

A SIMULATION MODEL FOR EVAPOTRANSPIRATION OF APPLIED WATER

Morteza N. Orang¹
J. Scott Matyac²
Richard L. Snyder³
Shu Geng⁴
Sara Sarreshteh⁵

ABSTRACT

The SIMETAW program was written to provide a new and innovative tool for estimating evapotranspiration of applied water (ETAW), which is a seasonal estimate of the water requirement for evapotranspiration of a crop minus any water supplied by effective rainfall. ETAW information is needed to determine consumptive use requirements. In addition to using measured weather data, the SIMETAW program simulates daily weather data from monthly climate data. Simulation of daily weather data where only monthly means exist is a good tool for filling missing data points. In addition, the simulation program is useful for studying the effects of climate change on ETAW. All of the ETAW calculations are done on a daily basis, so the estimation of effective rainfall and, hence, ETAW is greatly improved over earlier methods. In addition, the use of the widely adopted Penman-Monteith equation for reference evapotranspiration (ET_0) and improved methodology to apply crop coefficients for estimating crop evapotranspiration is used to improve ETAW accuracy.

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.

¹ Associate land and water use analyst, California Department of Water Resources – Division of Planning and Local Assistance, PO Box 942836, Sacramento, CA 94236-0001

² Senior land and water use analyst, California Department of Water Resources – Division of Planning and Local Assistance, PO Box 942836, Sacramento, CA 94236-0001

³ Biometeorologist, University of California, Atmospheric Science, Davis, CA 95616

⁴ Biostatistician, University of California, Agronomy and Range Science, Davis, CA 95616

⁵ Post graduate researcher, University of California, Atmospheric Science, Davis, CA 95616

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.

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.

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.

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.

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.

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 (Gabriel and Neumann, 1962; Stern, 1980; Larsen and Pense 1982; and 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 rain days to obtain all parameters for the Gamma and Markov Chain models.

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.

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, $i = 1, 2 \dots, 365$ and for the k^{th} variable.

SIMETAW simplifies the parameter estimation procedure of Richards 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 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.

REFERENCE EVAPOTRANSPIRATION CALCULATION

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

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

where Δ is the slope of the saturation vapor pressure at mean air temperature curve ($\text{kPa } ^\circ\text{C}^{-1}$), R_n and G are the net radiation and soil heat flux density in $\text{MJ m}^{-2}\text{d}^{-1}$, γ is the psychrometric constant ($\text{kPa } ^\circ\text{C}^{-1}$), T is the daily mean temperature ($^\circ\text{C}$), 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 ($^\circ\text{C}$) for the day, and e_a is the actual vapor pressure (kPa) calculated from the mean dew point temperature ($^\circ\text{C}$) for the day. The coefficient 0.408 converts the $R_n - G$ term from $\text{MJ m}^{-2}\text{d}^{-1}$ to mm d^{-1} and the coefficient 900 combines together several constants and converts units of the aerodynamic component to mm d^{-1} . The product $0.34 u_2$, in the denominator, is an estimate of the ratio of the 0.12-m tall canopy surface resistance ($r_c=70 \text{ s m}^{-1}$) to the aerodynamic resistance ($r_a=205/u^2 \text{ s m}^{-1}$). 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 et al. (1999).

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 Stroonsnijder (1987) and refined by Snyder et al. (2000) is used to estimate bare-soil crop coefficients. This method gives K_c values as a function of wetting frequency and ET_o that are quite similar to the widely used bare soil coefficients that were published in Doorenbos and Pruitt (1977). 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 $P_s > 2 \times ET_o$.

Field and row crops

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 (Fig. 1).

Tabular default K_c values corresponding to important inflection points in Fig. 1 are stored in the SIMETA 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% to 75% 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% 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.

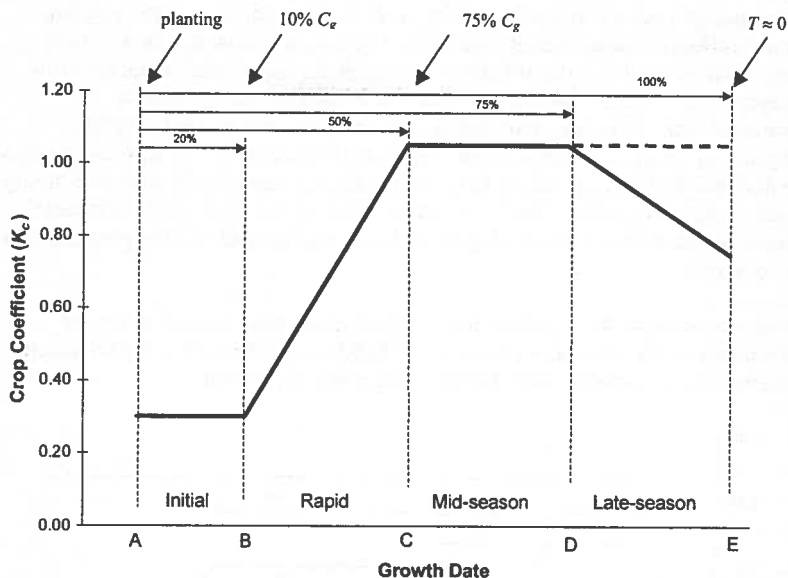


Figure 1. Hypothetical crop coefficient (K_c) curve for typical field and row crops showing the growth stages and percentages of the season from planting to critical growth dates.

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 SIMETA W program, these field crops are identified as type-2 crops.

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. 2). The season begins with rapid growth at leafout 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 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.

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 K_{c2} and K_{c3} values again depend on energy balance characteristics, (2) canopy morphology effects on turbulence, and (3) plant physiology differences between the crop and reference crop. The K_{c1} corresponds to K_{cB} and K_{c3} corresponds to K_{cE} . Again, the K_c is initially fixed at K_{c2} during midseason, so $K_{c2}=K_{cC}=K_{cD}$. However, the K_{cC} and K_{cD} 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 SIMETA_W, adding 0.35 to the in-season, no-cover K_c for a mature crop, but not to exceed 1.15, is used.

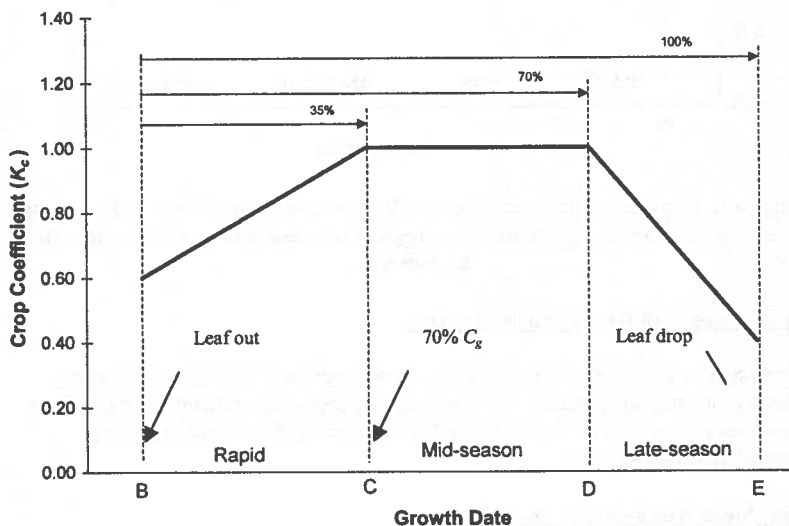


Figure 2. Hypothetical crop coefficient (K_c) curve for typical deciduous orchard and vine crops showing the growth stages and percentages of the season from leaf out to critical growth dates.

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 .

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. 3). 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.

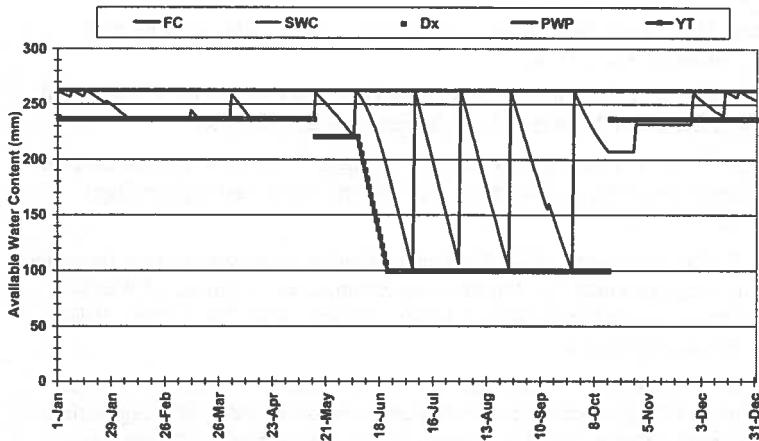


Figure 3. An annual water balance for cotton showing fluctuations in soil water content between field capacity and the maximum depletion during the off-season and between field capacity and the YTD during the season.

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 preceding 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.

REFERENCES

- Allen, R.G., L.S. Pereira, D. Raes, and M. Smith. 1999. Crop evapotranspiration: Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56, FAO, Rome.
- Berman, M.B., 1971. Generating gamma distributed variates for computer simulation 12:1241-1247.
- Gabriel, K.R. and J. Neumann, 1962. A Markov Chain model for daily rainfall occurrence at Tel Aviv. Q.J.R. Meteorol. Soc., 88:90-95.
- Geng, S., F. W. T. Penning de Vries, and I. Supit, 1986. A simple method for generating daily rainfall data. Agricultural and Forest Meteorology 36:363-376.
- Geng, S. and J. Auburn, 1987. Weather simulation models based on summaries of long-term data. In: International Symposium on Impact of Weather Parameters on the Growth and Yield of Rice. April 7-10, 1986. IRRI. Manila, Philippines.
- Geng, S., J. Auburn, E. Brandstetter and B. Li, 1988. A program to simulate meteorological variables: Documentation for SIMMETEO. Agronomy Progress Report No. 204. Department of Agronomy and Range Science, University of California, Davis.
- Itenfisu, D., R.L. Elliot, R.G. Allen and I.A. Walter. 2000. Comparison of Reference Evapotranspiration Calculations across a Range of Climates. Proc. of the National Irrigation Symposium, November 2000, Phoenix, AZ, American Society of Civil Engineers, Environmental and Water Resources Institute, New York, NY

- Larsen, G.A. and R.B. Pense, 1982 Stochastic simulation of daily climate data for agronomic models. *Agron. J.* 74:510-514.
- Richardson, C. W. and D.A. Wright, 1984. WGEN: a model for generations daily weather variables. USDA-ARS-8, Springfield, VA.
- Snyder, R.L., K. Bali, F. Ventura, and H. Gomez-MacPherson. 2000. Estimating evaporation from bare or nearly bare soil. *J. of Irrig. & Drain. Engng.* 126 (6): 399-403.
- Stern, R.D., 1980. The calculation of probability distribution for models of daily precipitation. *Arch. Met. Geoph. Biokl., Ser. B*, 28:137-147.
- Stroosnijder, L. 1987. Soil evaporation: test of a practical approach under semi-arid conditions. *Netherlands Journal of Agricultural Science*, 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.