A Simulation Model for Evapotranspiration of Applied Water

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Abstract

The California Department of Water Resources and the University of California recently developed a weather generator application program "SIMETAW" to simulate many years of daily weather data from climatic records and to estimate reference evapotranspiration (ET_o) and crop evapotranspiration with the simulated data. In addition, simulated daily rainfall, soil water holding characteristics, effective rooting depths, and ET_c are used to determine effective rainfall and to generate hypothetical irrigation schedules to estimate the seasonal and annual evapotranspiration of applied water (*ETaw*), where *ETaw* is an estimate of the crop evapotranspiration minus any water supplied by effective rainfall. The actual water requirement is estimated by dividing by the application efficiency. Weather generators allow one to investigate how climate change might affect the water demand in California. In this paper, we will discuss how the simulation model uses monthly input data to generate daily weather data over variable periods of record and how *ETaw* is determined.

Keywords: *Evapotranspiration, Crop Coefficients, Crop Water Requirements, Evapotranspiration of Applied Water, Climate Change.*

1- Introduction

The 'Simulation of Evapotranspiration of Applied Water' program (SIMETAW) was developed to help the State of California to plan for future water demand by agriculture and landscape irrigation. Using Borland Professional C++, the program was written by Sara Sarreshteh based on a design by R. Snyder, M. Orang, S. Geng, and S. Matyac. SIMETAW has a user-friendly design and, while mainly empirical, it accounts for many factors affecting crop coefficients that are generally ignored in other programs. Rainfall, soil water-holding characteristics, effective rooting depths, and ET_c are needed to determine effective rainfall. Combining crop evapotranspiration (ET_c) with effective rainfall estimates provides net water application requirements for various crops. When divided by the weighted mean application efficiency, the result is a site-specific total irrigation requirement to produce a crop. Weather generators allow us to investigate how changes in weather will affect the water demand in the state. This paper will discuss how the simulation model uses monthly input to generate daily weather data over variable periods of record and the advantages of the new model over traditional long-term ET_c estimates.

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2- Entering Crop and Soil Information

Crop and soil information are input into a data file and the data are stored under a filename using the 'Detailed Analysis Unit' or 'DAU', which is used by the State of California as a region for determining ETaw. The input data include the crop name, planting and ending date, initial growth irrigation frequency, pre-irrigation information, immaturity factors, presence of cover crops, soil water holding characteristics, maximum soil and rooting depths, etc. Data are saved as a row of data in the DAUnnn.csv file before going onto the next crop-soil combination entry. Each row of data in the file contains information on crop growth, crop coefficients, irrigation frequency, cover crops, crop maturity, etc.

3- Calculating the Yield Threshold Depletion

Crop rooting depth, soil depth, and water holding characteristics are used to determine the yield threshold depletion (YTD), which is used for determining an irrigation schedule. A user selects one of three general categories for the soil water holding characteristics. If a light soil is selected, the program uses 0.075 inches per inch for the available water holding capacity of the soil. A value of 0.125 inches per inch is used for the water holding capacity of a medium textured soil. For a heavy soil, a value of 0.175 inches per inch is used. The selected value is multiplied by the smaller of the rooting depth or the soil depth to determine the plant available water (PAW) within the soil reservoir at the maximum rooting depth for the crop. Although not strictly correct, the water holding content at field capacity for the soil reservoir is estimated as twice the available water holding content. This is only done to simplify graphing of the results. The YTD for the crop is calculated as the product of the allowable depletion (expressed as a fraction) and the PAW. In reality, the rooting depth and PAW increases as the roots extend, but, because of the additional complexity, this is ignored in the SIMETAW model.

4- Entering Climate Data

Either daily or monthly climate data are used to determine ETaw in SIMETAW. The daily data can come from CIMIS (California Irrigation Management Information System) or from a non-CIMIS data source as long as the data are in the correct format, which is described in the HELP files. After reading the data, ETaw can be calculated directly from the raw daily data. In addition, the monthly means can be calculated from the daily files and then daily data are generated using the simulation program. Since daily data were input directly, the calculation of monthly data for use in simulation of daily data is unnecessary. However, it was included to test if similar results are obtained using raw or simulated data.

The monthly data can be read from a file or calculated from daily CIMIS or non-CIMIS data files, or from some other source. The monthly data file must have the proper, comma-delimited format as described in the HELP files. SIMETAW will generate daily weather data for a specified period of record from the monthly data.

SIMETAW either generates a daily data file from monthly data or uses a raw data file consisting of daily solar radiation, maximum, minimum and dew point temperature, and wind speed for calculating daily ET_o. After calculating ET_o, if the data were generated, the program sorts the rainfall data within each month to force a negative correlation between rainfall amount and ET_o rate. Only the rainfall dates are sorted and there is no change in the dates for the weather and ET_o data. The results are output to a file with the extension 'wrk'. For non-simulated (raw) data, the data are directly saved in the file with the 'wrk' extension without sorting the rainfall dates.

5- Weather Simulation

Weather simulation models are often used in conjunction with other models to evaluate possible crop responses to environmental conditions. One important response is crop evapotranspiration (*ET_c*). Crop evapotranspiration is commonly estimated by multiplying reference evapotranspiration by a crop coefficient. In SIMETAW, daily data are used to estimate reference evapotranspiration. Rainfall data are then used with estimates of ET_c to determine ETaw. One can either use raw or simulated daily data for the calculations.

5.1- Rainfall

Characteristics and patterns of rainfall are highly seasonal and localized, so a making a general, seasonal model that is applicable to all locations is difficult. Recognizing the fact that rainfall patterns are usually skewed to the right toward extreme heavy amount and that the rain status of previous day tends to affect present day's condition, a gamma distribution and Markov chain modeling approach was applied to described rainfall patterns for periods within which rainfall patterns are relatively uniform [1–4]. This approach consists of two models: two-state, first order Markov chain and a gamma distribution function. These models require long-term daily rainfall data to estimate model parameters. SIMETAW however, uses monthly averages of total rainfall amount and number of rain days to obtain all parameters for the Gamma and Markov Chain models.

5.2- Wind Speed

The simulation of wind speed is a simpler procedure, requiring only the gamma distribution function, as described for rainfall. While using a gamma distribution provides good estimates of extreme values of wind speed, there is a tendency to have some unrealistically high wind speed values generated for use in ET_o calculations. Because wind speed depends on atmospheric pressure gradients, no correlation between wind speed and the other weather parameters used to estimate ET_o exists. Therefore, the random matching of high wind speeds with conditions favorable to high evaporation rates leads to unrealistically high ET_o estimates on some days. To eliminate this problem, an upper limit for simulated wind speed was set at twice the mean wind speed. This is believed to be a reasonable upper limit for a weather generator used to estimate ET_o because extreme wind speed values are generally associated with severe storms and ET_o is generally not important during such conditions.

5.3- Temperature, Solar Radiation, and Humidity

Temperature, solar radiation, and humidity data usually follow a Fourier series distribution. Therefore, the model of these variables may be expressed as:

$$X_{ki} = \mu_{ki} (1 + \delta_{ki} C_{ki}) \quad (1)$$

where k = 1, 2 and 3 (k=1 represents maximum temperature; k = 2 represents minimum temperature; and k =3 represents solar radiation). μ_{ki} is the estimated daily mean and C_{ki} is the estimated daily coefficient of variation of the i^{th} day, i = 1, 2, … , 365 and for the k^{th} variable.

SIMETAW simplifies the parameter estimation procedure of Richardson and Wright [4], requiring only monthly means as inputs. From a study of 34 locations within the United States, the coefficient of variability (CV) values appear to be inversely related to the means. The same approach is used to calculate the daily CV values. In addition, a series of functional relationships between the parameters of the mean curves and the parameters of the coefficient of variation curves, which made it possible to calculate C_{ki} coefficients from μ_{ki} curves without additional input data requirement, were developed.

6- Reference Evapotranspiration Calculation

Reference evapotranspiration (ET_o) is estimated from daily weather data using a modified version of the Penman-Monteith equation [5–7]. The equation is:

$$ET_o = \frac{0.408\ \Delta\ (R_n - G) + \gamma \dfrac{900}{T + 273} u_2\ (e_s - e_a)}{\Delta + \gamma\ (1 + 0.34\ u_2)} \qquad (2)$$

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 (^{o}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 (^{o}C) for the day, and e_a is the actual vapor pressure (kPa) calculated from the mean dew point temperature (^{o}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 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 m (5 ft) and 2.0 m (6.6 ft) above the grass-covered soil surface. For a complete explanation of the equation, see Allen and others [5]. If only temperature data are available, then the SIMETAW calculates daily ET_o using the Hargreaves-Samani equation. The equation may be written:

$$ET_o = 0.0023\ (T_c+17.8)\ R_a\ (T_d)^{1/2} \qquad (3)$$

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 (degrees centigrade).

If pan data are used in the program, then the program automatically estimates daily ET_o rates using a fetch value (i.e. upwind distance of grass around the pan). The approach in the SIMETAW provides a simple method to estimate ET_o from *Epan* data without the need for wind speed and relative humidity data.

6.1- Verification of the Simulated Reference Evapotranspiration

We used number of years of estimated daily ET_o data from CIMIS (California Irrigation Management Information System) at Davis, Oceanside, and Bishop to validate our model predictions of ET_o. The performance of our model ET_o predictions was evaluated at sites influenced by coastal and windy desert climates. Figures 1, 2, and 3 compare daily mean ET_o estimates of SIMETAW and CIMIS averaged over the period of records. As seen in figures, a close agreement between CIMIS-based estimates of ET_o and those of the SIMETAW model exists. Bishop is influenced by a windy desert environment on the eastern side of the Sierra

Nevada range. Oceanside is a coastal site in San Diego County. Davis is in the Central Valley influenced by the Delta weather pattern.

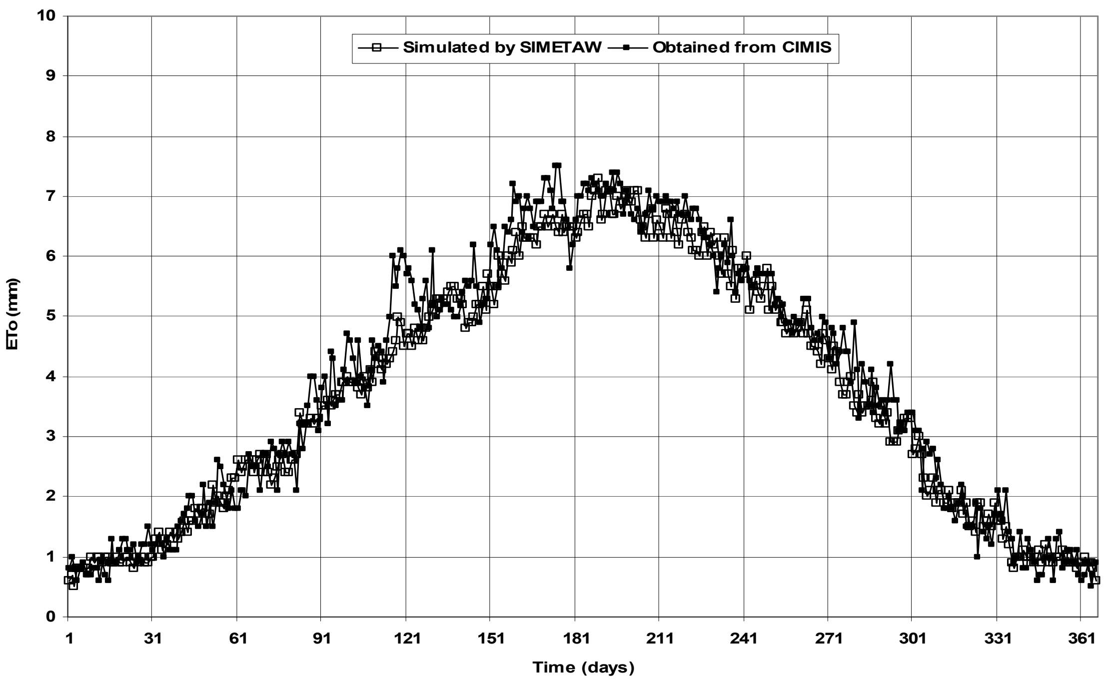

Figure 1. Comparison of daily ET_o estimates from SIMETAW and CIMIS at Davis, California

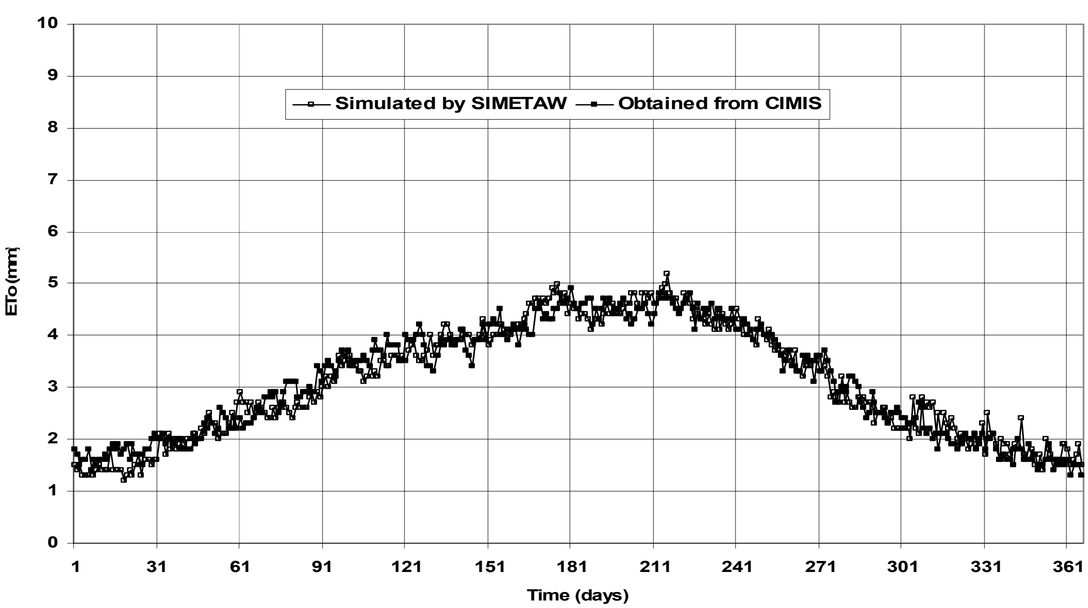

Figure 2. Comparison of daily ET_o estimates from SIMETAW and CIMIS at Oceanside, California

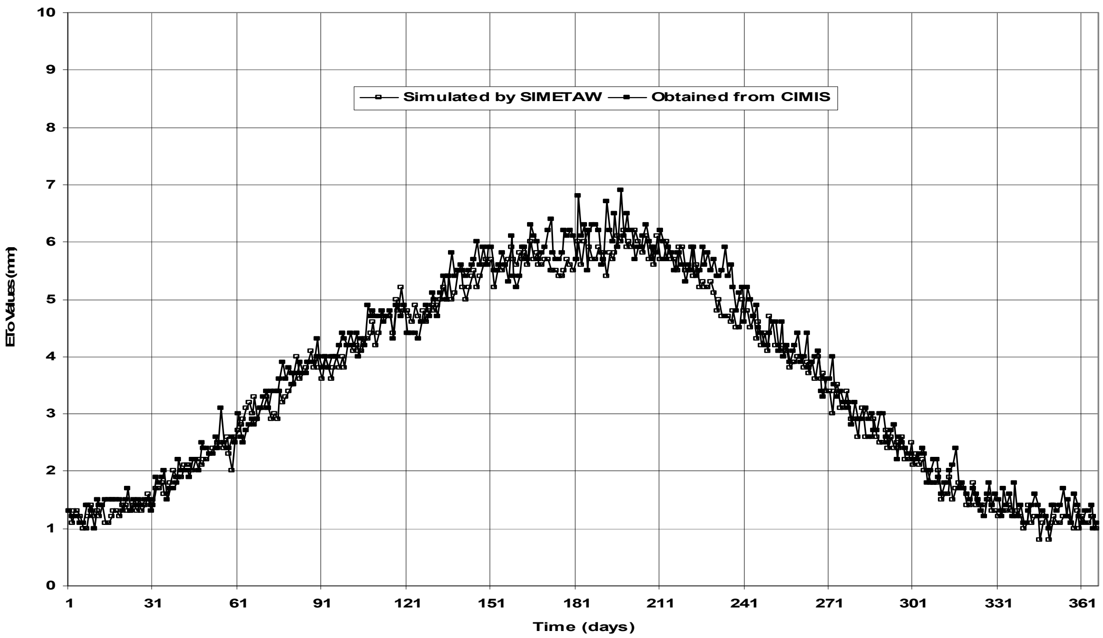

Figure 3. Comparison of daily ET_o estimates from SIMETAW and CIMIS at Bishop, California

7- Crop Coefficients

While reference crop evapotranspiration accounts for variations in weather and offers a measure of the ‘evaporative demand’ of the atmosphere, crop coefficients account for the difference between the crop evapotranspiration and ET_o. The main factors affecting the difference are (1) light absorption by the canopy, (2) canopy roughness, which affects turbulence, (3) crop physiology, (4) leaf age, and (5) surface wetness. Because evapotranspiration (*ET*) is the sum of evaporation (*E*) from soil and plant surfaces and transpiration (*T*), which is vaporization that occurs inside of the plant leaves, it is often best to consider the two components separately. When not limited by water availability, both transpiration and evaporation are limited by the availability of energy to vaporize water. During early growth of crops, when considerable soil is exposed to solar radiation, ET_c is dominated by soil evaporation and the rate depends on whether or not the soil surface is wet. If a nearly bare-soil surface is wet, the ET_c rate is slightly higher than ET_o, when evaporative demand is low, but it will fall to about 80% of ET_o under high evaporation conditions. However, as a soil surface dries off, the evaporation rate decreases considerably. As a canopy develops, solar radiation (or light) interception by the foliage increases and transpiration rather than soil evaporation dominates ET_c. Assuming there is no transpiration-reducing water stress, light interception by the crop canopy is the main factor determining the ET_c rate. Therefore, crop coefficients for field and row crops generally increase until the canopy ground cover reaches about 75%. For tree and vine crops the peak K_c is reached when the canopy has reached about 70% ground cover. The difference between the crop types results because the light interception is somewhat higher for the taller crops.

During the off-season and during initial crop growth, *E* is the main component of *ET*. Therefore, a good estimate of the K_c for bare soil is useful to estimate off-season soil evaporation and ET_c early in the season. A two-stage method for estimating soil evaporation presented by Stroonsnjider [8] and refined by Snyder and others [9] is used to estimate bare-soil crop coefficients. This method gives *Kc* values as a function of wetting frequency and *ETo* that are quite similar to the widely used bare soil coefficients that were published in

Doorenbos and Pruitt [10]. The soil evaporation model is used to estimate crop coefficients for bare soil using the daily mean ET_o rate and the expected number of days between significant precipitation (P_s) on each day of the year. Daily precipitation is considered significant when $P_s > 2 \times ET_o$.

7.1- Field and Row Crops

Crop coefficients are calculated using a modified Doorenbos and Pruitt [10] 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 (see Fig. 1).

Tabular default K_c values corresponding to important inflection points in Fig. 4 are stored in the SIMETAW program. The value *Kc1* corresponds to the date B *Kc* (*KcB*). For field and row crops, *Kc1* is used from date A to B. The value *Kc2* is assigned as the *Kc* value on date C (*KcC*) and D (*KcD*). Initially, the *KcC* and *KcD* values are set equal to *Kc2*, but for tree and vine crops, the values for *KcC* and *KcD* are adjustable for the percentage shading by the canopy to account for sparse or immature canopies. During the rapid growth period, when the field and row crop canopy increases from about 10% to 75% ground cover, the K_c value changes linearly from *KcB* to *KcC*. For deciduous tree and vine crops, the Kc increases from KcB to KcC as the canopy develops from leaf out on date B to about 70% shading on date C. During late season, the K_c changes linearly from *KcD* on date D to *KcE* at the end of the season. The values for *KcB* and *KcC* depend on the difference in (1) energy balance due to canopy density and reflective qualities, (2) crop morphology effects on turbulence, and (3) physiological differences between the crop and reference crop.

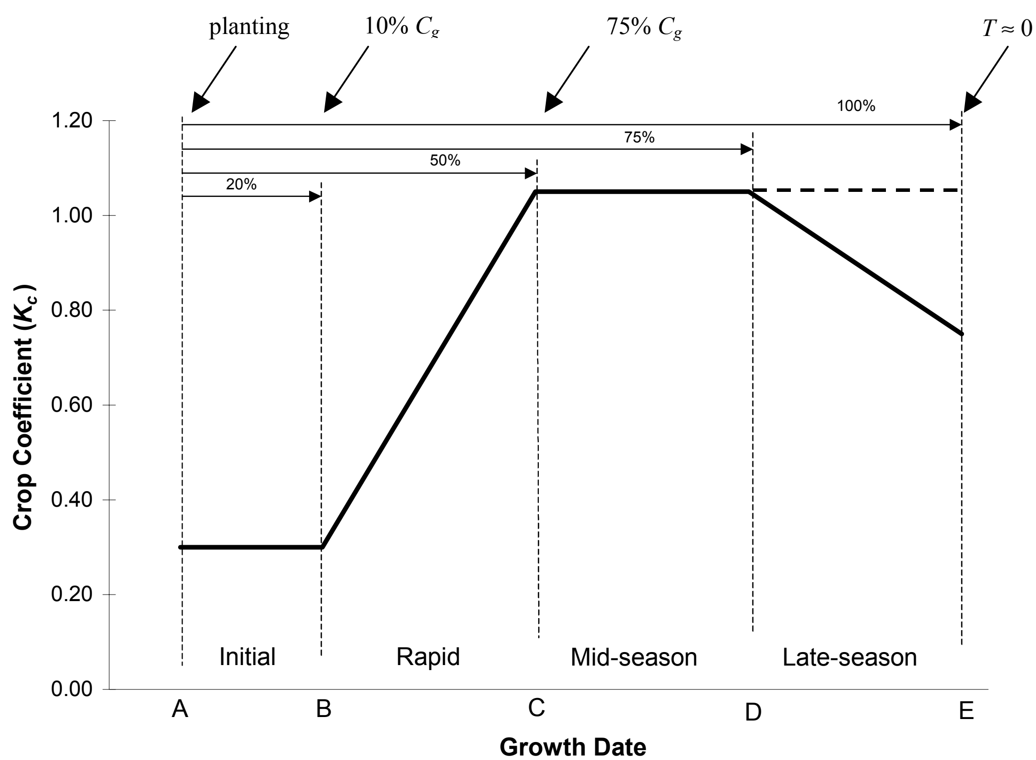

Figure 4. Hypothetical crop coefficient (K_c) curve for typical field and row crops showing the growth stages and percentages of the season from planting to critical growth dates.

7.2- Field Crops with Fixed Crop Coefficients

Fixed annual K_c values are possible for some crops with little loss in accuracy. These crops include pasture, warm-season and cool-season turfgrass, and alfalfa averaged over a season. In the SIMETAW program, these field crops are identified as type-2 crops.

7.3- Deciduous Tree and Vine Crops

Deciduous tree and vine crops, without a cover crop, have similar K_c curves but without the initial growth period (Fig. 5). The season begins with rapid growth at leafout when the K_c increases from *KcB* to *KcC*. The midseason period begins at approximately 70% ground cover. Then, unless the crop is immature, the K_c is fixed at *KcC* until the onset of senescence on date D (*Kc2=KcC=KcD*). During late season, when the crop plants are senescing, the K_c decreases from *KcD* to *KcE*. The end of the season occurs at about leaf drop or when the tree or vine transpiration is near zero.

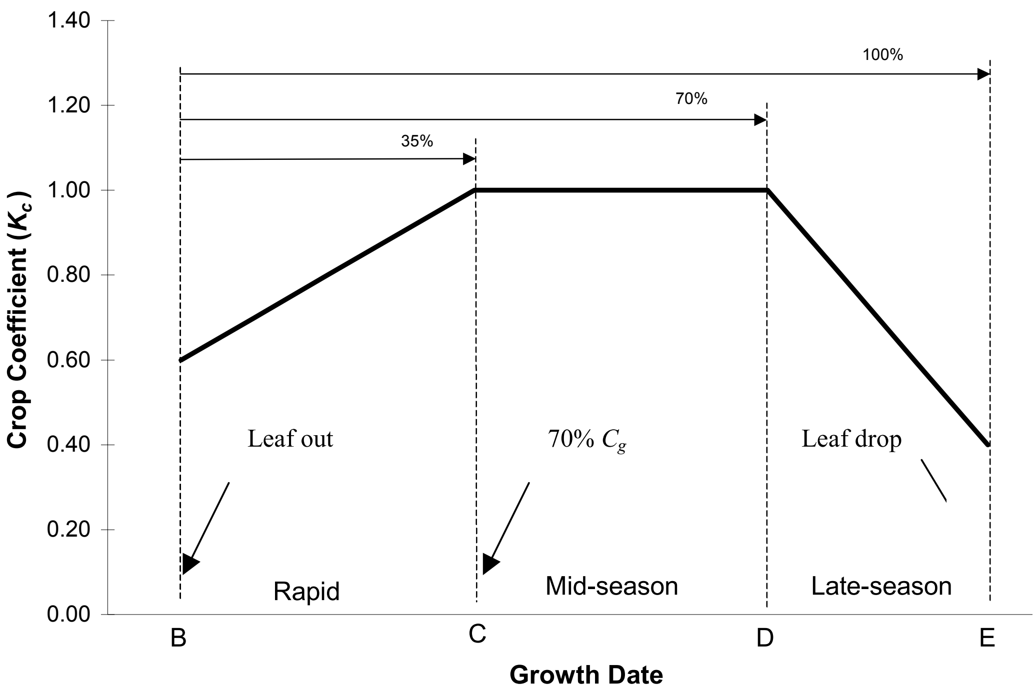

Figure 5. Hypothetical crop coefficient (K_c) curve for typical deciduous orchard and vine crops showing the growth stages and percentages of the season from leaf out to critical growth dates

The initial K_c value is refined by using the K_c for bare soil evaporation on that date based on ET_o and rainfall frequency. The assumption is that the ET_c for a deciduous orchard or vineyard at leaf out should be about equal to the bare soil evaporation. The *Kc2* and *Kc3* values again depend on (1) energy balance characteristics, (2) canopy morphology effects on turbulence, and (3) plant physiology differences between the crop and reference crop. The *Kc1* corresponds to *KcB* and *Kc3* corresponds to *KcE*. Again, the K_c is initially fixed at *Kc2* during midseason, so *Kc2=KcC=KcD*. However, the *KcC* and *KcD* can be adjusted for sparse or immature canopies. Adjustments can also be made for the presence of a cover crop.

With a cover crop, the K_c values for deciduous trees and vines are increased depending on the amount of cover. In SIMETAW, adding 0.35 to the in-season, no-cover K_c for a mature crop, but not to exceed 1.15, is used.

7.4- Subtropical Orchards

For mature subtropical orchards (e.g., 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.

8- ET of Applied Water Calculations

The ET_o data come from the 'name.wrk' file, which is created from either input raw or simulated daily weather data. The K_c values are based on the ET_o data and crop, soil, and management specific parameters from a row in the 'DAUnnn.csv' file. During the off-season, crop coefficient values are estimated from bare soil evaporation as previously described. It is assumed that all water additions to the soil come from rainfall and losses are only due to deep percolation. Rainfall runoff as well as surface water running onto a cropped field is ignored. Because the water balance is calculated each day, this assumption is reasonable.

During the off-season, if the soil water depletion (SWD) is less than the YTD, ET_c is added to the previous day's SWD to estimate the depletion on the current day. However, the maximum depletion allowed is 50% of the PAW in the upper 30 cm of soil. If the SWD at the end of a growing season starts at some value greater than the maximum soil water depletion, then the SWD is allowed to decrease with rainfall additions but it is not allowed to increase with ET_c (Fig. 6). If half of the available water is gone from the upper 30 cm, it is assumed that the soil surface is too dry for evaporation. Once the off-season SWD is less than the maximum depletion, it is again not allowed to exceed the maximum off-season depletion.

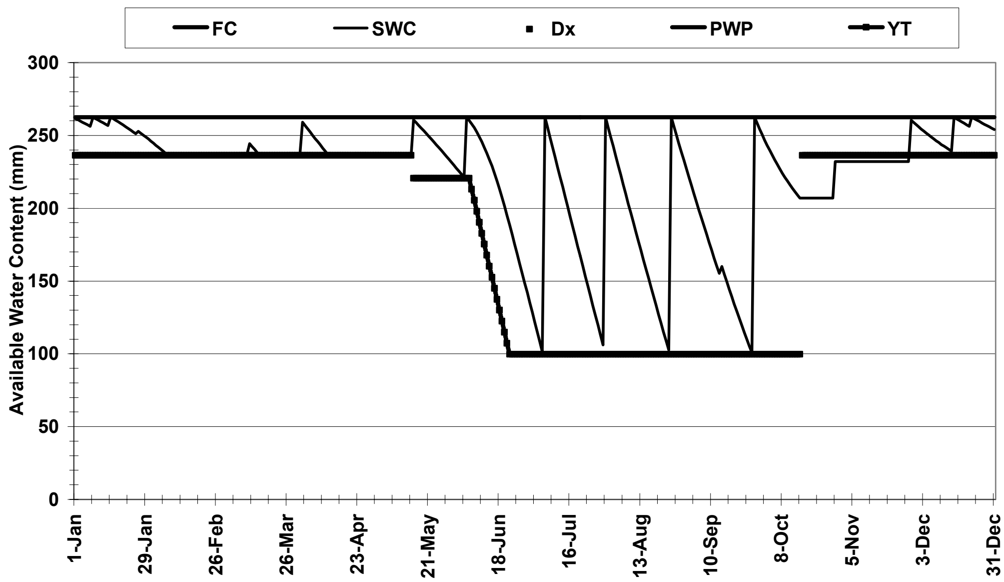

Figure 6. An annual water balance for cotton showing fluctuations in soil water content between field capacity and the maximum depletion during the off-season and between field capacity and the YTD during the season.

If a crop is pre-irrigated, then the SWD is set equal to zero on the day preceding the season. If it is not pre-irrigated, then the SWD on the day preceding the season is determined by water balance during the off-season before planting or leafout. It is assumed that the SWD equals zero on December 31 proceeding the first year of data. After that the SWD is calculated using water balance for the entire period of record.

During the growing season, the SWD depletion is updated by adding the ET_c (or by subtracting ET_c from the soil water content 'SWC') on each day (Fig. 3). If rainfall occurs, SWD is reduced by an amount equal to the rainfall. However, the SWD is not allowed to be less than zero. This automatically determines the effective rainfall as equal to the recorded rainfall if the amount is less than the SWD. If the recorded rainfall is more than the SWD, then the effective rainfall equals the SWD. Irrigation events are given on dates when the SWD would exceed the YTD. It is assumed that the SWD returns to zero on each irrigation date. The ETAW is calculated both on a seasonal and an annual basis as the cumulative ET_c minus the effective rainfall. The calculations are made for each year over the period of record as well as an overall average over years. The results are output to a summary table.

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