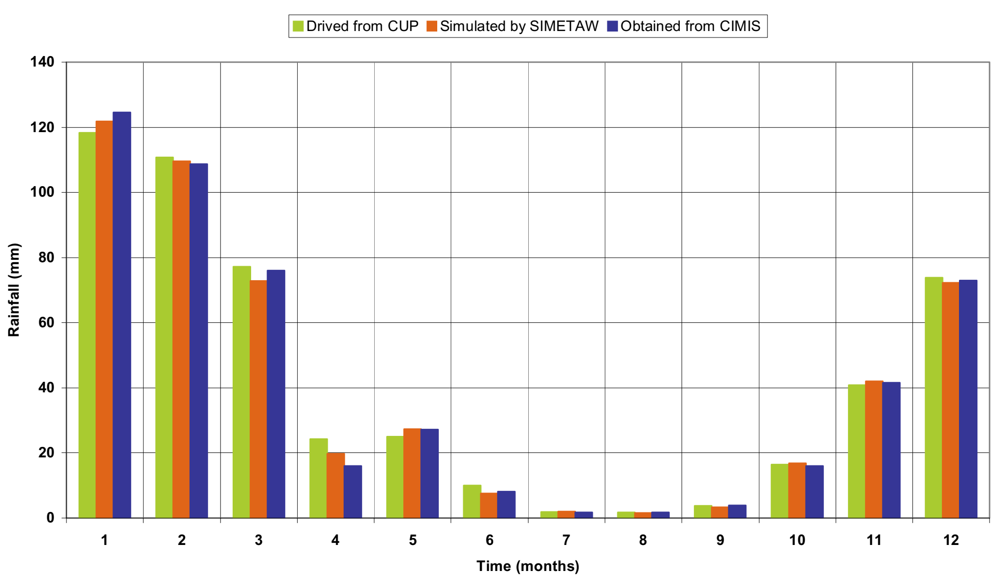


Figure 6
Comparison of Monthly Total Rainfall Values from Three Different Methods at Davis, Calif.



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Worksheets

CUP has 19 Excel worksheets. The first eight worksheets are 'Disclaimer,' 'HelpAbout,' 'About Cup,' 'HELP,' 'ET_o Zones Map,' 'ET_o Zones,' 'Weather Input,' and 'Input_Output.' 'HelpAbout' provides information about the program. 'About CUP' explains the program. 'HELP' explains the various components of the program and provides step-by-step instructions for inputting data into the program. 'ET_o Zones' contains a map showing 18 zones of similar ET_o rates for California. The 'Weather Input' worksheet is used to input monthly mean weather or E_{pan} data to estimate ET_o (or monthly mean ET_o data directly) for estimating crop evapotranspiration (ET_c). If the solar radiation, temperature, humidity, and wind speed data are input, then the Penman-Montieth equation is used to calculate ET_o. If only temperature data are input into the table, then the Hargreaves-Samani equation is used to calculate ET_o. If pan data are input, the program automatically estimates daily ET_o rates using a fetch value (that is, upwind distance of grass around the pan). ET_o and crop data are entered into the 'Input_Output' worksheet, which then displays the summary of inputs and monthly and seasonal outputs. The 'Crop References' worksheet contains a list of crops, crop numbers, estimated growth date, and K_c information. 'Calculation' worksheet shows all of the growth date and K_c as well as the daily calculations of ET_o, K_c and ET_c for each of the growth periods. 'Weather Output' provides one year of daily solar radiation, maximum and minimum temperature, wind speed, dew point temperature, and rainfall data. CUP also outputs one year of daily calculated crop coefficients, ET_o, and ET_c data by crop in the 'Daily ETc-Output' worksheet. 'Monthly Output' provides monthly total values of ET_o, ET_c, and rainfall during the growing season and off-season.

The 'K_c Chart' worksheet shows a plot of the calculated seasonal crop coefficients with colored lines representing each growth period. 'ET_o Chart' worksheet plots daily ET_o with different colored lines for each growth period. The 'ET_o_ET_c Chart' provides a bar graph of ET_o and ET_c totals by month during the growing season for the current crop information. There are also summary worksheets for K_c values, ET_o and ET_c. After data entry, the current crop information and calculated K_c data in the 'Input_Output' worksheet can be printed to one row in the 'Summary of K_c' worksheet. ET_o data are printed to 'Summary of ETo', and ET_c data are printed to 'Summary of ET_c.'

Input_Output Worksheet

Crop information is entered into cells on the left-hand side of the 'Input_Output' worksheet. To use monthly mean weather, raw ETo and pan data, 88 is input into the California ET_o Zone number. Next a crop number is entered into the Crop Number cell. CUP provides a list of crops and crop numbers in the 'Crop References' worksheet. That worksheet also contains the percentage of the season to various growth dates (explained later), K_c values at critical growth points, and sample start and end dates for the season.

Note that the crop numbers have one digit to the left and two digits to the right of a decimal point. The single digit identifies the crop type, and the double digit identifies the crop. When a crop is selected, the growth, K_c, and default start-end information are automatically used for the calculations. The start date corresponds to planting for field and row crops and to leaf-out date for tree and vine crops. Non-deciduous trees, turfgrass, and pasture crops start on January 1 and end on December 31. If different from the default values, the start and end dates can be changed in the 'Input_Output' worksheet.

The initial K_c value for most crops depends on wetting frequency from rainfall and/or irrigation. As the canopy shading increases, the contribution of soil evaporation to ET_c decreases while the contribution of transpiration increases. In the 'Input_Output' worksheet, the rainfall frequency during early growth is input to determine a K_c for near bare soil evaporation. Similarly, the irrigation frequency is entered and a K_c determined for near bare-soil evaporation during initial growth of field and row crops. CUP compares K_c values from the 'Crop References' worksheet with those based on rainfall and irrigation frequency and selects the largest of the three for use in calculating ET_c. If no rainfall or irrigation frequency is entered, the K_c from the A-B column in the 'Crop References' worksheet is used as the initial growth K_c. The starting K_c for type-2 crops (for example, turfgrass and pasture) and for type-4 crops (for example, subtropical orchards) is not affected by the irrigation or rainfall frequency entries.

Cover crops affect ET_c rates, and CUP accounts for the contributions. The cover crop start and end dates are input into cells under the "Enter 1st Cover Crop (day/mon)." Because some crops have cover crops in spring and fall but not in the summer, a second set of cover crop dates can be input under "Enter 2nd Cover Crop (day/mon)". During a period with a cover crop, the value 0.35 is added to the "clean cultivated" K_c value. However, the K_c is not allowed to exceed 1.15 or to fall below 0.90.

The right-hand side of the 'Input_Output' worksheet shows the weighted mean K_c, ET_o, ET_c, and seasonal ET_c values by month for the selected crop and input information. The daily mean ET_o rates by month are also shown below the other data. Below that set of cells, there are "Copy/Paste" and "Delete" buttons. When the Copy/Paste button is pressed, results of the calculations are sent to 'Summary ET_o,' 'Summary K_c,' and 'Summary ET_c' worksheets. The Delete button clears all entries from the summary worksheets. To retain all of the data entries, save the CUP file as an Excel workbook with a different name. To save only the summary sheets, with the summary sheet displayed, save as a tab or comma delimited file. After saving the desired output data, click the Delete button to erase data from the summary worksheets.

Calculation Worksheet

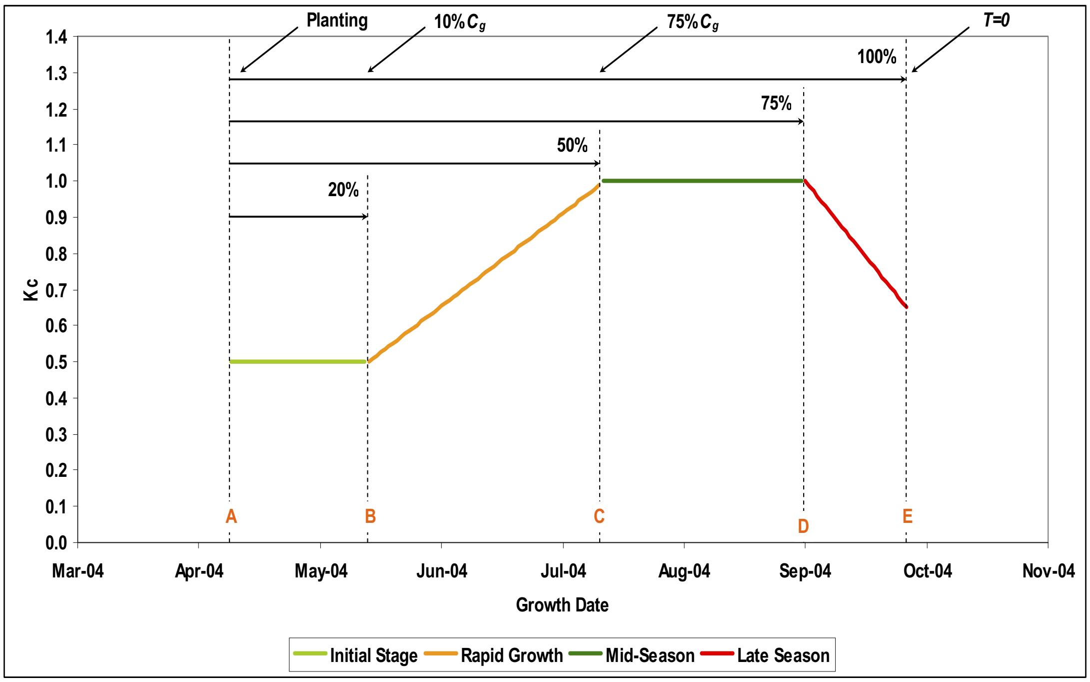
The 'Calculation' worksheet shows the selected and input data as well as critical dates for growth and cover crops and the daily calculations of ET_o, K_c and ET_c by the growth stages. The main factors affecting the difference between ET_c and ET_o are (1) light absorption by the canopy, (2) canopy roughness, which affects turbulence, (3) crop physiology, (4) leaf age, and (5) surface wetness. When not limited by water availability, both transpiration and evaporation are limited by the availability of energy to vaporize water. Therefore, for unstressed crops, solar radiation (or light) interception by the foliage and soil mainly affect the ET_c rate.

As field and row crops grow, the canopy cover, light interception, and the ratio of transpiration (T) to ET increases until most of the ET comes from T and evaporation (E) is a minor component. The K_c increases with canopy cover until reaching about 75 percent cover. For tree and vine crops the peak K_c is reached when the canopy has reached about 70 percent ground cover. The difference between the crop types is that the light interception is higher for the taller crops.

Field and Row Crop K_c Values

Field and row crop K_c values are calculated using a method similar to that described by Doorenbos and Pruitt (1977). A generalized curve is shown in Figure 7. 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 percent to 75 percent 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 7
Hypothetical Crop Coefficient Curve for Field and Row Crops
Using Percentage of Season to Delineate Growth Dates



The dashed line is for fresh market crops with no late-season K_c drop (that is, there is no date D)

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Doorenbos and Pruitt (1977) provides estimated number of days for each of the four growth periods to help identify the end dates of growth periods. However, because there are climate and varietal differences 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 (Figure 7). Irrigation planners need only enter the planting and end dates. The intermediate dates are determined from the percentages, which are easily stored in a computer program.

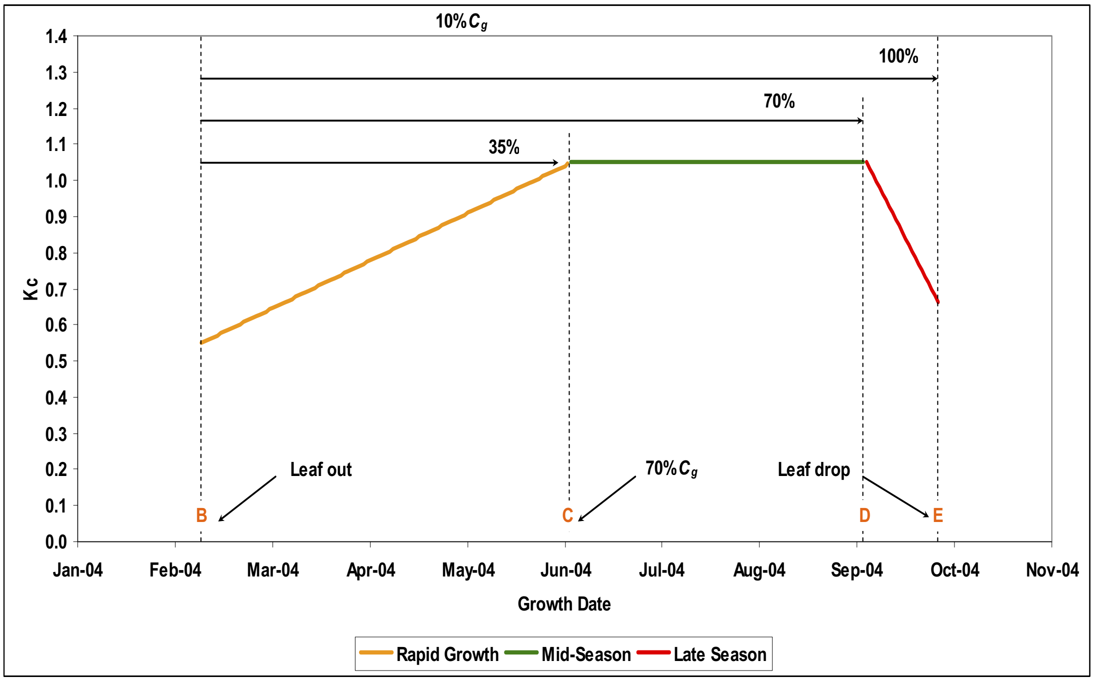
During initial growth of field and row crops, the default K_c value (K_c1) is used for K_cA and K_cB unless it is overridden by entering a K_c based on rainfall or irrigation frequency. If a soil wetting based K_c1 is desired, the irrigation or rainfall frequency is entered in the 'Input_Output' worksheet.

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 Kc values are possible for some crops (for example, turfgrass and pasture) with little loss in accuracy.

Deciduous Tree and Vine Crop K_c Values

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 (Figure 8). 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 percent 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 percent 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.

Figure 8
Hypothetical Crop Coefficient Curve for Deciduous Tree and Vine Crops Using Percentage of Season to Delineate Growth Dates



There is no initial growth period, so the season starts at leaf out on date B

Correcting K_cB for Soil Evaporation

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.

Correcting for Cover Crops

With a cover crop, the K_c values for deciduous trees 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 1.15 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.

Immature Trees and Vines

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).

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

Subtropical Orchards

For mature subtropical orchards (for example, citrus), using a fixed K_c during the season provides acceptable ET_c estimates. However, if higher, 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.

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

Field Crops and Landscape Covers with Fixed K_c Values

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.

Estimating Bare Soil K_c Values

A soil evaporation K_c value, based on ET_o and rainfall frequency is needed as a minimum (baseline) 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 and others (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).

If the mean monthly weather and ET_o data are input into the 'Weather Input' worksheet, including the number of significant rainy days per month, CUP calculates a baseline soil evaporation curve. Daily precipitation is considered significant when $Ps > 2 \times ET_o$. Whenever, the K_c for bare soil evaporation is bigger than the K_c based on table or calculated K_c values, the higher K_c value is used.

Extra Features of CUP

The CUP application program uses MS Excel software as a tool to help water agencies, engineers, consultants, educators, and growers obtain accurate estimates of crop water requirement information from monthly mean data. The program takes input weather data and estimates historical means of reference evapotranspiration (ET_o) using the Penman-Montieth equation. If only temperature data are available, the Hargreaves-Samani equation is used. CUP also converts monthly pan evaporation data to ET_o estimates using the latest methodology. In addition, CUP estimates the annual trend in daily ET_o and weather data. In the past, only monthly, biweekly, or weekly data were available in the literature; daily data from CUP improves the ET_c estimation. Alternatively, CUP can select monthly ET_o values from the California ET_o map, and it can estimate ET_o from class 'A' pan evaporation using the latest conversion methods. The program helps users determine improved crop coefficient (K_c) values for estimating crop evapotranspiration (ET_c). Rather than using only linear estimates of the K_c values for various growth stages, CUP accounts for differences in soil evaporation to refine the early season K_c values. CUP can be used as a tool for teaching and conducting research. In addition, the application outputs a wide range of tables and charts useful for irrigation planning. CUP's input and output data are in both English and metric units.

More information on CUP is available at DWR's Web site:
www.waterplan.water.ca.gov/landwateruse/wateruse/Ag/wuagricultural.htm

References

Doorenbos J., Pruitt WO 1977. Rev. "Crop water requirements." *FAO Irrig. and Drain*. Paper 24, FAO of the United Nations, Rome, p. 144.

Snyder, R.L., Bali, K., Ventura, F, and Gomez-MacPherson, H. 2000. "Estimating evaporation from bare or nearly bare soil," *J. Irrigation and Drainage Division*, American Society of Civil Engineers, 126(6):399-403.

Stroosnijder, L., 1987. "Soil evaporation: test of a practical approach under semi-arid conditions," *Netherlands J. Agri. Sci.*, 35:417-426.

Walter, I.A., R.G. Allen, R. Elliott, M.E. Jensen, D. Itenfisu, B. Mecham, T.A. Howell, R. Snyder, P. Brown, S. Echings, T. Spofford, M. Hattendorf, R.H. Cuenca, J.L. Wright, D. Martin. 2000. *ASCE's Standardized Reference Evapotranspiration Equation.* Proc. of the Watershed Management 2000 Conference, June 2000, Ft. Collins, CO, American Society of Civil Engineers, St. Joseph, MI.