# SIMETAW (Simulation of Evapotranspiration of Applied Water)

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The Simulation of Evapotranspiration of Applied Water (SIMETAW) simulates weather data from monthly climate data and estimates reference evapotranspiration ($ET_o$) and crop evapotranspiration ($ET_c$) with the simulated data. In addition, simulated daily rainfall, soil water holding charactersistics, 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 ($ET_{aw}$), where $ET_{aw}$ is an estimate of the crop evapotranspiration minus any water supplied by effective rainfall. SIMETAW allows one to investigate how climate change may affect water demand in California. All $ET_{aw}$ calculations are done on a daily basis, so the estimation of effective rainfall and, hence, $ET_{aw}$ is greatly improved over earlier methods. In addition, the use of the widely adopted Penman-Monteith equation for reference evapotranspiration ($ET_o$) and improved methodology to apply crop coefficients for estimating crop evapotranspiration is used to improve $ET_{aw}$ accuracy.

## Methodology

### 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 $ET_{aw}$. One can either use raw or simulated daily data for the calculations.

### Rainfall

Characteristics and patterns of rainfall are highly seasonal and localized, it is difficult to create a general, seasonal model that is applicable to all locations. Recognizing the fact that rainfall patterns are usually skewed to the right toward extreme heavy amount and that rain status of the previous day tends to affect the present day condition, a gamma distribution and Markov chain modeling approach was applied to described rainfall patterns for periods within which rainfall patterns are relatively uniform (Gabriel and Neumann 1962, Stern 1980, Larsen and Pense 1982, Richardson and Wright 1984). 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.

### Wind Speed

The simulation of wind speed is a simpler procedure, requiring only the gamma distribution function as described for rainfall. Although 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

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$ET_o$ 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.

### 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:

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

where k = 1, 2 and 3 (k=1 represents maximum temperature; k = 2 represents minimum temperature; and k =3 represents solar radiation), $\mu_{ki}$ 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 (1984), 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 were developed 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 $\mu_{ki}$ curves without additional input data requirement.

### Simulation Accuracy

Nine years of daily measured weather data (1990–1998) from the California Irrigation Management Information System (CIMIS) in Davis were used in the model to simulate 30 years of daily weather data. The weather data consist of $R_s$, $T_{max}$, $T_{min}$, wind speed, $T_{dew}$, and rainfall. The weather data simulated from SIMETAW were compared with the data from CIMIS. Figures 1, 2, and 3 show that $R_s$, $T_{max}$, and rainfall values predicted from SIMETAW were well correlated with those values obtained from CIMIS. Similar results were observed for $T_{min}$, wind speed, and $T_{dew}$ data.

**Figure 1.**
**Comparison of Measured and Simulated Daily Solar Radiation Data at Davis, California**

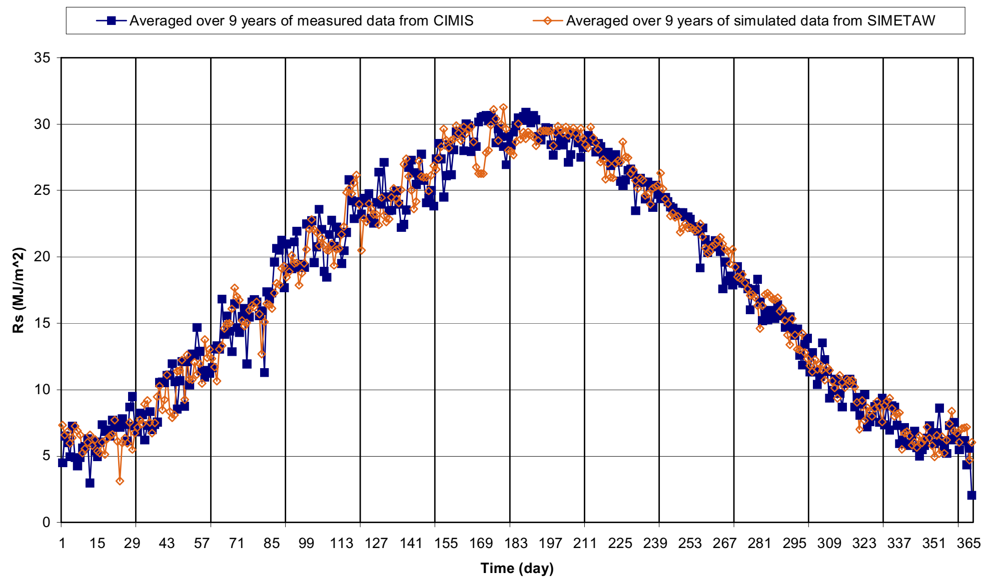


**Figure 2**
**Comparison of Measured and Simulated Maximum Air Temperaure Data at Davis, California**

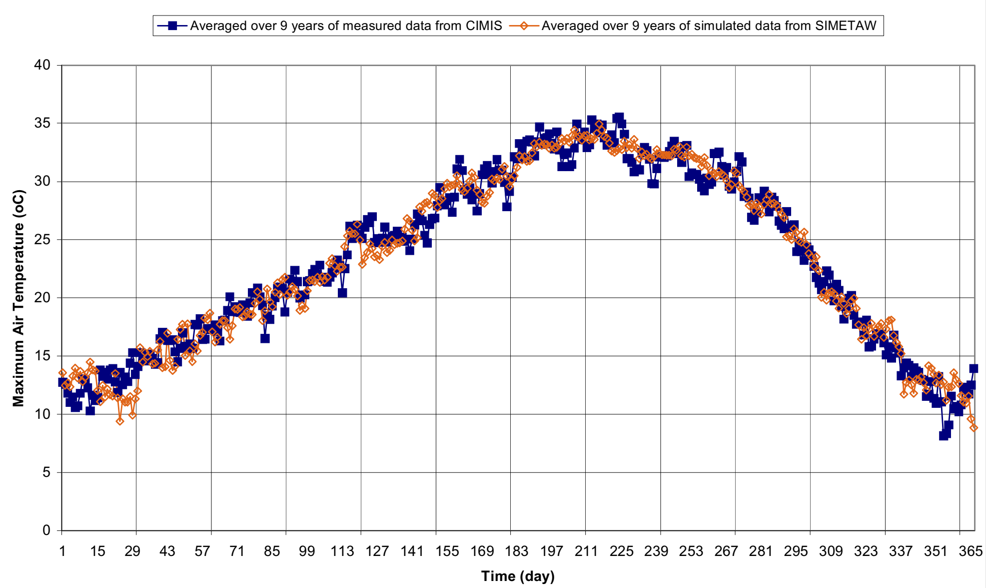


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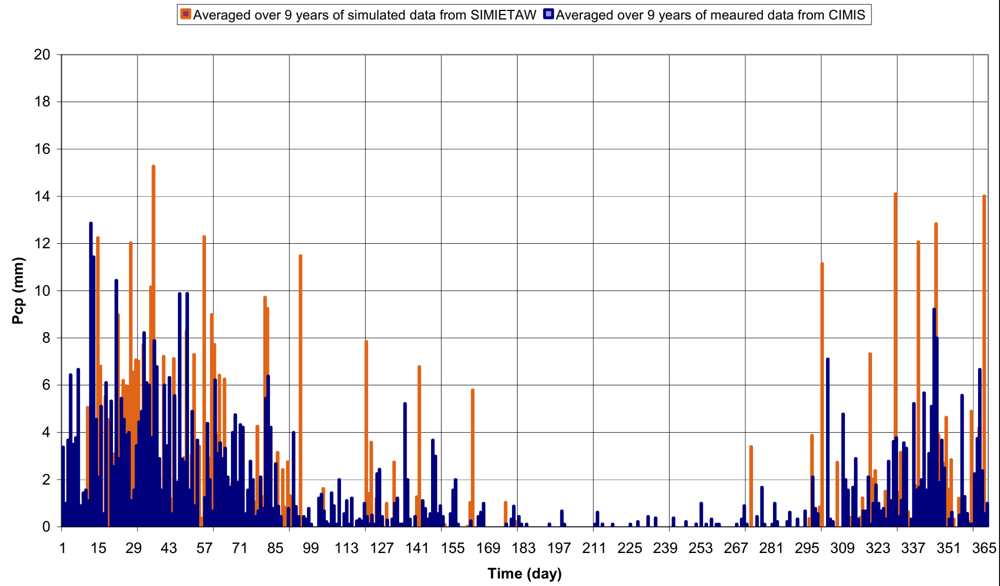
**Figure 3**
**Comparison of Measured and Simulated Precipitation Data at Davis, California**




## Reference Evapotranspiration Calculation

Reference evapotranspiration ($ET_o$) is estimated from daily weather data using a modified version of the Penman-Monteith equation (Allen and others 1999, Walter and others 2000, Itenfisu and others 2000). The equation is:

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

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 ($^oC$), $u_2$ 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 several constants and converts units of the aerodynamic component to mm $d^{-1}$. The product 0.34 $u_2$ in the denominator is an estimated 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 (1999).

If only temperature data are available, then 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 (that is, 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.

### Verification of the Simulated Reference Evapotranspiration

As a final verification of the SIMETAW model, we compared our model predictions of $ET_o$ with number of years of estimated daily $ET_o$ data from CIMIS at Davis, Oceanside, and Bishop. The performance of our model $ET_o$ predictions was evaluated at sites influenced by coastal and windy desert climates. Figures 4, 5, and 6 compare daily mean $ET_o$ estimates of SIMETAW and CIMIS averaged over the period of records. As seen in the figures, a close agreement exists between CIMIS-based estimates of $ET_o$ and those of the SIMETAW model. Bishop is influenced by a windy desert environment on the eastern side of the Sierra Nevada. Oceanside is a coastal site in San Diego County. Davis is in the Central Valley, which is characterized during summer by clear, hot, dry days with strong, cooling southwest winds in the afternoons.

**Figure 4**
**Comparison of Estimated and Simulated Reference Evapotranspiration Data at Davis, California**

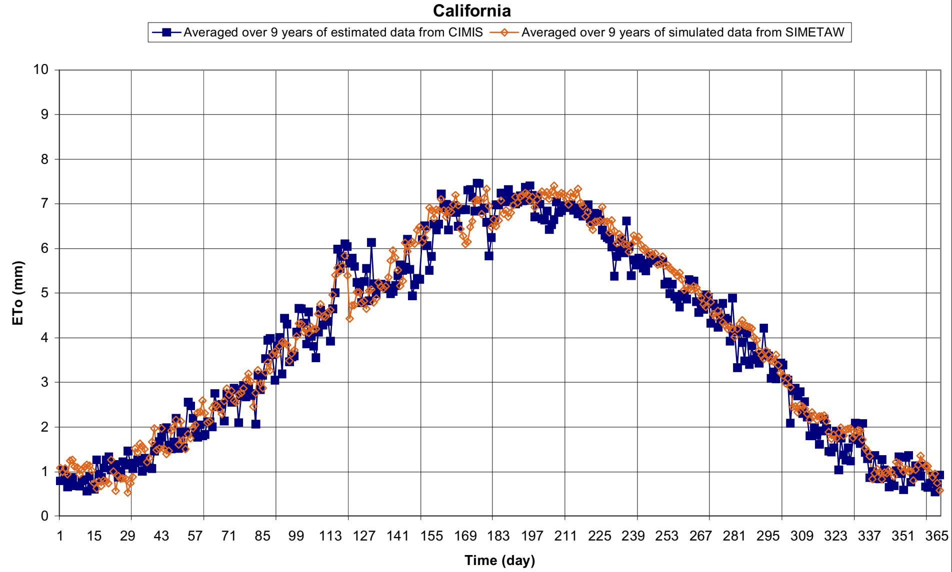



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**Figure 5**
**Comparison of Estimated and Simulated Reference Evapotranspiration Data at Oceanside, California**

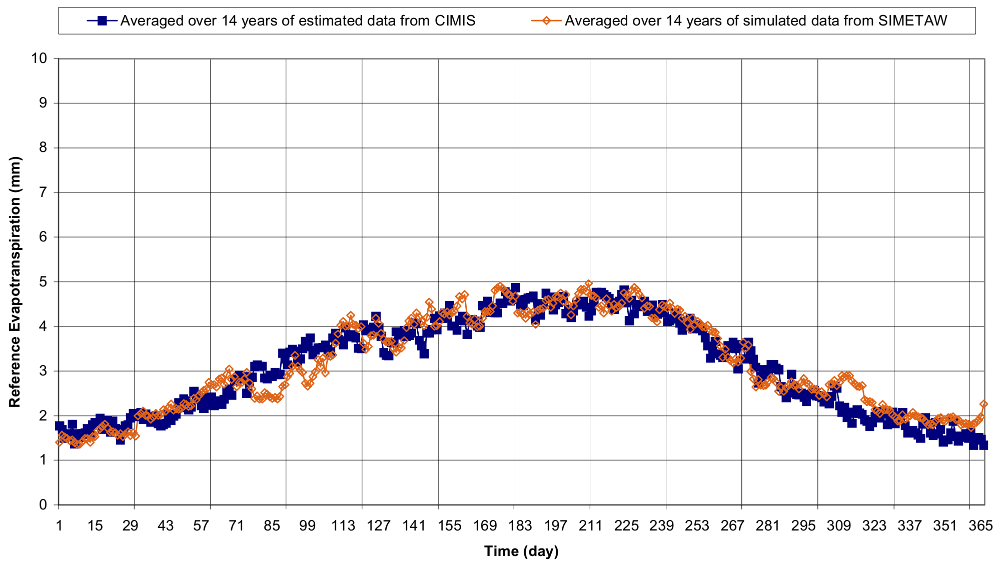
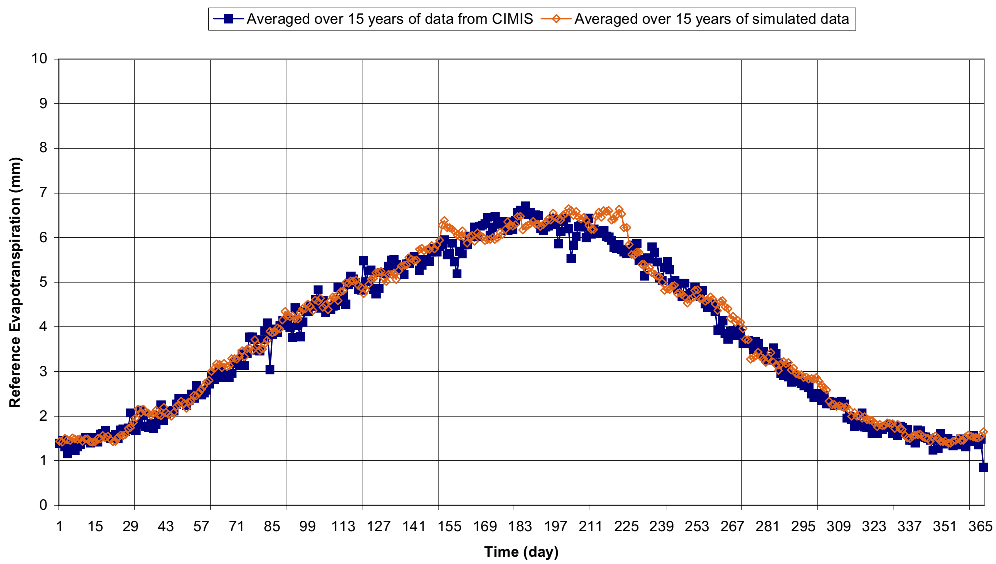



**Figure 6**
**Comparison of Estimated and Simulated Reference Evapotranspiration Data at Bishop, California**

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### Input Climate Data

Either daily or monthly climate data are used to determine $ET_{aw}$ in SIMETAW. Daily data can come from CIMIS or from a non-CIMIS data source as long as data are in the correct format. After reading the data, $ET_{aw}$ 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. Daily data are input directly, so the calculation of monthly data for use in simulation of daily data is unnecessary. However, it was included to test whether similar results were 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. SIMETAW generates 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. Furthermore, the program can simulate daily $ET_o$ data directly from monthly means of $ET_o$ and $E_{pan}$ data.

### 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 the plant leaves, the components are best considered 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 percent 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 percent. 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 results because the light interception is somewhat higher for the taller crops.

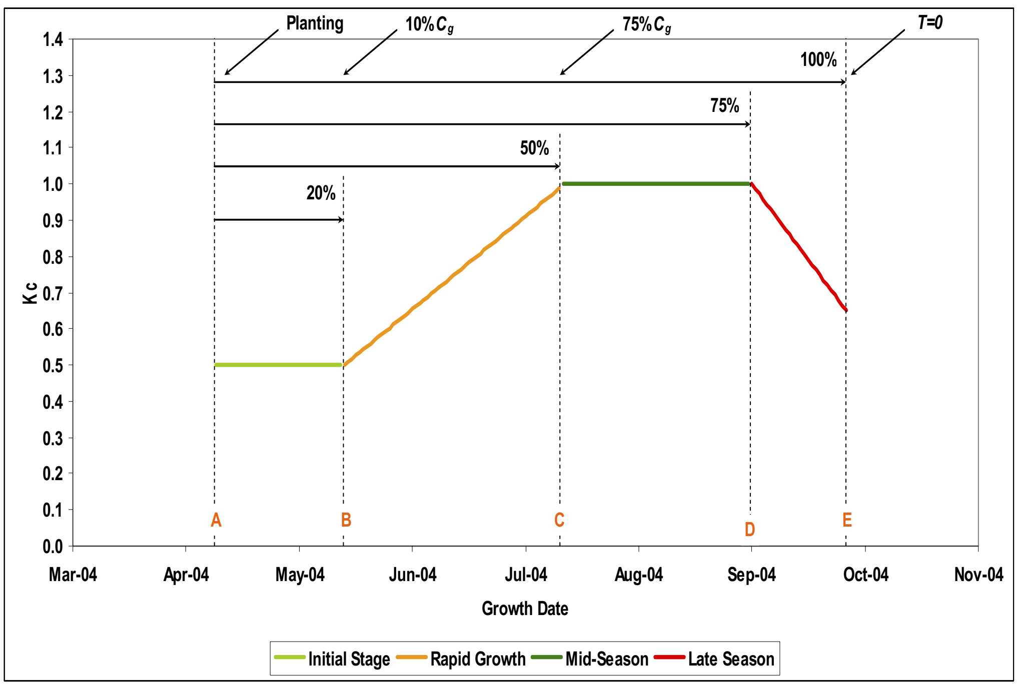
### Crop Coefficient Estimation

Crop coefficients are calculated using a modified Doorenbos and Pruitt (1977) 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.

## Field and Row Crops

Tabular default $K_c$ values corresponding to important inflection points in Figure 7 are stored in the SIMETAW program. The value $K_c1$ corresponds to the date B $K_c$ ($K_cB$). For field and row crops, $K_c1$ is used from date A to B. The value $K_c2$ is assigned as the $K_c$ value on date C ($K_cC$) and D ($K_cD$). Initially, the $K_cC$ and $K_cD$ values are set equal to $K_c2$, but for tree and vine crops, the values for $K_cC$ and $K_cD$ 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 percent to 75 percent ground cover, the $K_c$ value changes linearly from $K_cB$ to $K_cC$. For deciduous tree and vine crops, the $K_c$ increases from $K_cB$ to $K_cC$ as the canopy develops from leaf out on date B to about 70 percent shading on date C. During late season, the $K_c$ changes linearly from $K_cD$ on date D to $K_cE$ at the end of the season. The values for $K_cB$ and $K_cC$ 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 7**
**Hypothetical Crop Coefficient ($K_c$) Curve for Typical Field and Row Crops Showing Growth Stages and Percentages of the Season from Planting to Critical Growth Dates**

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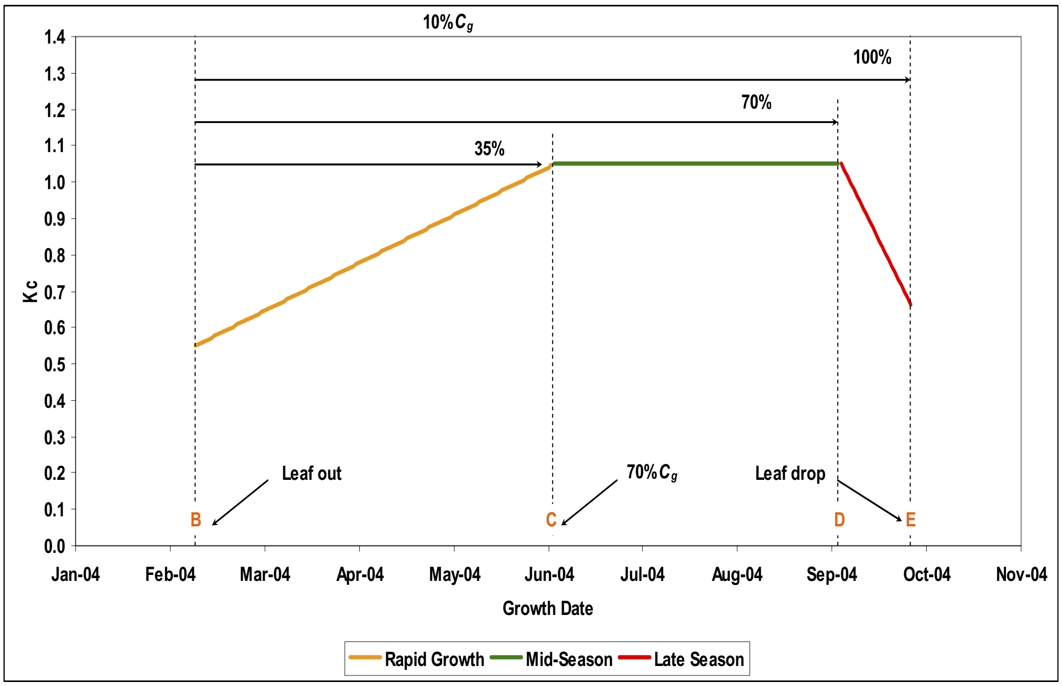
### Deciduous Tree and Vine Crops

Deciduous tree and vine crops, without a cover crop, have similar $K_c$ curves but without the initial growth period (Figure 8). 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 at $K_cC$ until the onset of senescence on date D ($K_c2$=$K_cC$=$K_cD$). During late season, when the crop plants are senescing, the $K_c$ decreases from $K_cD$ to $K_cE$. The end of the season occurs at about leaf drop or when the tree or vine transpiration is near zero.

**Figure 8**
**Hypothetical Crop Coefficient (Kc) Curve for Typical Deciduous Orchard and Vine Crops Showing Growth Stages and Percentages of the Season from Leaf Out to Critical Growth Dates**

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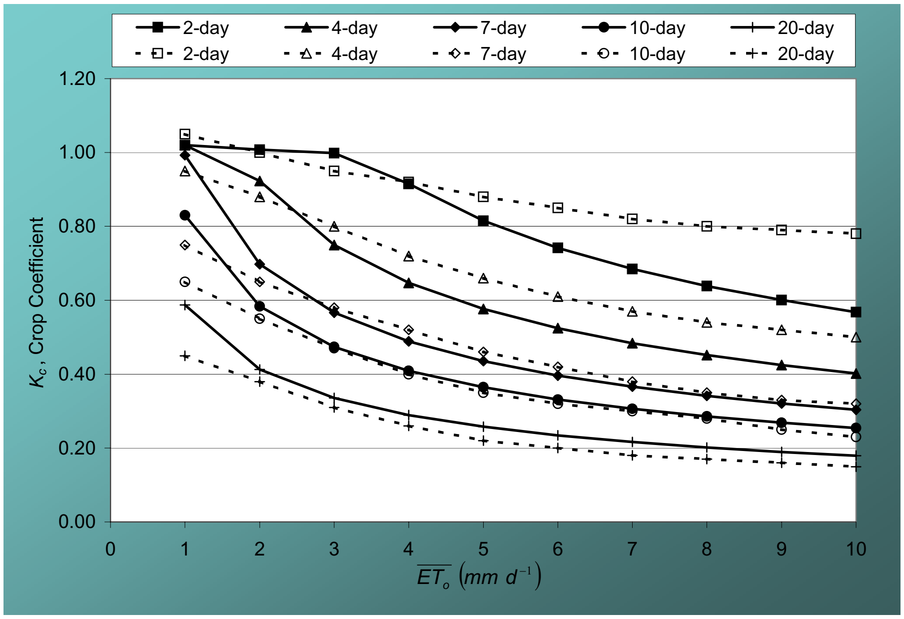
### Correcting the Initial $K_c$ for Wetting Frequency

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 in estimating off-season soil evaporation and $ET_c$ early in the season. A two-stage method for estimating soil evaporation presented by Stroosnijder (1987) and refined by Snyder and others (2000) is used to estimate bare-soil crop coefficients. As shown in Figure 9, this method gives $K_c$ values as a function of mean $ET_o$ and wetting frequency in days that are quite similar to the widely used bare soil coefficients published in Doorenbos and Pruitt (1977). In Figure 9 solid lines represent the model used in the SIMETAW, and dashed lines are from Doorenbos and Pruitt (1977). The soil evaporation model estimates 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 $P_s > 2 \times ET_o$.

**Figure 9**
**Crop Coefficient ($K_c$) Values for Nearly Bare-Soil Evaporation as Function of Mean $ET_o$ Rate and Wetting Frequency in Days**

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### Correcting the $K_c$ for Immature Trees and Vines

SIMETAW accounts for immaturity effects on crop coefficients for tree and vine crops. 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 ($C_g$).

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

### Correcting the $K_c$ for Immature Subtropical Orchards

For an immature orchard, the mature $K_c$ values ($K_{cm}$) are adjusted for their percentage ground cover ($C_g$) using the following criteria.

$$\text{If } \sqrt{\sin\left(\frac{C_g}{70}\frac{\pi}{2}\right)} \geq 1.0 \text{ then } K_c = K_{cm} \text{ or else } K_c = K_{cm}\sqrt{\sin\left(\frac{C_g}{70}\frac{\pi}{2}\right)} \tag{5}$$

### 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 $K_c$ value is not allowed to exceed 1.15 or to fall below 0.90. SIMETAW allows beginning and end dates to be entered for two periods when a cover crop is present in an orchard or vineyard.

### 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 turf grass, and alfalfa averaged over a season. In the SIMETAW program, these field crops are identified as type-2 crops.

### ET of Applied Water Calculations

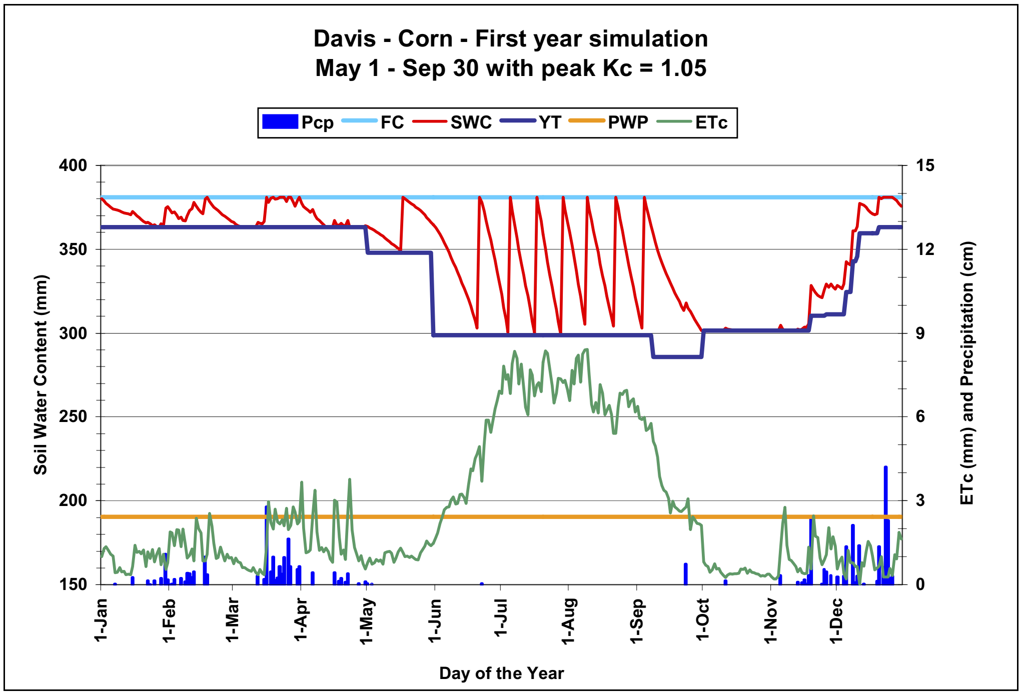
The $ET_o$ data come from the "name.wrk" file, which is created from either input raw or simulated daily weather data. The $K_c$ values are based on the $ET_o$ data and crop, soil, and management specific parameters from a row in the 'DAUnnn.csv' file. During the off-season, crop coefficient values are 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.

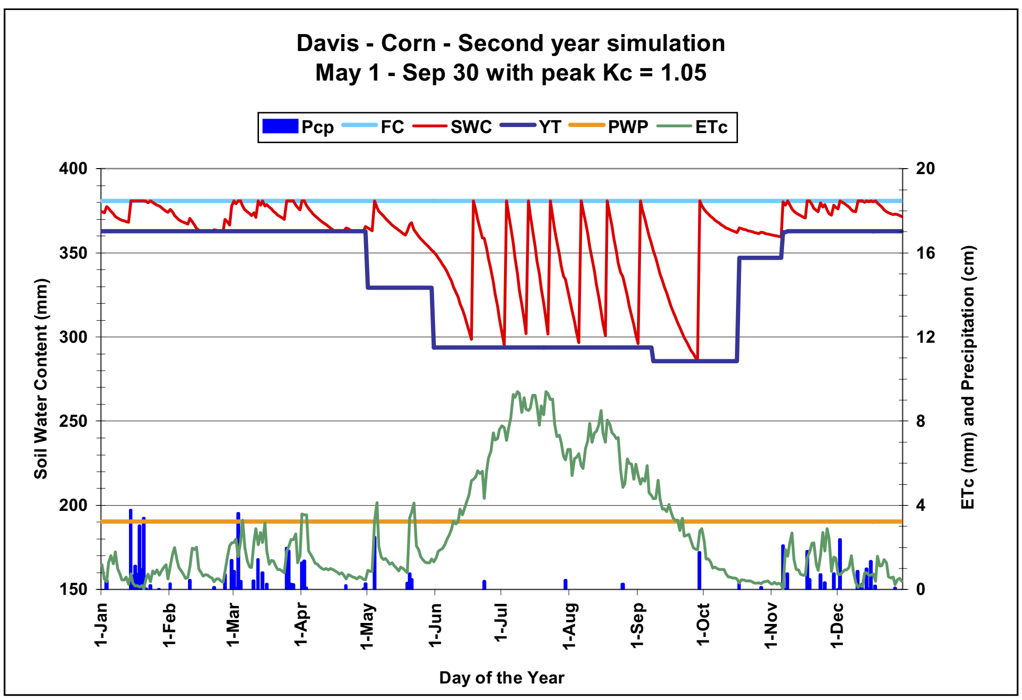
During the off-season, if the soil water depletion (SWD) is less than the yield threshold depletion (YTD), $ET_c$ is added to the previous day's SWD to estimate the depletion on the current day. However, the maximum depletion allowed is 50 percent of the PAW in the upper 30 cm of soil. If the SWD at 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 $ET_c$ (Figure 10). 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.

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 leaf out. 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 (Figure 10). 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 $ET_{aw}$ is calculated both on a seasonal and 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.

**Figure 10 Annual Water Balance for Cotton Showing Fluctuations in Soil Water Content (SWC) between Field Capacity (FC) and Maximum Depletion during Off-season and between FC and Yield Threshold Depletion (YTD) during Season**

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 Simulation of Evapotranspiration of Applied Water

## General Applications

SIMETAW was written specifically to estimate $ET_{aw}$ for calculating irrigation water requirements when water demand planning. However, the program has many additional applications. For hydrology the SIMETAW application can provide evapotranspiration boundary conditions for groundwater and surface water models, which can lessen the potential for floods and can improve the management of water banking, aquifers, dams and reservoirs, and sea water intrusion in the Sacramento-San Joaquin Delta. In addition the program can be used to help California growers obtain improved crop coefficients for use in irrigation management. Use of SIMETAW to determine water demand by region can help manage water transfers throughout California. Because the program generates many years of simulated weather data from monthly climate data, it can be used to study how changes in the monthly means may affect weather in the future. This can have implications for protection against frost, which causes more economic losses in the United States than any other weather-related phenomenon. Climatic changes in temperature, rainfall patterns, and humidity could all influence future daily weather conditions and could lessen or increase the probability of freezing temperatures. Changes in climate and their effect on daily weather can also influence air pollution within the state; SIMETAW can be used to simulate possible scenarios.

Air pollution is clearly a major problem in California, and SIMETAW could help identify an increased potential for major pollution events that could result from changes in rainfall patterns, temperature, etc. Another major problem in California is wildfire, which could worsen if the climate changes. SIMETAW can be used to study the impact of changes in monthly climate data on future weather conditions. This could impact biomass production in forests and rangeland, and changes in weather conditions could influence whether or not the natural ecosystems will experience more water stress and make them more prone to fire events. Of course, changes in the climate could impact human health because of effects on air pollution as well as temperature extremes. SIMETAW can provide scenarios of possible weather extremes resulting from changes in monthly climate data. SIMETAW can also be applied to refine the monthly mean $ET_o$ rates (in/day) of California $ET_o$ Zone map. In addition, SIMETAW can be used as a tool to fill in missing data points from long-term data sets, which could be helpful for developing rainfall-runoff models, etc. There is considerable research on the use of regulated deficit irrigation (RDI) to more efficiently use water in crop production, which could potentially decrease water demand. The SIMETAW program has a stress factor built-in to account for reductions in $ET_{aw}$ due to the use of RDI.

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

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